Intraseasonal periodicity in the Southern Hemisphere circulation on regional spatial scales

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Abstract

Atmospheric wave activity in the Southern Hemisphere extratropical circulation exhibits robust periodicity on timescales of ~20-25 days. Previous studies have demonstrated the robustness of the periodicity in hemispheric-averages of various eddy quantities. Here the authors explore the projection of the periodicity onto regional spatial scales.

The periodicity in the Southern Hemisphere wave activity derives from the development of out-of-phase anomalies in eddy-kinetic energy on the upstream side of decaying extratropical wave packets as they propagate to the east. The out-of-phase anomalies in eddy-kinetic energy give rise to periodicity not only on hemispheric-scales, but also on regional scales when the circulation is sampled along an eastward path between ~5-15 m/s. It is argued that the development of out-of-phase anomalies on the upstream side of decaying wave packets is consistent with two-way interactions between wave activity advected eastward at the Rossby group velocity, and baroclinicity advected eastward at a comparatively slow rate.
**Introduction**

Hemispheric-scale variability in the Southern Hemisphere (SH) extratropical circulation can be viewed in the context of two distinct structures, both of which exhibit a high degree of zonal-symmetry: 1) the southern annular mode (SAM; Kidson 1988; Hartmann and Lo 1998; Thompson and Wallace 2000) and 2) its baroclinic counterpart, the baroclinic annular mode (BAM; Thompson and Woodworth 2014).

The two patterns have very different signatures in the extratropical flow. The SAM emerges as the leading empirical orthogonal function (EOF) of zonal-mean kinetic energy, is characterized by north-south shifts in the extratropical jet, and is associated with large variations in the eddy fluxes of momentum (Hartmann and Lo 1998; Thompson and Wallace 2000). In contrast, the BAM emerges as the leading EOF of the eddy kinetic energy, is characterized by a hemispheric-scale monopole in extratropical wave amplitudes, and is associated with large variations in the eddy fluxes of heat (Thompson and Woodworth 2014). The differences between the structures also extend to their time variations. As is the case for most large-scale patterns of extratropical variability, the SAM can be modeled as Gaussian red-noise with a decorrelation timescale of ~10 days (Hartmann and Lo 1998; Feldstein 2003). Interestingly, the power spectrum of the BAM is not consistent with Gaussian red-noise, but rather exhibits robust periodic variability on timescales of ~20-25 days (Thompson and Woodworth 2014; Thompson and Barnes 2014).

The periodicity associated with the BAM has potentially important implications for understanding intraseasonal climate variability on hemispheric scales: It is readily apparent in hemispheric-means of extratropical eddy kinetic energy, the eddy fluxes of
heat, precipitation, and longwave cloud radiative effects (Thompson and Barnes 2014; Li and Thompson 2016). However, to what extent the periodicity projects onto regional-scale variations in the flow - and thus its potential implications for regional weather - remain unclear.

The purpose of this study is to explore the periodicity in the BAM on regional spatial scales. To do so, we will revisit the “downstream development” of synoptic-scale disturbances (e.g., Simmons and Hoskins 1979; Lee and Held 1993; Chang 1993; Chang and Yu 1999; Chang 1999; Chang 2005). The results support the central findings of previous observational analyses of downstream development, namely that wave packets in the extratropical flow propagate to the east at a rate consistent with the Rossby group velocity. But the results also highlight a novel aspect of extratropical disturbances not documented in previous work: as wave packets propagate eastward and decay, they are accompanied by opposite signed anomalies in eddy kinetic energy that form to the west of the decaying wave packet. The opposite signed anomalies give rise to the observed periodicity in zonal-mean eddy kinetic energy. They also give rise to periodicity on regional scales, but only when the circulation is sampled along eastward paths between ~5-15 m/s. We argue that the signature of periodicity in SH eddy-kinetic energy on regional scales is consistent with two-way interactions between 1) wave activity in the upper troposphere, which propagates eastward at the Rossby wave group velocity, and 2) baroclinicity in the lower troposphere, which is advected eastward at a comparatively slow rate.

Section 2 provides details on the Data and Methods. Section 3 explores the periodicity in SH eddy kinetic energy in the context of individual wave packets. In
Section 4 we develop a simple model of periodicity in extratropical wave packets and provide a physical interpretation of the observations. Concluding remarks are provided in Section 5.

2. Data and methods

The observational analyses are based on 4 x daily resolution values of the European Centre for Medium-Range Weather Forecasts Interim reanalysis data set (ERA-Interim; Dee et al. 2011). The reanalyses data were processed on a 1.5° x 1.5° grid and for the period January 1, 1979-December 31, 2015 (a total of 13514 days). All observational results are based on analyses of anomalous data for all calendar days of the year, where anomalies are formed by 1) calculating the long-term average of the data as a function of calendar day; and 2) subtracting the resulting seasonal cycle from the data as a function of grid box and vertical level.

