Frequency-dependent behavior of the barotropic and baroclinic modes of zonal jet variability in a dry dynamical core model

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Abstract

An idealized dynamical core model is used to explore the differences between the low- and high-frequency (periods greater and less than 30 days) behavior of the first two principal components of zonal mean zonal wind and eddy kinetic energy, i.e., the barotropic/baroclinic annular modes of variability of the extratropical circulation. The modes show similar spatial characteristics in the different frequency ranges considered, however the ranking of the modes switches in some cases from one range to the other. There is some cancelation in the signatures of eddy heat flux and eddy kinetic energy in the leading low-pass and high-pass filtered zonal wind mode, partly explaining their small signature in the total. At low frequencies, the first zonal wind mode describes latitudinal shifts of both the midlatitude jet and its associated storm tracks, and the persistence of zonal wind anomalies appears to be sustained primarily by a baroclinic, rather than a barotropic, feedback. On shorter time scales, the behavior is more complicated and transient.
1. Introduction

The leading modes of variability of the extratropical circulation are referred to as “annular modes” (see, e.g. Thompson and Wallace, 2000, and Thompson et al. 2000), and are usually derived using Empirical Orthogonal Function (EOF) analysis of meteorological fields such as geopotential height and zonal mean zonal wind. Limpasuvan and Hartmann (1999, 2000) and Lorenz and Hartmann (2001, 2003) described the eddy-mean flow interactions that maintain the annular modes. Karoly (1990), Hartmann and Lo (1998) and Lorenz and Hartmann (2001), amongst others, have argued that in the Southern Hemisphere, there is a positive feedback between high frequency (synoptic) eddies and the zonal mean flow. In each hemisphere, the leading EOF of zonal wind takes the form of a dipolar structure centered on the mean jet which, alone, would describe latitudinal fluctuations of the jet. The second EOF peaks at the maximum of the mean jet, with reversed sign in its wings; alone, this component describes intensification and narrowing of the jet. However, these modes are not mutually independent and, together, they describe the poleward propagation of jet anomalies (James and Dodd, 1996; Feldstein 1998; Lee et al., 2007) through nonzero lag-correlations (Sparrow et al., 2009).

More recently, Thompson and Woodworth (2014) and Thompson and Barnes (2014) argued that variability in the Southern Hemisphere extratropical zonal flow could be described in terms of two distinct structures: a mode with an equivalent-barotropic-like structure (the Southern Annular Mode, or SAM, derived from EOF analysis of zonal mean zonal wind), and a baroclinic annular mode (the BAM, the leading EOF of eddy kinetic energy, (EKE)). The former dominates the variability in zonal mean kinetic energy and momentum fluxes, while the latter dominates the variability in eddy kinetic energy and eddy fluxes of heat; conversely, the eddy
heat fluxes and eddy kinetic energies associated with the SAM explain very small fractions of
the total variance in their respective fields, while the BAM accounts for only a small fraction of
the variance in the wave fluxes of momentum. These studies suggest that this decoupling
between the wave fluxes of heat and momentum associated with the SAM and the BAM imply
independent barotropic and baroclinic variations of the storm tracks, respectively. They also
appear to have implications for the nature of eddy, mean flow, interactions in SAM dynamics,
since in some theories the baroclinic feedback is seen as critical to the mechanism of jet

Sparrow et al. (2009) used a dynamical core model to examine the behavior of the two leading
zonal wind EOFs. Given the separation of characteristic timescales between the eddy forcing and
the zonal wind (Lorenz and Hartmann 2001), they used a 30 day cutoff to distinguish high and
low frequencies and showed that their model’s annular modes behave differently at low and high
frequencies. In particular, their composites of Eliassen Palm (EP) fluxes associated with low-
and high-pass filtered data show different behavior of the leading mode in the two frequency
ranges, which implies, in particular, some cancelation of heat fluxes between the two.

