On the Importance of a Midlatitude Oceanic Frontal Zone

for the Baroclinic Annular Mode in the Southern Hemisphere

MORIO NAKAYAMA* (nakayama@atmos.rcast.u-tokyo.ac.jp)

Research Center for Advanced Science and Technology, The University of Tokyo, Tokyo, Japan

HISASHI NAKAMURA (hisashi@atmos.rcast.u-tokyo.ac.jp)

Research Center for Advanced Science and Technology, The University of Tokyo, Tokyo, Japan, and Japan Agency for Marine-Science and Technology, Yokohama, Japan

FUMIAKI OGAWA (fumiaki.ogawa@gfi.uib.no)

Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway

Submitted to J. Climate in May, 2020

* Corresponding author: Morio Nakayama, Research Center for Advanced Science and Technology, The University of Tokyo; E-mail: nakayama@atmos.rcast.u-tokyo.ac.jp
Abstract

As a major annular variability in the Southern Hemisphere, the baroclinic annular mode (BAM) represents the pulsing of extratropical eddy activity. This study assesses the influence of a midlatitude oceanic frontal zone on BAM and its dynamics through a set of “aqua-planet” atmospheric general circulation model experiments with zonally uniform sea-surface temperature (SST) profiles prescribed. Though idealized, one experiment with realistic frontal SST gradient well reproduces observed BAM signatures and time evolution as a manifestation of a typical lifecycle of migratory baroclinic eddies. In the other experiment, elimination of the frontal SST gradient leads to marked weakening and equatorward shift of the BAM-associated variability, in association with the corresponding modifications in the climatological-mean stormtrack activity. The midlatitude oceanic frontal zone enhances and thereby anchors the BAM variability by energizing sub-weekly eddies through maintaining near-surface baroclinicity and moisture supply to cyclones. The former is through anomalous heat supply from the ocean that acts to restore the near-surface baroclinicity under the anomalous meridional eddy heat flux. Those experiments and observations further indicate that BAM modulates eddy momentum flux to induce a modest but robust meridional shift of the polar-front jet, suggesting that BAM can help maintain the Southern Annular Mode.
1. Introduction

Large-scale tropospheric variability in the extratropical Southern Hemisphere (SH) is characterized by two types of “annular modes”. One is the Southern Annular Mode (SAM), which represents meridional shifts of an eddy-driven polar-frontal jet (PFJ) (Thompson and Wallace 2000). The other mode is the Baroclinic Annular Mode (BAM), which represents pulsing of extratropical eddy activity (Thompson and Woodworth 2014; hereafter referred to as TW14). SAM is often identified through an empirical orthogonal function (EOF) analysis applied to anomalies in zonal wind or sea-level pressure (SLP) within the extratropical SH, while BAM is through that to anomalous eddy kinetic energy (EKE).

TW14 pointed out that SAM and BAM play different roles in the energy cycle within the extratropical troposphere. SAM is associated with variability of both eddy momentum flux and kinetic energy of zonal-mean flow but with little variability of eddy heat flux and EKE, while the opposite is the case for BAM. From this viewpoint, SAM is driven by “barotropic” processes and thus referred to as “barotropic” annular mode, while BAM is driven by “baroclinic” processes and therefore named “baroclinic” annular mode. TW14 concluded that SAM and BAM are almost decoupled. TW14 also found that BAM is characterized by quasi-periodicity with period of 20–30 days. Thompson and Barnes (2014; hereafter referred
to as TB14) explained this periodicity by simple model that contains a negative feedback loop between extratropical baroclinicity, poleward eddy heat flux and radiative dumping. Wang and Nakamura (2015, 2016) confirmed the periodic behavior of EKE and eddy heat flux.

The extratropical energy cycle, in which SAM and BAM are involved, is mainly related to the fluxes of heat and momentum associated by wavy disturbances whose characteristics depend strongly on their time scales. Blackmon (1976) and Blackmon et al. (1977, 1984) found that low-frequency disturbances with periods longer than about a week show quasi-stationary features, which sometimes form blocking-flow configurations, while high-frequency sub-weekly disturbances are in a good correspondence with migratory synoptic-scale baroclinic eddies. Regions of large variance associated with high-frequency disturbances are called “stormtracks” where those baroclinic eddies recurrently develop.

Deepening our understanding of the dynamics of BAM variability that manifests pulsing of eddy activity should be based on our understanding of the mechanisms for a life cycle of baroclinic eddies. For efficient development of baroclinic eddies, strong meridional temperature gradient (i.e., baroclinicity) is required, as illuminated in linear theories by Charney (1947) and Eady (1949). In recent years, Nakamura et al. (2004) and Nakamura and Shimpo (2004) suggested the importance of midlatitude oceanic frontal zones, characterized
by pronounced meridional gradients of sea-surface temperature (SST) as the confluence zones of warm and cool ocean currents, in maintaining surface baroclinicity for recurrent development of baroclinic eddies. They showed that a sharp contrast of heat supply from the ocean across the frontal zone allows efficient restoration of surface baroclinicity relaxed by systematic poleward eddy heat transport. They argued that this efficient restoration can explain the observed tendency for the major stormtracks to form near the oceanic frontal zones. For example, the Antarctic Polar Frontal Zone (APFZ) is a circumpolar belt of strong SST gradients observed at 40–55ºS, and the core region of the SH stormtrack is collocated with the strongest SST gradient along APFZ in the South Indian Ocean (Nakamura and Shimpo 2004; Nakamura et al. 2004, 2008).

In order to highlight the importance of a midlatitude oceanic frontal zone for the stormtrack formation, Nakamura et al. (2008) compared a pair of aqua-planet atmospheric general circulation model (AGCM) experiments in which two different fields of zonally uniform SST were prescribed, one with frontal SST gradients in midlatitudes and the other without. They demonstrated that the frontal SST gradients energize baroclinic eddies and thereby anchor a stormtrack through the differential sensible heat supply across the oceanic frontal zone, referred to as “oceanic baroclinic adjustment” (Sampe et al. 2010). Its
effectiveness has been also confirmed in a high-resolution coupled GCM (Nonaka et al. 2009), a regional atmospheric model (Taguchi et al. 2009) and a steady response of a planetary-wave model (Hotta and Nakamura 2011). Through aqua-planet AGCM experiments, Ogawa et al. (2012) assessed the dependence of climatological stormtrack activity and PFJ on the latitude of an oceanic frontal zone, while Nakamura et al. (2008) and Sampe et al. (2013) pointed out that the oceanic frontal zone is necessary for realistic reproduction of SAM in the model. Ogawa et al. (2016) argued that SAM is a manifestation of wobbling between the two dynamical regimes; one is under the strong influence of the oceanic frontal zone and the other is controlled by atmospheric internal dynamics. These studies motivate us to assess the importance of an oceanic frontal zone for BAM manifested as pulsing of stormtrack activity.