Eddy kinetic energy is defined as $0.5 \times (u^*^2 + v^*^2)$, where * denotes departures from the zonal-mean. The eddy kinetic energy is first calculated at 4 x daily resolution and then averaged over 24 hour periods to form daily mean values.

The BAM index time series is defined as the leading principal component time series of EKE calculated computed over all levels and latitudes within the domain 1000-200 hPa and 20°-70°S. The data are weighted by the square root of the cosine of latitude and the mass represented by each vertical level before calculating the PC time series.

Power spectra are found by: 1) Calculating the spectra for subsets of the data that are 500 days in length. All subsets are treated with a Hanning window and have an
overlap with adjacent subsets of 250 days. 2) Averaging the subset power spectra over all subsets. And 3) Applying a 5 point running mean to the resulting mean power spectrum. Independent spectral estimates in the resulting mean spectrum have roughly 270 degrees of freedom. The statistical significance of spectral peaks in Fig. 6 is found by applying the F-statistic to the ratio of 1) the amplitude of individual spectral peaks to 2) a red-noise fit to the time series. The red-noise fit is estimated from the lag-one autocorrelation of the time series. Spectra are shown in units cycles per day (cpd).

The significance of the correlations in Fig. 3 are estimated using a two-tailed test of the t-statistic. The effective number of degrees of freedom for the significance test is estimated as:

\[
\text{n}_{\text{eff}} = n \frac{1 - r_{1x} r_{1y}}{1 + r_{1x} r_{1y}}
\]

where \( n \) is the number of timesteps, \( r_{1x} \) and \( r_{1y} \) are the lag-one autocorrelations of the time series being correlated (typically ~0.25 for the eddy kinetic energy time series used in the analysis), and \( n_{\text{eff}} \) is the effective number of degrees of freedom. As discussed in Section 3, the results shown in Fig. 3 are averages of correlations calculated for all 240 base longitudes in the analysis. To be conservative, we did not increase \( n_{\text{eff}} \) even though the averaging affords a larger number of degrees of freedom than analyses based on a single base longitude.
3. Observed periodicity in extratropical eddy kinetic energy

The structure and time-dependent behavior of the BAM are reviewed briefly in Fig. 1. The left panel shows the structure of the BAM in the anomalous eddy kinetic energy at 300 hPa; the right panel shows the power spectrum of the associated BAM index time series. The spatial structure of the BAM is marked by hemispheric-scale fluctuations in eddy kinetic energy that span much of the SH storm track within the latitude band roughly 40°-60°S (Thompson and Woodworth 2014). Its time dependent behavior is dominated by a broad spectral peak on timescales of roughly 20-25 days (right panel; Thompson and Woodworth 2014). As noted in the introduction, the periodicity in the BAM is readily apparent in $SH$-mean eddy kinetic energy. In this section, we will explore its projection onto regional spatial scales.

Figure 2 examines the spectrum of SH eddy kinetic energy on increasingly small zonal scales. The results are generated as follows. First, we average eddy kinetic energy over the latitude band 40°-60°S, which corresponds to the approximate meridional span of the storm track and thus of the BAM (Fig. 1 left; the 40° and 60° latitude bands are indicated by the solid black lines). The resulting data matrix (hereafter $EKE_{40-60°S}$) is resolved as a function of time and longitude. Next, we calculate the power spectrum of $EKE_{40-60°S}$ over various zonal scales: all longitudes (panel a); longitudinal windows of width 180° (panel b); longitudinal windows of width 90° (panel c); and longitudinal windows of width 30° (panel d). Note that the power spectra in panels b-d are found by averaging power spectra calculated for all possible windows of the indicated width (e.g., in the case of panel b, spectra are calculated and averaged over the longitudinal windows 1.5°E-181.5°E, 3°E-183°E… 180°E-0°E).
The power spectrum of zonal-mean $EKE_{40-60^\circ S}$ (panel a) exhibits robust periodicity on time scales of ~20-25 days and is very similar to the power spectrum of the BAM (Fig. 1b; Thompson and Woodworth 2014) and upper tropospheric eddy kinetic energy averaged over the entire SH (Thompson and Barnes 2014). The spectrum of $EKE_{40-60^\circ S}$ averaged over 180° longitudinal windows (panel b) also exhibits enhanced power in the ~20-25 day range, but the amplitude of the peak is diminished relative to the zonal-mean case. The periodicity is further diminished when the width of the longitudinal window is reduced to 90 degrees. It is largely imperceptible when the zonal scale is reduced to 30 degrees (~8000 km; panel d).