In this paper we use a similar model to explore the low- and high-frequency behavior of the first
two EOFs of each of the zonal mean wind and EKE. The temporal filtering is intended to
separate different dynamical regimes. For periods less than about 30 days, one is resolving the
baroclinic life cycles and thus highlighting an essentially transient mutual interaction between
the eddies and the mean flow, while at longer periods the eddies may respond to jet changes in a
quasi-steady manner while the mean flow may respond to the eddy variability as to a forcing that
is stochastic in time. We do indeed find different characteristics in the two frequency bands, and
that, for example, the eddy heat flux signature at low frequency of the model’s SAM is much
more in keeping with ideas of baroclinic feedback than appears to be the case in the absence of filtering.

2. Model

We use an idealized model, similar to that of Polvani and Kushner (2002), with some modifications as described below. The model is dry and hydrostatic, solving the global primitive equations with T42 resolution in the horizontal and 40 $\sigma$ levels in the vertical. There is no surface topography. Radiation and convection schemes are replaced by relaxation to a zonally symmetric equilibrium temperature profile, identical to Held and Suarez (1994) in the troposphere and, in the stratosphere, a perpetual-solstice version of the equilibrium temperature specifications used in Sheshadri et al. (2015), with winter conditions in the southern hemisphere. These choices result in a model configuration with reasonable annular mode timescales in the winter hemisphere (the decorrelation times of the principal component autocorrelation functions associated with the first two EOFs of zonal mean zonal wind are 19 and 13 days). The model was run for 13000 days, and the last 10000 days are used in the analysis.

Following Sparrow et al. (2009), we find it expedient to separate those time scales that are comparable with those of baroclinic eddy life cycles from the longer time scales. To this end, we apply a Lanczos filter to the zonal wind and EKE (defined as $\frac{1}{2} [u'^2 + v'^2]$, where primes denote departures from the zonal mean and square brackets denote the zonal mean). EOFs are calculated separately from the unfiltered, low-pass filtered, and high-pass filtered data. For all results shown here, we follow Sparrow et al. (2009) in using a 30 day cutoff for the filtering. The major
characteristics of the results are insensitive to choices between 20-60 days; using a 10 day cutoff has a more profound impact.

3. Results

3.1 Model climatology

The climatological time-mean zonal-mean zonal wind, eddy kinetic energy (EKE) and EP flux and its divergence in the winter hemisphere are shown in Figure 1. The subtropical and eddy-driven tropospheric jets are almost separated, with the latter peaking around 47°S; EKE has a broad upper tropospheric maximum encompassing both jets, but peaking a few degrees equatorward of the eddy-driven jet. The upward EP fluxes indicate a broad lower tropospheric baroclinic source of wave activity (poleward eddy heat flux) extending from about 25°S (near the latitude of the subtropical jet) to the poleward edge of the midlatitude jet at about 55°S. Correspondingly, in the upper troposphere the equatorward EP fluxes (poleward eddy momentum flux) extend from the midlatitude jet to the equatorward edge of the subtropical jet at around 15°S.