The purpose of this study is to assess the impact of the oceanic frontal zone on BAM as observed in the SH and thereby deepen our understanding of its dynamics. As in the previous studies, we analyze output data of aqua-planet AGCM experiments with zonally uniform SST profiles. In the idealized “aqua-planet” setting, where no landmass and sea ice exist, the effect of planetary waves as seen especially in the Northern Hemisphere is suppressed, allowing us to investigate the fundamental dynamics of BAM.

The rest of this paper is structured as follows. Details of the aqua-planet experiments and
analysis procedures are described in section 2. After the overview of the climatological mean
fields simulated in our experiments presented in section 3, the features of BAM and the effect
of the oceanic frontal zone are described in section 4. Detailed dynamics of BAM and the
influence from the ocean are discussed in section 5 by investigating time evolution of BAM.
In section 6, our findings of the relationship between BAM and SAM are discussed. In section
7, we re-examine the quasi-periodic behavior of BAM pointed out by TW14 and TB14.
Concluding remarks are presented in section 8.

2. Data and Method

In this study, we analyze the output of aqua-planet experiments that 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). In the experiments, the model horizontal
resolution of T79, which corresponds to ~150 km grid intervals, is adequate to resolve strong
SST gradient associated with oceanic frontal zones as observed in the South Indian Ocean.
The model has 56 vertical levels up to 0.09 hPa.
As the model lower-boundary condition for the experiments, zonally uniform SST
profiles (Fig. 1) were prescribed with no landmass and sea ice, as in Sampe et al. (2010, 2013).
For assessing the effect of oceanic frontal zones, we compare the CTL and NF experiments conducted by Ogawa et al. (2012, 2016). The SST profile prescribed in the CTL experiment is based on the OISST data (Reynolds et al. 2007). The climatological SST profiles over the South Indian Ocean (60°-80°E) for austral winter (June-August) and austral summer (December-February) were prescribed to the model southern and northern hemispheres, respectively, which are characterized by oceanic frontal zones at 45° latitude in both hemispheres. In the NF experiment, by contrast, SST gradients in midlatitudes were replaced with a reduced uniform SST gradient to eliminate the oceanic frontal zones. In the CTL experiment SST gradients poleward of the frontal zones have been replaced with the same uniform SST gradient as in the NF experiment. In both experiments, the minimum of SST was set to −1.79°C to realize the ice-free condition. For robust statistics, the model was integrated for 120 months after 6 months of spin-up under perpetual insolation fixed to its solstice condition.

In this study, sub-weekly fluctuations of a given variable associated with transient eddies (denoted below by primes) are extracted with a high-pass filter with a cut-off period of 8 days, as in Ogawa et al. (2012, 2016). Eddy statistics, including eddy kinetic energy (EKE), meridional eddy heat and momentum fluxes, are defined locally as \( \frac{u'^2 + v'^2}{2} \), \( v'T' \) and \( u'v' \).
respectively, where the notations are standard. For conciseness, we define $v$ as poleward meridional flow, so that positive values of $v'T$ and $u'v'$ in each hemisphere correspond to poleward eddy fluxes of heat and westerly momentum, respectively. Low-frequency variability of a given variable and the corresponding modulations in the eddy statistics are extracted through 8-day low-pass filtering. Climatological means and anomalies are defined as 120-month means and deviations from them, respectively.

The model BAM is defined as the first EOF (EOF1) of low-frequency variability in $[EKE]$, where the square brackets represent zonal-mean statistics. The EOF analysis was applied separately to each of the model hemispheres within the meridional domain defined by 20$\degree$–70$\degree$ in latitude and from the 925 to 200 hPa levels. This domain is almost the same as used in TW14. Prior to the EOF analysis, the data has been weighted with both the square root of cosine of latitude and the mass represented by each vertical level. The normalized principal component time series for EOF1 is hereinafter referred to as a “BAM index”, and by definition its positive values correspond to positive anomalies of $[EKE]$.

As the reference dataset, we analyze the daily statistics derived from the Japanese 55-year reanalysis data (JRA-55; Kobayashi et al. 2015), which is available on a 1.25$\degree$×1.25$\degree$ grid system. The results here are based on the data from 1979 to 2017 (39 years). Climatological
means are calculated for each quantity by first applying 31-days running mean and then
39-year averaging for each calendar day. Anomalies of a given variable are defined as
deviations from its climatological means.

The BAM signature in JRA-55 has been extracted as EOF1 of 8-day low-pass-filtered
daily anomalies of [EKE] within the aforementioned meridional domain. The EOF analysis
was applied separately for the austral winter (June-August) and summer (December-February).
The data has been weighted as in the same manner as in the analysis for the aqua-planet
experiments.

3. Model reproducibility of the climatological-mean state

Before discussing the characteristics of the model-simulated BAM, we present an
overview in Figs. 2 and 3 of the climatological-mean eddy activity and \[u\], respectively,
simulated in the aqua-planet AFES experiments and observed in the SH. In both hemispheres
of the CTL experiment (Figs. 2c-d and 3c-d), both the stormtrack axis marked by meridional
maxima in [EKE] and \[v'T'\] and eddy-driven PFJ axis, into which upper-level eddy
momentum flux converges, are collocated near the oceanic frontal zone at 45º (indicated with
black triangles), as shown in previous studies (Nakamura et al. 2008; Sampe et al. 2010;
Ogawa et al. 2012). The removal of the oceanic frontal zones leads to a marked reduction in the stormtrack activity and PFJ strength in addition to equatorward shifts of their axes by ~5° (Figs. 2e-f and 3e-f). These results suggest that the oceanic frontal zones energize sub-weekly eddies and thereby anchor the stormtrack and PFJ climatologically (Nakamura et al. 2004, 2008).

Figures 2 and 3 also reveal the seasonality of the stormtrack and PFJ. In the lower and mid-troposphere the stormtrack activity measured by $[v'T']$ is somewhat weaker in the summer hemisphere than in the winter hemisphere, whereas the opposite is the case in the upper troposphere in both the experiments and reanalysis. The wintertime weakening of eddy activity around the midlatitude PFJ core is also evident in [EKE], especially in the CTL experiment and reanalysis. This is probably because part of the eddy activity tends to be trapped into the intense STJ core in winter (Nakamura and Shimpo 2004). Actually, the upper-level stormtrack measured by [EKE] is meridionally broader in winter, especially in the CTL experiment and reanalysis.

Though idealized, the CTL experiment thus well reproduces the seasonality in the stormtrack activity and the westerlies observed in the SH by Nakamura and Shimpo (2004) (Figs. 2a-b and 3a-b), including the close association among the stormtrack, eddy-driven PFJ
and the oceanic frontal zone (Nakamura et al. 2004). There is a slight difference, however, in
the latitudinal positions of their axes, which is \(~45^\circ\) in the CTL experiment but \(~50^\circ\) in the
observations. This is consistent with the slight latitudinal difference of the oceanic frontal
zone between the CTL experiment and observations (indicated with black and red triangles,
respectively). Furthermore, a near-surface maximum of \([v'T']\) observed at 60~65ºS in the
wintertime SH (Fig. 2b) is missing in the simulations. This is perhaps due to a strong thermal
contrast across the sea-ice edge, which can act as another baroclinic zone to energize eddies.

4. Model BAM and its sensitivity to the oceanic frontal zone

In each of the model hemispheres, EOF1 of [EKE], which represents BAM, explains
more than half of the total variance, as in the observations (Table 1). In each of the
experiments EOF1 accounts for a slightly smaller fraction of the [EKE] variance in winter
than in summer, as observed. Nevertheless, EOF1 is still dominant and well separated from
the second EOF (EOF2) in both seasons, according to the criterion by North et al. (1982).

Interestingly, EOF1 in the NF experiment is even better separated from EOF2 than in the CTL
experiment.

Figure 4 shows anomalies of [EKE] and \([v'T']\) both regressed against the BAM index,
which are thus typical for its positive phase. In the CTL experiment, broad meridional
monopole structures are evident in both the $[\text{EKE}]$ and $[\nu’T’]$ anomalies in each of the
hemispheres (Figs. 4c-d), which is overall consistent with the observed BAM (Figs. 4a-b) in
our analysis and TW14. These anomalies peak at the latitude of the oceanic frontal zone or
slightly poleward in both the CTL experiment and the reanalysis, corresponding to the peak
latitude of the climatological-mean stormtrack activity (Figs. 2a-d). Therefore, the BAM
represents such pulsing of the stormtrack activity that a unit standard deviation of the BAM
index corresponds to $\sim$25% increase in $[\text{EKE}]$ and $[\nu’T’]$ from their climatological means in
both the lower and upper troposphere, respectively.

Figure 5 shows anomalies of $[u]$ and $[u’v’]$ regressed against the BAM indices in the
same manner as in Fig. 4. In the CTL experiment, the regressed anomalies in $[u]$ exhibit
positive and negative peaks poleward and equatorward, respectively, of the climatological PFJ
core (Figs. 5c-d), as in the reanalysis (Figs. 5a-b). Therefore, BAM represents a slight
meridional shift of the PFJ axis rather than a pulsing of its intensity. This feature is consistent
with the anomalous eddy forcing on the PFJ via anomalous upper-level $[u’v’]$, which is
divergent around the anomalous easterlies and convergent around the anomalous westerlies
both in the reanalysis and CTL experiment (Figs. 5a-d). If composited separately for positive
and negative events of BAM, significant latitudinal differences of the PFJ axis (by 1~2º) are detected especially in the summer hemisphere for each of the two experiments and reanalysis (Table 2). Though not pointed out by TW14, these interesting BAM signatures observed in the PFJ will be discussed further in Section 6.

Figures 4 and 5 also reveal the seasonality of the BAM anomalies, which is not discussed by TW14, either. Upper-tropospheric anomalies in stormtrack activity are weaker in winter than in summer, while wintertime [EKE] anomalies are meridionally broader as pointed out by Wang and Nakamura (2016). In the lower and mid-troposphere, by contrast, anomalies in stormtrack activity, especially [v'T'], are stronger in the winter hemisphere. As pointed earlier, another peak of anomalous [v'T'] is observed in winter near surface of 60~65ºS. These BAM-associated anomalies in stormtrack activity and their seasonality are both coherent with their climatological-mean counterpart (Fig. 2), corresponding to the pulsing of the stormtrack activity as the characteristic of BAM (TW14). The seasonality in the structure and amplitude of the BAM anomalies thus reflects that in the climatological-mean stormtrack activity in both the CTL experiment and reanalysis.

In the NF experiment, the regressed anomalies of eddy activity and [u] are greatly weakened while shifted equatorward by 5~10º (Figs. 4e-f and 5e-f) relative to their
counterpart in the CTL experiment. The weakening in the anomalous stormtrack activity and

\[ [u] \] is \(~25\%\) in the upper troposphere, whereas that in lower-tropospheric \([v'T']\) reaches as

much as \(~60\%\). The marked weakening in the BAM anomalies due to the elimination of the

frontal SST gradient are very similar to those simulated in their climatological-mean fields

(Fig. 2). The magnitude ratio of the BAM anomalies to the corresponding climatological

means is thus comparable between the CTL and NF experiments. These results strongly

suggest the potential importance of the oceanic frontal zone for the BAM variability, which

will be discussed in detail in the next section.

5. Time evolution of BAM anomalies

The dynamics of the BAM anomalies can be understood deeper by investigating their

typical time evolution, as shown in lag-latitude sections in Figs. 6-9, where the anomalies are

regressed against the BAM indices for the aqua-planet experiments and the reanalysis. In the

summer hemisphere of the CTL experiment (middle row in Fig. 6), \([\text{EKE}]\) anomalies

maximize, by definition, simultaneously with the BAM index, while the peak times of \([v'T']\)

and \([\omega'T']\) anomalies precede the \([\text{EKE}]\) peak by \(~1\) day, where \(\omega\) denotes pressure velocity.

As pointed out by TW14, this lag relationship is consistent with the energetics of baroclinic
development of synoptic-scale eddies from zonal-mean available potential energy to eddy available potential energy (EAPE) and then to EKE. The peak times of the \([u'v']\) and \([u]\) anomalies lag the [EKE] anomaly peak by ~1 day and 1~3 days, respectively, which is also consistent with the energy conversion from EKE to zonal-mean kinetic energy. The entire evolution of the BAM signature thus corresponds to a typical lifecycle of baroclinic eddies. The aforementioned lead-lag relationship overall holds also in the reanalysis (left panels in Fig. 6), confirming the reproducibility of the BAM dynamics in the CTL experiment. The lead-lag relationship holds also in the NF experiment (right panels in Fig. 6), although the corresponding anomalies are entirely displaced equatorward and the \([u'v']\) anomalies peak almost simultaneously with the [EKE] anomalies. These experiments therefore suggest that the essential dynamics of BAM is atmospheric internal dynamics and frontal SST gradients energize sub-weekly baroclinic eddies, thus augmenting the BAM variability. In fact, magnitudes of the anomalous eddy activity and \([u]\) are reduced by 25%~60% in the NF experiment relative to the CTL experiment (Figs. 4 and 5).