3.2 Leading EOFs of zonal mean zonal wind

The two leading EOFs of zonal mean zonal wind are shown in Figure 2, for the unfiltered data, and for the low-pass and high-pass filtered data respectively. In the unfiltered data, these two EOFs exhibit the characteristics noted by Lorenz & Hartmann (2001) and Sparrow et al. (2009), amongst others, with EOF1 being dominated by a dipole straddling the climatological midlatitude jet, with a weak tertiary maximum near 20° on the equatorward edge of the subtropical jet, while EOF2 is in quadrature with EOF1, with its primary extremum coincident
with the climatological jet. Together, as discussed by Sparrow et al. (2009), these modes
describe the poleward propagation of zonal wind anomalies noted in the atmosphere by Feldstein
(1998) and in models by James and James (1992). The EOF structures are remarkably robust to
the time filtering (as noted by Hartmann and Lo, 1998): the low- and high-pass filtered EOFs are
very similar to those of the unfiltered case, with one important caveat. We have here followed
conventional usage by ranking the EOFs according to the fraction of variance they explain; as it
happens, the EOF that corresponds most closely to the first mode in the unfiltered and low-pass
cases appears as the second mode in the high-pass data, while the leading high-pass mode clearly
corresponds to the second mode in the unfiltered and low-pass data. That being the case, we
designate the leading mode $U_1$, $U_{1\text{LP}}$, and $U_{1\text{HP}}$ as EOF1, EOF$_{1\text{LP}}$ and EOF$_{2\text{HP}}$ (where the
superscripts LP and HP refer to low-pass and high-pass data), and the second mode $U_2$, $U_{2\text{LP}}$ and
$U_{2\text{HP}}$ as EOF2, EOF$_{2\text{LP}}$ and EOF$_{1\text{HP}}$, respectively. Once these associations are made, there is
remarkably little difference in EOF structure between the different frequency bands: mode $U_1$
has a node near the climatological midlatitude jet maximum at $47^\circ$, with extrema in the middle
and upper troposphere at around $39^\circ$ and $56^\circ$, with a weaker tertiary peak near $24^\circ$, while mode
$U_2$ has extrema near the midlatitude jet maximum at $47^\circ$ and near $30^\circ$, with a weaker extremum
near $65^\circ$. Differences between the frequency bands take the form of small variations in the
relative magnitude of these extrema.

Regressions against mode $U_1$ of zonal mean zonal wind, EKE, and eddy heat and momentum
fluxes are shown for unfiltered, low-pass, and high-pass data in Figure 3. (Note that since the
regressions are made against the principal component of $u$ in the relevant frequency band, the
low-pass and high-pass regressions are not strictly additive although, given the similarity of the
EOFs, they are approximately so.) In the unfiltered data, EKE shows a dipolar structure in
latitude similar to that of the zonal wind, with increased (decreased) EKE almost coincident with
westerly (easterly) wind anomaly, though with a slight equatorward shift. The low-pass EKE
signature is very similar to (and stronger than) the unfiltered signature, while that of the high-
pass mode is quite different, and weaker, showing a much broader region of decreased EKE in
association with an equatorward shift of the jet, and a latitudinal structure quite different from
that of the wind anomalies. The eddy heat flux component of the unfiltered U1 mode is weak,
especially in the lower troposphere, but in the upper troposphere above about 300 hPa it displays
a dipole structure that almost coincides with that of the wind anomalies, with increased
(negative) heat flux coincident with the anomalous westerlies. The low-pass signal has a similar
latitude structure but is deeper, the dipole extending down to the surface; increased westerlies,
and increased low-level baroclinicity, thus being associated with increased eddy heat flux. The
high-pass signal, by contrast, is weak in the upper troposphere and has the opposite sign in the
lower troposphere where, to a first approximation, the heat fluxes are weaker (/stronger) where
the zonal wind anomalies are westerly (/easterly), and thus spatially out of phase with the low-
level baroclinicity. The momentum flux pattern associated with the unfiltered mode U1 is
dominated by northward fluxes extending from about 60° to about 40°S; as has been noted
frequently before (e.g. Karoly 1990; Robinson 1994; Hartmann and Lo, 1998), these fluxes are
of a sense to reinforce the zonal wind anomalies. Unlike the heat fluxes, the low-pass and high-
pass momentum fluxes are similar to each other and to the total, the only difference being a
slight equatorward displacement of the high-pass fluxes relative to the others.