The influence of the oceanic frontal zones on the BAM anomalies can be highlighted in the associated heat and moisture exchanges with the underlying ocean as revealed in their lag-regression anomalies (Fig. 7). In each of the experiments and the reanalysis, the positive
phase of BAM accompanies anomalies in surface air temperature (SAT) that are negative in
the subtropics and positive in midlatitudes (Figs. 7a-c). This is due to the enhanced poleward
eddy heat transport associated with BAM as evident in the delayed peak of the midlatitude
SAT anomalies. As a result, meridional SAT gradient across the stormtrack is reduced, but the
reduction accounts only for 1% of the climatological value for each of the experiments per
unit standard deviation of the BAM index. Likewise, the corresponding fractional reduction in
the 925-hPa temperature gradient is also only 5% (3%) in the CTL (NF) experiment (not
shown). As seen in Figs. 7d-f, anomalies of sensible heat flux (SHF) from the ocean exhibit
almost the same latitudinal distribution as that of SAT but with the opposite signs (Figs. 7a-c).
For each of the experiments, they correspond to 9% increase in the meridional SHF gradient
from its climatology across the oceanic frontal zone. Thus, the SHF anomalies act to restore
the meridional gradient of near-surface temperature modified by BAM, as climatologically
operative along oceanic frontal zones (Nonaka et al. 2009; Sampe et al. 2010; Hotta and
Nakamura 2011). Under the assumption of the 1-km depth for the atmospheric mixed layer,
the above restoration is very efficient with a typical timescale of less than a day. In the SH,
despite landmasses and zonal asymmetries of the SST front, the above restoration is still
evident with comparable efficiency around 45ºS, where the major oceanic frontal zone exists
The comparison between the CTL and NF experiments highlights the influence of the oceanic frontal zone. In the CTL experiment, meridional SHF gradient is enhanced across the oceanic frontal zone at 45º (Fig. 7e) under the enhanced \([v'T']\) (Fig. 6b), which allows the efficient restoration of the meridional SAT gradient to maintain the anomalous eddy activity. In fact, similar association is found also in the observed BAM (Figs. 6a and 7d). In the NF experiment, however, the meridional gradient of the anomalous SHF weakens by ~65% compared with the CTL experiment (Fig. 7f). Reflecting the weakness of the background SAT gradient, the restoration time scale for the meridional SAT gradient is also shorter than a day but still ~10% longer than in the CTL experiment. These results suggest that the enhanced anomalous SHF in the presence of the oceanic frontal zone allows the effective restoration of near-surface baroclinicity for recurrent development of baroclinic disturbances and thereby maintains enhanced eddy activity during the positive phase of BAM.

The BAM activity is also associated with zonal-mean moisture anomalies. In both the CTL experiment and reanalysis, the precipitation anomaly peaks simultaneously with the \([EKE]\) anomaly around 55º latitude (Figs. 7j-k), primarily on the poleward side of the stormtrack. The anomaly represents enhanced condensation associated with poleward-moving
warm, moist airflows under the augmented stormtrack activity. Energetically, the enhanced latent heat release within the warm poleward airflow leads to increased EAPE generation. The enhanced precipitation also corresponds to the peak of anomalous \[-\omega'T'\] for the increased conversion of EAPE to EKE (Fig. 6e). The EAPE generation by enhanced precipitation is evident also in the reanalysis, where the peak time of anomalous precipitation at 45~50°S around the stormtrack axis precedes the [EKE] peak by 1~2 days (Fig. 7j). The precipitation anomaly can be supported in part by anomalous evaporation (i.e., latent heat flux (LHF)) from the warm ocean under the subtropical high-pressure belt (~30° latitude, marked with a zero line of climatological near-surface [u] in Fig. 3) (Fig. 7h). Actually, anomalous poleward eddy moisture flux is observed in the lower troposphere (not shown).

In the NF experiment, the subpolar center of precipitation anomalies shifts equatorward by ~5° in addition to another peak at ~40° latitude. This equatorward shift is consistent with the corresponding shift of stormtrack activity (Figs. 3c-f). The precipitation anomaly is ~20% larger than in the CTL experiment in spite of the weaker anomalous stormtrack activity (Figs. 7k-l). This is probably because SST poleward of the oceanic frontal zone at 45° is higher in the NF experiment than in the CTL experiment (Fig. 1a). The anomalous LHF is slightly stronger in the CTL experiment (Figs. 7h-i), similar to the anomalous SHF.
The time evolution of the BAM anomalies in the winter hemisphere is shown in Figs. 8 and 9 in the same manner as in Figs. 6 and 7, respectively. As in the summer hemisphere, the essential dynamics of BAM in the CTL experiment corresponds to a typical lifecycle of baroclinic eddies (Fig. 8), which is overall consistent with its counterpart in the reanalysis. In the NF experiment, anomalies in eddy activity and \([u]\) are largely weakened by the removal of the oceanic frontal zone, which again highlights the above-mentioned impacts of the frontal SST gradient on BAM. Compared with the summer hemisphere, however, this weakening is less marked in the upper-tropospheric anomalies in \([\text{EKE}]\) and \([u'v']\), maybe because the enhanced wintertime STJ acts as an effective waveguide (Nakamura and Shimpo 2004). Still, the weakening is pronounced in the lower-tropospheric \([v'T']\) anomalies under the removal of the SST front (Figs. 8b-c). The wintertime anomalies in SHF and LHF associated with BAM are qualitatively the same as those in the summer hemisphere (Figs. 9d-i). The peak of the wintertime LHF anomaly shifts into the subtropics (20°-30° latitude) in both experiments and the reanalysis, which is consistent with the meridional broadening of the BAM anomalies. It is also consistent with equatorward shifts of the Hadley cell and subtropical high-pressure belt (identified as lines of climatological near-surface \([u] = 0\) in Fig. 3).
6. Relationship between BAM and SAM