Mode U2 is illustrated in Figure 4. Both for the unfiltered data and for the similar results from
the low-pass data, the EKE signal in association with an anomalously strong and narrow
midlatitude jet is negative almost everywhere, especially in the wings of the jet where the
westerly flow is anomalously weak. The high-pass signal is dipolar, with increased EKE on the subtropical side of the jet, opposing the low pass signal, but reinforcing the negative low pass signal on its poleward side. The eddy heat fluxes, in total, weaken in association with the stronger jet of the positive phase of mode U2. As for mode U1, the low-pass heat fluxes exhibit the behavior one might expect in the steady limit, viz., strengthened where the jet, and local baroclinicity, is anomalously strong, and weakened where the jet is weak. However, the stronger high-pass eddy heat fluxes, which dominate the unfiltered signal, again show the opposite relationship with the zonal wind anomaly, with weakened fluxes when the jet is strengthened. The eddy momentum fluxes are weaker than for mode U1 and dipolar, but dominated by poleward fluxes equatorward of the mean jet, and weaker (much weaker, for the high-pass case) equatorward fluxes on its poleward side. In the low-pass and in the unfiltered data, the latitudes of convergent (divergent) momentum fluxes are almost coincident with the westerly (easterly) wind anomalies, thus being of a sense to reinforce the wind anomalies. The anomalous high pass fluxes, by contrast, are convergent (divergent) on the equatorward flanks of the anomalous westerly (easterly) flow.

3.3 Leading EOFs of eddy kinetic energy

The first three EOFs of EKE are shown in Figure 5. The first EOF is similar across the different frequency bands, showing a monopolar increase of EKE centered at about $35^\circ$S, between the climatological subtropical and midlatitude jets; we denote this mode E1. The second and third EOFs describe dipolar and tripolar modes and, as for the zonal wind EOFs, the ranking of each differs between low pass and high pass data; the dipolar mode appears as the second EOF in the unfiltered and high-pass data, but as the third in the low-pass data; following the classification of the zonal wind modes, we denote this mode E2. In the positive phase of mode E2, EKE
increases near and on the poleward flank of the climatological jet, and decreases near the subtropical jet, such that the EKE maximum shifts poleward.

Figure 6 shows regressions onto mode E1. The zonal wind signal is weaker (by about a factor of about 2) than for the zonal wind modes U1 and U2, and not congruent with either of them. The pattern of wind anomalies in the unfiltered data is clearly dominated by the low pass signal; the spatial distribution of the wind signal in the high pass data is quite different. The eddy fluxes, by contrast, are dominated by the high pass contribution. The high-pass eddy heat fluxes associated with the enhanced EKE of positive E1 are everywhere increased, especially just equatorward of the peak EKE and the weak easterly wind anomaly. The momentum fluxes are anomalously poleward, peaking in the same latitudes as the increased EKE, between the midlatitude and subtropical jets. In the high pass range, both heat and momentum fluxes are somewhat stronger than for the zonal wind modes; in the low pass range, heat fluxes are comparable with, and momentum fluxes much weaker than, the same quantities in the zonal wind modes.

Regressions onto mode E2 are shown in Figure 7. Once again, the zonal wind signals in the low pass and high pass ranges are quite different, with the net unfiltered signal differing from both; in fact, the spatial structure of the unfiltered wind signal is similar to that of mode U1. Just as for mode E1, the eddy fluxes are dominated by the high pass contribution, and the heat fluxes are intensified in association with weaker baroclinicity.

4. Discussion

The leading U and E modes in the model show many of the same characteristics as the corresponding annular mode (SAM) and baroclinic annular mode (BAM) described for the southern hemisphere atmosphere by Thompson and Woodworth (2014), although there are some
differences. Mode E1 is associated with weak zonal flow anomalies (though apparently not as weak as for the BAM) and a strong heat flux signal; one clear difference from the observed BAM is the strong momentum flux component of E1. Like the SAM, mode U1 displays a strong zonal wind component, corresponding to a shift of the midlatitude jet, and clear signal in momentum flux (which is however, weaker than the E1 signal, in contrast to what Thompson and Woodworth (2014) found in relation to the SAM/BAM signals). Also like the SAM, the U1 EKE signal is weak, as is its heat flux component, especially in the lower troposphere; the latter, especially, appears at first sight to run counter to ideas that the storm track, and its manifestations in eddy statistics, migrate in latitude in concert with the jet shifts. However, some characteristics of the modes appear somewhat different when separated into components with periods less than, and greater than, 30 days.