As shown in Figs. 6m-r, the summertime BAM-associated maximum of [EKE] anomalies in each of the two experiments and the reanalysis tends to slightly precede the corresponding \([u]\) anomalies that represent the slight meridional shift of the PFJ with a certain projection onto SAM-associated \([u]\) anomalies. This result suggests non-negligible relationship between BAM and SAM, which was not pointed out by TW14. To show this statistically, we have defined a SAM index for each experiment or the reanalysis by applying an EOF analysis to low-frequency \([u]\) anomalies within the same domain as used for defining the BAM index. Figures 10a-d compare the meridional profiles of 300-hPa \([u]\) anomalies associated with SAM and BAM. In each of the reanalysis and two experiments and regardless of the season, the BAM-associated \([u]\) anomalies are found to exhibit a strong projection onto those with SAM, while the former is substantially weaker than the latter. In the reanalysis, for example, the BAM anomalies in \([u]\) are only \(~20\%\) in strength of the corresponding SAM anomalies for each season, whereas the corresponding fractions are around 35% and 45% for the CTL and NF experiments, respectively. In the summer hemisphere (Figs. 10a,c), the \([u]\) anomalies associated with BAM and SAM share very similar latitudinal profiles with respect to their maxima, minima and nodes. The similarity is reduced, however, in the winter hemisphere...
(Figs. 10b,d), but the two \([u]\) anomalies still overlap poleward of the climatological PFJ axis.

In Figs. 10e-h the meridional profiles of 300-hPa [EKE] anomalies are compared between SAM and BAM in the same manner as in Figs. 10a-d. As pointed by TW14, the [EKE] anomalies are much stronger for BAM, as a manifestation of pulsing of stormtrack activity (Figs. 10e-f). Except in the summer hemisphere of the NF experiment, the poleward PFJ shift with the positive SAM is preceded by ~1 day by the peak of poleward extension or shift of the stormtrack (Figs. 10g-h, evolution of the SAM anomalies is not shown) rather than its pulsing. Nevertheless, the [EKE] anomalies associated with BAM and SAM considerably overlap on the poleward side of the climatological-mean stormtrack (Figs. 10e-h).

These results suggest non-negligible relationship between the BAM and SAM anomalies, which was not pointed out by TW14. To confirm this relationship, we calculate lag-correlation coefficients and coherence between the BAM and SAM indices. Their cross and power spectra necessary to calculate their squared coherence have been obtained in the same manner as described in section 7. As evident in Figs. 11a-b, the correlation between the BAM and SAM indices is found to maximize when the latter is lagged by 1~3 days. Their maximum correlation is rather weak (around +0.2) but significantly positive in both experiments and the reanalysis. In the reanalysis, their coherence squared is found to exhibit a
significant peak (> +0.2) for the 30-50 day period in each of the seasons (not shown), which is
reproduced only in the winter hemisphere of the NF experiment. Otherwise, their coherence
squared in the model is significant at longer periods (not shown). Their phase relationships
are found consistent with the aforementioned lag-correlation analyses, confirming that BAM
acts to strengthen SAM.

7. Periodicity of the BAM index

In this section, we examine whether quasi-periodic behavior of BAM shown by TW14
and TB14 can be verified in our datasets by computing power spectra of our BAM indices
based on sub-weekly eddies, in the following manner. A daily BAM index for a given
hemisphere of a particular aqua-planet experiment was first divided into 256-day segments
with 128-day overlaps between the adjacent segments. Each of the segments was then tapered
with a cos10 window before exposed to 5-day running mean. The spectra obtained for all the
segments were finally averaged to obtain a single spectrum with at least 168 degrees of
freedom. Likewise, the daily BAM indices based on the JRA-55 were also divided into
256-day segments, but separately for warm (from 9 September to 21 or 22 May) and cold
(from 11 March to 21 November) seasons. Power spectra were then calculated separately for
each season in the same manner as for the aqua-planet experiments.

Figures 12a-b show the observed BAM spectra, which are characterized by marginally significant peaks at the periods of 25~30 days and 30~40 days for the warm and cold seasons, respectively. This result is consistent with the observed quasi-periodic behavior of BAM as pointed out by TW14 and TB14, while suggesting its slight seasonality. Meanwhile, the BAM spectrum for each of the aqua-planet experiments (Figs. 12c-f) exhibits no distinct peak except for the summer hemisphere of the NF experiment. Nevertheless, the spectra for the simulated BAM deviate significantly from the corresponding red spectra for the periods longer than 20 days.

Although the periodic behavior of BAM is hinted as above in both the reanalysis and aqua-planet experiments, the corresponding spectral peaks are less distinct than those found in the previous studies (e.g., TW14). This is probably because of our extraction of sub-weekly eddies through high-pass filtering for calculating the BAM indices. To confirm this, we repeated the spectral analysis but applied to the BAM indices defined as in the previous studies. Specifically, we recalculated EKE from deviations from the zonal means before exposed to an EOF analysis. As shown in Fig. 13, the power spectrum thus calculated for the BAM index based on the JRA-55 data for each of the warm and cold seasons of the SH
exhibits a distinct peak at the periods of 20–30 days, in good agreement with TW14, TB14, Wang and Nakamura (2015, 2016) and Boljka et al. (2018). The spectral peak is more evident for the warm season than for the cold season, as pointed out by Wang and Nakamura (2016). The distinct peaks are also found in the corresponding spectra for the CTL and NF experiments except for the summer hemisphere of the NF experiment. These results suggest that periodic behavior of BAM is essentially owing to internal atmospheric dynamics. They also suggest that contributions not only from sub-weekly baroclinic eddies but also from low-frequency quasi-stationary eddies should be considered to fully understand the mechanisms for the periodic behavior of BAM.

8. Discussion and concluding remarks

In the present study, the importance of a midlatitude oceanic frontal zone for BAM is assessed through a comparison between aqua-planet AGCM experiments with and without the realistic frontal SST gradient. Though idealized, the aqua-planet experiment with the midlatitude frontal SST gradient well reproduces the BAM variability observed in the SH that represents pulsing of midlatitude stormtrack activity measured by EKE and poleward heat flux associated with sub-weekly eddies. The elimination of the midlatitude frontal SST
gradient yields marked weakening in the BAM-associated anomalies of stormtrack activity and the equatorward shift of the BAM signatures. These modifications in the BAM variability due to the removal of the oceanic frontal zone are in good correspondence to those in the climatological stormtrack activity, which can be attributed to the marked reduction of near-surface baroclinicity maintained by differential heat supply across the midlatitude oceanic frontal zone (Nakamura et al. 2008; Sampe et al. 2010; Hotta and Nakamura 2011). In other words, the midlatitude oceanic frontal zone enhances and anchors the BAM variability by energizing baroclinic eddies through maintaining near-surface baroclinicity. Specifically, anomalous SHF from the ocean associated with BAM around the oceanic frontal zone acts to restore meridional near-surface SAT gradient modulated by anomalous poleward eddy heat flux and thereby maintain the BAM variability. Comparison between the two experiments demonstrates that this restoring effect is effective enough against enhanced modulations of near-surface baroclinicity by BAM in the presence the oceanic frontal zone.