The U modes show remarkably similar spatial zonal wind structures in the low pass and high pass ranges (although the ranking of the EOFs differs in some cases from one range to the other); nevertheless, the eddy signatures are in some cases very different. In the raw data, there is evidently some cancellation occurring between low pass and high pass contributions to eddy kinetic energy and eddy heat fluxes. At low frequencies, the eddy heat and momentum fluxes behave qualitatively as one might expect for zonal wind perturbations in steady state. In particular, mode U1 is associated with increased heat flux, and increased EKE, coincident with the latitudes of anomalous westerlies and strengthened low-level baroclinicity. In fact, the whole pattern of eddy fluxes appears simply to shift in concert with the shift in the midlatitude jet. This is illustrated in Figure 8, which compares mean zonal winds and EP fluxes in association with departures of low pass mode U1 of plus or minus two standard deviations. The shift of the midlatitude jet, and the separation and merging with the subtropical jet, are clearly evident, as is
the broadening of the region of low-level baroclinicity in the positive phase. Correspondingly, the region of baroclinic wave generation, evident in the vertical component of the EP fluxes, extends poleward in concert with the jet shift, as does the poleward edge of the region of poleward upper tropospheric momentum fluxes (evident as the poleward edge of the region of equatorward EP fluxes). In the subtropics, by contrast, there is little change in either zonal wind or momentum fluxes. The overall picture of the eddy signal associated with mode U1 at low frequency, therefore, is like that described by Robinson (1994) and Hartmann (2007): a quasi-steady response of increased baroclinic wave generation, and locally increased EKE, in association with a poleward shift of the jet and corresponding poleward extension of the baroclinic zone. The convergence of the upward component of the anomalous EP fluxes in the upper troposphere is balanced primarily by divergence of the horizontal component; i.e., the region of climatological upper tropospheric divergence in the horizontal component (Figure 1) shifts along with the jet. Thus, the poleward jet shift is associated with enhanced momentum flux convergence at the latitude of the anomalous westerlies, and divergence in the anomalous easterlies equatorward of the mean jet as is evident in Figure 9, which shows the regression of the EP flux divergence against U1. Note that differences in wave breaking in the subtropics are not evident here. While there are divergence anomalies in the upper troposphere, the low-level dipole, associated with anomalies in baroclinic eddy generation, dominates the vertical integral and hence also the vertically-integrated momentum flux divergence\(^1\). Thus, the model variability at low frequency appears to be sustained primarily by low-level baroclinic eddy feedback (Robinson 1994, 1996; Hartmann 2007) rather than by upper tropospheric barotropic processes:

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\(^1\) Note that the EP flux divergence at the lowest model level is calculated here by imposing zero eddy heat flux at the lower boundary; hence its vertical integral equals the vertically integrated convergence of the eddy momentum flux.
anomalous momentum fluxes arise primarily from anomalous baroclinic sources of wave activity, feeding the upper tropospheric momentum fluxes, rather than from anomalies in the upper tropospheric sinks of barotropic wave activity associated with the shifting jet (Chen and Held 2007; Chen et al. 2008; Barnes and Thompson 2014).

The higher frequency characteristics of mode U1 are quite different, most notably because the heat flux anomalies display the opposite relationship to the wind anomalies, while the momentum flux anomalies are very similar those of the low pass regression. Taken together, these facts reveal the transient nature of the wave, mean-flow interaction inherent in this mode on these time scales, which encompass those of baroclinic eddy life cycles. It is remarkable, however, how the momentum flux forcing of the changing mean flow is so similar across the two frequency ranges, such that the barotropic dynamics of the zonal flow may be less dependent on time scale than the eddy heat fluxes and EKE appear to be. However, the relationship between momentum and heat fluxes is quite different between the low pass and high pass cases.