Unlike in previous studies (e.g., TW14), we analyzed the BAM-associated modulations of sub-weekly eddy activity, which has led to the elucidation of the dynamical characteristics of BAM as a manifestation of a typical lifecycle of baroclinic eddies. We have revealed that the BAM-modulated sub-weekly eddy activity alters eddy momentum flux, acting to induce
zonal wind anomalies that have a significant projection onto those associated with SAM. This new finding suggests that BAM can help maintain SAM through modifying westerly momentum transport by transient eddies. It has been shown that SAM owes its existence to barotropic forcing by transient eddy activity for maintaining PFJ and its meridional migration (e.g., Thompson and Wallace 2000; Lorentz and Hartmann 2001; Sampe et al. 2013). Our study suggests that the BAM-modulated sub-weekly eddy activity may also contribute to SAM variability. It remains unsolved why SAM and BAM variations become uncorrelated if one extracts BAM variability from all eddy activities defined as departures from the zonal means. For solving this issue, assessing the contributions from low-frequency quasi-stationary eddies to BAM variability is probably useful, although it is beyond the scope of the present study. The assessment may also be useful for deepening our understanding of the periodic behavior of BAM.

It should be noted that, owing to their idealized setting, our aqua-planet AGCM experiments are not designed for fully reproducing the BAM variability observed in the SH but rather for extracting its fundamental dynamics. For example, the SST field prescribed for our CTL experiment is zonally uniform and taken from its climatological field in the South Indian Ocean, where one of the most distinct frontal SST gradients is observed (Nakamura
and Shimpo 2004; Nakamura et al. 2004). Thus, the impact of the oceanic frontal zone on BAM should be somewhat overestimated in our CTL experiment if compared with its counterpart observed in the SH. In fact, Ogawa et al. (2016) demonstrated that the behavior of the observed SAM depends on the latitudinal position of the oceanic frontal zone over each of the ocean basins, leading to zonal asymmetries in the SAM signature. Investigation of the zonal asymmetries in BAM signatures over the SH will be conducted in our future study.

Furthermore, prescribing the fixed SST profiles for our aqua-planet AGCM experiments is also unrealistic. In reality, both the SST and westerly fields vary on interannual and longer time scales, for example, under the remote influence from the Tropics. The effect of sea ice may not be negligible, as the wintertime BAM signature in near-surface meridional eddy heat flux is maximized around 65°S (Fig. 3b). The impact of sea ice on BAM cannot be assessed in our aqua-planet experiments and will therefore be addressed in a different framework in our future study. Nevertheless, the characteristics of BAM simulated in the CTL experiment, including its structure, time evolution and periodicity, are similar to those observed in the SH, indicating that the essential dynamics of BAM associated primarily with migratory baroclinic eddies is extracted in our aqua-planet experiment with midlatitude frontal SST gradient.

Following the previous studies, including TW14, TB14, Wang and Nakamura (2015,
and Boljka et al. (2018), we used zonal-mean statistics of eddy activity and the background state in recognition of the high annularity of BAM. One should keep it in mind, however, that BAM variability is a manifestation of eastward propagating transient eddies along the stormtrack (TW14). The zonal averaging automatically eliminates zonally asymmetric processes, including downstream development of baroclinic eddies. In our future study, investigating the modulated behavior of individual synoptic-scale eddies typical for the onset, peak and decay stages of the positive and negative phases of BAM will provide deeper insight into the BAM dynamics with implications for local influence of BAM and improvement of its predictability.
Acknowledgments: This study is supported in part by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through a Grant-in-Aid for Scientific Research in Innovative Area 6102 and the Arctic Challenge for Sustainability (ArCS-2) Program, by the Japanese Ministry of Environment through the Environment Research and Technology Development Fund 2-1904 and by the Japan Science and Technology Agency through Belmont Forum CRA “InterDec”. The JRA-55 reanalysis dataset has been provided through the Data Consortium of the Japan Meteorological Agency, and the NOAA Optimum Interpolation SST data (OISST) through the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their website (http://www.cdc.noaa.gov/). The Grid Analysis and Display System (GrADS), NCAR Command Language (NCL) and Gnuplot were used for drawing figures.
References


Kobayashi, S., and Coauthors, 2015: The JRA-55 Reanalysis: General specifications and basic


Thompson, D. W. J., and J. D. Woodworth, 2014: Barotropic and baroclinic annular variability in


Table 1  Fraction (%) of the total variance of [EKE] explained by EOF1 (EOF2).

<table>
<thead>
<tr>
<th></th>
<th>summer</th>
<th>winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>JRA-55</td>
<td>65.9 (18.2)</td>
<td>52.9 (23.1)</td>
</tr>
<tr>
<td>CTL</td>
<td>62.7 (20.3)</td>
<td>56.2 (18.9)</td>
</tr>
<tr>
<td>NF</td>
<td>70.0 (10.7)</td>
<td>60.1 (16.5)</td>
</tr>
</tbody>
</table>
TABLE 2  Latitudes (°) of PFJ axis, defined as the 850-hPa $[u]$ maximum, averaged separately for the positive and negative phases of BAM. The former and latter are defined as the days when the BAM index exceeds a unit standard deviation positively and negatively, respectively. Latitudinal differences between the two phases ("positive" minus "negative") are shown in the bottom row. Asterisks (*) denote the difference significant at the 95% confidence level. The zonal-mean latitude of the midlatitude oceanic frontal zone is indicated in parentheses.