At low frequency, mode E1 exhibits signals in the eddy fluxes that are in many ways similar to those at mode U1 at low frequency, viz.: enhanced low-level heat flux coincident with a deep, but baroclinic, westerly wind anomaly, with the associated upward EP flux feeding horizontal EP fluxes and thus upper tropospheric momentum fluxes converging into the westerlies. However, much stronger and deeper eddy flux signals are evident in the high-pass range. As for the low-pass signals, enhanced eddy heat fluxes are associated with (and at the same latitudes as) enhanced EKE, and with the easterly wind anomaly. Thus as for mode U1, at high frequencies, the heat fluxes do not exhibit a quasi-steady relationship with the baroclinicity, indicating the transient nature of the interaction; Thompson and Barnes (2014) show observed southern hemisphere heat fluxes following peak baroclinicity by a few days. Indeed, the transient nature
of all modes in the high-pass range would be better revealed by lag relationships, as in
Thompson and Woodworth (2014) and Thompson and Barnes (2014), rather than the
instantaneous regressions that have been our focus here.

The two leading modes describe two kinds of jet variability. Mode E1 is characterized by a
monopolar heat flux increase, and a modest weakening of the jet, in association with increased
EKE and thus, consistent with the remarks of Thompson and Woodworth (2014) and the analysis
of Thompson and Barnes (2014), the variation of this mode is reminiscent of the “amplitude
vacillation” found in baroclinic annulus experiments (e.g., Hide 1958). Mode U1, on the other
hand, as has been noted by many others (e.g., Robinson, 1994; Hartmann and Lo, 1998;
Thompson and Wallace, 2000), describes a latitudinal shift, not only of the eddy-driven jet, but
also, at low frequency, of the storm track and its characteristic EKE and eddy heat fluxes. Its
high-pass component, however, exhibits less straightforward characteristics.

Of course, the U and E modes are derived from the same data set but by focusing on EOFs of
different variables, they highlight different aspects of dynamical variability. Nevertheless, they
are not independent of each other. Table 1 shows correlations exceeding 95% significance
between the principal components of each of these modes in the low pass and high pass ranges:
the largest correlations are found between U1 and E2 at high frequency, and between U2 and E1
at low frequency.

5. Conclusions
Mode U1, which is clearly the model’s equivalent of the SAM in the atmosphere, displays
distinct characteristics at periods greater or less than 30 days. At short periods, comparable with
characteristic time scales of baroclinic eddy life cycles, interaction between eddies and mean
flow is transient. At periods exceeding 30 days, symptoms of the storm track (eddy heat fluxes and eddy kinetic energy) simply migrate in concert with the shifting jet. In fact, the relationship between the eddies and the jet is consistent with a quasi-steady perspective: enhanced eddy heat fluxes and eddy kinetic energy being coincident with a locally strengthened jet and enhanced low-level baroclinicity. Thus, maintenance of persistent zonal wind anomalies appears to result primarily from a baroclinic, rather than barotropic, feedback mechanism.

Differences between modes U1 and E1 in many respects mirror those between the SAM and BAM modes (Thompson and Woodworth, 2014) in the atmosphere, but there are some differences, especially in respect of the strong eddy momentum fluxes associated with mode E1. The weakness of the eddy heat fluxes associated with the observed SAM is evident in the model’s mode U1; this was rationalized with respect to the concept of the jet/storm track association by the finding that the weak heat flux signal in the unfiltered data is in part a result of cancellation between low-frequency and high-frequency signals. Such frequency dependence is evident, if not quite so clearly, in the observed southern hemisphere: Figure 10 shows regressions onto the SAM index of zonal wind, eddy kinetic energy, heat and momentum fluxes, as for the model-based figures shown earlier. The high-pass EKE and eddy heat fluxes bear a similar relationship to the wind anomalies as for mode U1. The unfiltered EKE signal is dominated by the low-pass component, which reveals EKE migrating in latitude in phase with the westerly jet. The low-pass heat flux signal also exhibits enhanced fluxes in association with enhanced low-level baroclinicity as does mode U1, though in the observations the latitudinal coincidence is not as precise as in the model. Moreover, the high-pass component is, relative to the low-pass component, larger in the observations than in the model, resulting in less cancellation between the two in the unfiltered data.
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