<table>
<thead>
<tr>
<th></th>
<th>summer</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JRA-55</td>
<td>CTL</td>
<td>NF</td>
<td>JRA-55</td>
<td>CTL</td>
<td>NF</td>
</tr>
<tr>
<td></td>
<td>(48.3°)</td>
<td>(45.6°)</td>
<td></td>
<td>(48.5°)</td>
<td>(45.6°)</td>
<td></td>
</tr>
<tr>
<td>BAM positive</td>
<td>50.40</td>
<td>47.47</td>
<td>41.93</td>
<td>51.38</td>
<td>48.47</td>
<td>43.81</td>
</tr>
<tr>
<td>BAM negative</td>
<td>49.93</td>
<td>45.91</td>
<td>41.57</td>
<td>50.93</td>
<td>46.88</td>
<td>42.62</td>
</tr>
<tr>
<td>difference</td>
<td>*0.47</td>
<td>*1.56</td>
<td>*0.36</td>
<td>0.45</td>
<td>*1.59</td>
<td>*1.19</td>
</tr>
</tbody>
</table>
Figure Caption List

FIG. 1. Latitudinal profiles of (a) SST (°C) prescribed as the lower-boundary conditions for AGCM experiments and (b) magnitudes of its meridional gradient (°C/100 km). The profiles for CTL and NF experiments are plotted with black and blue solid lines, respectively.

FIG. 2. Meridional sections of the climatological-mean [EKE] (contour, m²/s²) and [v’T’] (shading, K•m/s) based on JRA-55 for the SH (a) summer and (b) winter. (c) and (d): As in (a) and (b), respectively, but for the model (c) summer and (d) winter hemispheres of the CTL experiment. (e) and (f): As in (c) and (d), respectively, but for the NF experiment. Red triangles indicate zonally-averaged latitudes of the oceanic frontal zone observed in the SH (~48.5°S), as calculated by zonally averaging the latitudes of the maximum SST gradient, weighted by the magnitude of the corresponding SST gradient. Black triangles indicate corresponding latitude in the SST profile for the CTL experiment (45.6°), which are also indicated with blue cusps for the NF experiment as a reference.

FIG. 3. As in Fig. 2, but for the climatological-mean [u] (contour, m/s; dashed lines for the easterlies) and [u’v’] (shading, m²/s²). Purple dotted lines represent zero lines of [u].

FIG. 4. As in Fig. 2, but for anomalies in [EKE] (contour, m²/s²) and [v’T’] (shading, K•m/s)
regressed against the BAM index based on JRA-55 for the SH (a) summer and (b) winter. (c) and (d): As in (a) and (b), respectively, but for the model (c) summer and (b) winter hemispheres in the CTL experiment. (e) and (f): As in (c) and (d), respectively, but for the NF experiment. [EKE] and \([v'T']\) anomalies precede the corresponding BAM index by 0 and 1 day, respectively.

FIG. 5. As in Fig. 4, but for the anomalies in \([u]\) (contour, m/s) and \([u'v']\) (shading, m²/s²) regressed onto the BAM index. \([u]\) and \([u'v']\) anomalies lag corresponding index by 2 and 0 days, respectively.

FIG. 6. Lag-latitude sections of anomalous (a) 850 hPa \([v'T']\), (d) 500 hPa \([-\omega'T']\), (g) 300 hPa \([EKE]\), (j) 300 hPa \([u'v']\), (m) 300 hPa \([u]\) and (p) 925 hPa \([u]\), based on JRA-55 for the summertime SH. (b), (e), (h), (k), (n), (q): As in (a), (d), (h), (j), (m), (p), respectively, but for the summer hemisphere of the CTL experiment. (c), (f), (i), (l), (o), (r): As in (b), (e), (h), (k), (n), (q), respectively, but for the NF experiment. Each panel represents typical evolution of anomalies of a particular variable during the positive phase of 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 (a-c) ±0.3, ±0.9, ±1.5, … (K·m/s), (d-f)
±0.003, ±0.009, ±0.015, … (Pa/s), (g-i) ±4, ±12, ±20, … (m²/s²), (j-l) ±2, ±6, ±10, … (m²/s²), (m-o) ±0.2, ±0.6, ±1.0, … (m/s), (p-r) ±0.1, ±0.3, ±0.5, … (m/s). Dashed lines are for negative anomalies. Red and blue shading shows the 95% confidence level of the corresponding positive and negative correlations, respectively. Triangles and cusps are the same as in Fig. 2.

FIG. 7. As in Fig. 6, but for BAM-associated anomalies in (a-c) 2 m temperature (SAT), (d-f) sensible heat flux (SHF), (g-i) latent heat flux (LHF) both from the ocean and (j-l) precipitation. Contours are drawn for (a-c) ±0.01, ±0.03, ±0.05, … (K), (d-f) ±0.2, ±0.6, ±1.0, … (W/m²), (g-i) ±1, ±3, ±5, … (W/m²), (j-l) ±0.04, ±0.12, ±0.20, … (mm/day).

FIG. 8. As in Fig. 6, but for the wintertime SH based on the JRA-55 and the winter hemispheres of the CTL and NF experiments.

FIG. 9. As in Fig. 7, but for wintertime SH based on the JRA-55 and the winter hemispheres of the CTL and NF experiments.

FIG. 10. Latitudinal profiles of anomalous 300-hPa [u] (m/s) regressed on (a-b) BAM and (c-d) SAM index for the (a, c) summer and (b, d) winter hemispheres. Thick and thin vertical
lines represent the latitude of the climatological PFJ (maximum 850-hPa \( u \)) for the summer and winter hemispheres, respectively) and STJ (peaks of 300-hPa \( u \) for the winter hemisphere), respectively. (e-h): As in (a-d), respectively, but for anomalous 300-hPa [EKE]. Vertical lines represent the latitudinal positions of climatological stormtrack axes detected as peaks of 300-hPa [EKE]. Red, black and blue colors indicate the results for the SH based on JRA-55, the CTL and NF experiments, respectively. Dots indicate the corresponding anomalies with significant correlations at the 95% confidence level. Each anomaly lags the corresponding index by +2, 0, 0 and –1 days for (a-b), (c-d), (e-f) and (g-h), respectively. Red and blue triangles indicate the zonally-averaged latitudes of the oceanic frontal zone observed in the SH and in the SST profile for the CTL experiment, respectively.

FIG. 11. Cross-correlation function between BAM and SAM indices for (a) summertime and (b) wintertime SH based on the JRA-55 (solid line) and the CTL (dashed line) and NF (dotted line) experiments. Positive lags mean that the BAM index leads the SAM index. Dots indicate statistically significant correlations with the 95% confidence.

FIG. 12. Power spectra of the BAM indices (black line) observed in the SH (a) warm and (b) cold seasons and simulated for the (c) summer and (d) winter hemispheres in the CTL
experiment. (e-f): As in (c) and (d), respectively, but for the NF experiment. Grey lines indicate the 95% confidence interval of the spectra. Vertical dashed lines represent the periods of 20 and 30 days. See the text for details.

FIG. 13. As in Fig. 12, but for the BAM indices derived from eddies in the same manner as in TW14 and other previous studies.
FIG. 1. Latitudinal profiles of (a) SST (°C) prescribed as the lower-boundary conditions for AGCM experiments and (b) magnitudes of its meridional gradient (°C/100 km). The profiles for CTL and NF experiments are plotted with black and blue solid lines, respectively.
FIG. 2. Meridional sections of the climatological-mean [EKE] (contour, m$^2$/s$^2$) and [$v' T'$] (shading, K$\cdot$m/s) based on JRA-55 for the SH (a) summer and (b) winter. (c) and (d): As in (a) and (b), respectively, but for the model (c) summer and (d) winter hemispheres of the CTL experiment. (e) and (f): As in (c) and (d), respectively, but for the NF experiment. Red triangles indicate zonally-averaged latitudes of the oceanic frontal zone observed in the SH (~48.5°S), as calculated by zonally averaging the latitudes of the maximum SST gradient, weighted by the magnitude of the corresponding SST gradient. Black triangles indicate
corresponding latitude in the SST profile for the CTL experiment (45.6°), which are also indicated with blue cusps for the NF experiment as a reference.
FIG. 3. As in Fig. 2, but for the climatological-mean $[u]$ (contour, m/s; dashed lines for the easterlies) and $[u'v']$ (shading, m$^2$/s$^2$). Purple dotted lines represent zero lines of $[u]$. 
FIG. 4. As in Fig. 2, but for anomalies in \[EKE\] (contour, m²/s²) and \[\nu'T'\] (shading, K•m/s) regressed against the BAM index based on JRA-55 for the SH (a) summer and (b) winter. (c) and (d): As in (a) and (b), respectively, but for the model (c) summer and (b) winter hemispheres in the CTL experiment. (e) and (f): As in (c) and (d), respectively, but for the NF experiment. \[EKE\] and \[\nu'T'\] anomalies precede the corresponding BAM index by 0 and 1 days, respectively.
FIG. 5. As in Fig. 4, but for the anomalies in \( [u] \) (contour, m/s) and \([u'v']\) (shading, m²/s²) regressed onto the BAM index. \([u]\) and \([u'v']\) anomalies lag corresponding index by 2 and 0 days, respectively.
FIG. 6. Lag-latitude sections of anomalous (a) 850 hPa [v’T’], (d) 500 hPa [−ω’T’], (g) 300 hPa [EKE], (j) 300 hPa [u’v’], (m) 300 hPa [u] and (p) 925 hPa [u], based on JRA-55 for the summertime SH. (b), (e), (h), (k), (n), (q): As in (a), (d), (h), (j), (m), (p), respectively, but for the summer hemisphere of the CTL experiment. (c), (f), (i), (l), (o), (r) : As in (b), (e), (h), (k), (n), (q), respectively, but for the NF experiment. Each panel represents typical evolution of anomalies of a particular variable during the positive phase of 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 (a-c) $\pm 0.3, \pm 0.9, \pm 1.5, \ldots$ ($K\cdot m/s$), (d-f) $\pm 0.003, \pm 0.009, \pm 0.015, \ldots$ ($Pa/s$), (g-i) $\pm 4, \pm 12, \pm 20, \ldots$ ($m^2/s^2$), (j-l) $\pm 2, \pm 6, \pm 10, \ldots$ ($m^2/s^2$), (m-o) $\pm 0.2, \pm 0.6, \pm 1.0, \ldots$ ($m/s$), (p-r) $\pm 0.1, \pm 0.3, \pm 0.5, \ldots$ ($m/s$). Dashed lines are for negative anomalies. Red and blue shading shows the 95% confidence level of the corresponding positive and negative correlations, respectively. Triangles and cusps are the same as in Fig. 2.
FIG. 7. As in Fig. 6, but for BAM-associated anomalies in (a-c) 2 m temperature (SAT), (d-f) sensible heat flux (SHF), (g-i) latent heat flux (LHF) both from the ocean and (j-l) precipitation. Contours are drawn for (a-c) ±0.01, ±0.03, ±0.05, … (K), (d-f) ±0.2, ±0.6, ±1.0, … (W/m²), (g-i) ±1, ±3, ±5, … (W/m²), (j-l) ±0.04, ±0.12, ±0.20, … (mm/day).
FIG. 8. As in Fig. 6, but for the wintertime SH based on the JRA-55 and the winter hemispheres of the CTL and NF experiments.
FIG. 9. As in Fig. 7, but for wintertime SH based on the JRA-55 and the winter hemispheres of the CTL and NF experiments.
FIG. 10. Latitudinal profiles of anomalous 300-hPa \([u]\) (m/s) regressed on (a-b) BAM and (c-d) SAM index for the (a, c) summer and (b, d) winter hemispheres. Thick and thin vertical lines represent the latitude of the climatological PFJ (maximum 850-hPa \([u]\) for the summer and winter hemispheres, respectively) and STJ (peaks of 300-hPa \([u]\) for the winter hemisphere), respectively. (e-h): As in (a-d), respectively, but for anomalous 300-hPa \([\text{EKE}]\).
Vertical lines represent the latitudinal positions of climatological stormtrack axes detected as peaks of 300-hPa [EKE]. Red, black and blue colors indicate the results for the SH based on JRA-55, the CTL and NF experiments, respectively. Dots indicate the corresponding anomalies with significant correlations at the 95% confidence level. Each anomaly lags the corresponding index by +2, 0, 0 and −1 days for (a-b), (c-d), (e-f) and (g-h), respectively. Red and blue triangles indicate the zonally-averaged latitudes of the oceanic frontal zone observed in the SH and in the SST profile for the CTL experiment, respectively.
FIG. 11. Cross-correlation function between BAM and SAM indices for (a) summertime and (b) wintertime SH based on the JRA-55 (solid line) and the CTL (dashed line) and NF (dotted line) experiments. Positive lags mean that the BAM index leads the SAM index. Dots indicate statistically significant correlations with the 95% confidence.
FIG. 12. Power spectra of the BAM indices (black line) observed in the SH (a) warm and (b) cold seasons and simulated for the (c) summer and (d) winter hemispheres in the CTL experiment. (e-f): As in (c) and (d), respectively, but for the NF experiment. Grey lines indicate the 95% confidence interval of the spectra. Vertical dashed lines represent the periods of 20 and 30 days. See the text for details.
FIG. 13. As in Fig. 12, but for the BAM indices derived from eddies in the same manner as in TW14 and other previous studies.