Why is the spectral peak in zonal-mean eddy kinetic energy so weak on spatial scales less than ~180°? To address this question, we generate a composite Hovmöller plot for eddy kinetic energy in the SH storm track region. The plot is formed as follows: 1) $EKE_{40-60^\circ S}$ at base longitude $\lambda$ is correlated with $EKE_{40-60^\circ S}$ at all other longitudes at time lags ranging from -30 to + 30 days; 2) step 1) is repeated for all base longitudes $0^\circ < \lambda < 360^\circ$; and 3) the resulting individual correlation plots are averaged to form a composite Hovmöller plot averaged over all base longitudes. Note that the general features highlighted in the composite Hovmöller plot are found in individual correlation plots based on a single base longitude, but that averaging the correlation plots over all base longitudes increases the sample size of the analysis. (In practice, the mean of correlation coefficients drawn from individual samples underestimates the population correlation, e.g., Fischer 1921. But the bias is small for sample sizes larger than ~30 and is not expected to affect the interpretation of the results).
The resulting composite Hovmöller plot is shown in the left panel of Figure 3. The primary features in the time/longitude evolution of EKE$_{40-60^\circ S}$ have been documented extensively in previous analyses of the “downstream development” of wave packets in numerical models (Simmons and Hoskins 1979), the Northern Hemisphere storm tracks (Chang 1993; Chang and Yu 1999) and the SH storm tracks (Lee and Held 1993; Chang 1999; Chang 2005). The results confirm two widely established aspects of disturbances in the extratropical storm tracks: 1) individual disturbances in EKE propagate to the east at a rate consistent with the Rossby phase speed (roughly 8 m/s in Fig. 3a) whereas 2) the envelope of successive disturbances in EKE propagates to the east at a rate consistent with the Rossby group velocity (roughly 25 m/s in Fig. 3a). However, the results also reveal a novel aspect of SH extratropical disturbances that has not been highlighted in previous work: a band of negative EKE anomalies that form to the west of the original wave packet as it propagates eastward. The negative anomalies in EKE are very weak, but are statistically significant at the 95% level based on a two-tailed test of the t-statistic (see Section 2). As discussed later, the negative anomalies in EKE play a central role in driving the periodicity in the flow on hemispheric scales.

The right panel in Figure 3 shows the corresponding correlations for zonal-mean EKE$_{40-60^\circ S}$. Interestingly, the negative correlations begin to develop somewhat earlier on regional scales (left panel) than they do in the zonal-mean (right panel). The reasons for this apparent discrepancy stem from the timescale of the decaying positive anomalies associated with the original wave packet relative to the developing negative anomalies that form in its wake. When the negative regional-scale correlations in EKE first develop, they are accompanied by positive correlations to the east that act to oppose the projection
of the negative anomalies onto the zonal-mean. The negative correlations project most
clearly onto the zonal-mean after the original wave packet has largely decayed, after day
~8.

Figures 4 and 5 provide an alternative view of the Hovmöller plot of SH eddy-
kinetic energy. The results are identical to those shown in the left panel of Fig. 3 but for
two differences: 1) we have applied a 30 degree longitude running mean to the
correlation coefficients to visually enhance the downstream development of the wave
packet relative to the phase of individual eddies (the spatial smoothing is applied only to
enhance the wave packet in Figs. 4 and 5, and is not applied to other results in the study)
and 2) we have displayed the results as a series of filled line plots. Figure 4 shows the
correlations out to lag +12. Figure 5 focuses on results at positive lag and shows
correlations out to lag +30. Note that in both figures: 1) the base longitude of the analysis
is denoted by relative longitude 0˚; and 2) the results are repeated in longitude so that the
anomalies can be traced as they wrap around the globe. The associated zonal-mean
correlations are shown in the right panels of both figures.

The results in Figs. 4 and 5 visually enhance the negative EKE anomalies that
develop to the west of the original wave packet as it decays. The negative anomalies
develop around lag +5, propagate eastward in the lee of the original wave packet, peak
around day ~+10, and decay by day ~+20. The negative anomalies in EKE are followed
by a new packet of positive anomalies in EKE that have largest amplitude around 25 days
after the peak in the original wave packet (Fig. 5). The positive anomalies at lags greater
than ~20 days are relatively weak, but nevertheless give rise to significant positive
correlations in the zonal-mean (Fig. 5, right panel).
The unique time/longitude pattern of successive positive and negative EKE anomalies highlighted in Figs. 4 and 5 are important for two reasons: 1) they give rise to the periodicity in the spectrum of zonal-mean EKE and 2) they lead to weak but significant periodicity in power spectra of regional-scale EKE following the flow towards the east, as shown next.

Figure 6 shows the power spectra of EKE$_{40-60^\circ S}$ following the flow towards the east at rates ranging from 0 m/s to 25 m/s. For each rate, the spectra are 1) calculated separately for all starting zonal grid boxes and then 2) averaged over all starting grid boxes. For example, the spectra at 10 m/s is found by 1) rearranging the EKE$_{40-60^\circ S}$ data matrix so that the first day in the matrix corresponds to EKE$_{40-60^\circ S}$ at zonal grid box $i$, the second day to EKE$_{40-60^\circ S}$ at zonal grid box $i+\Delta i$, where $\Delta i$ corresponds to the number of grid boxes traveled in one day at 10 m/s; etc; 2) calculating the power spectrum of the resulting data matrix for all starting zonal grid boxes; and 3) averaging the resulting power spectra. The black circles on the contour plot indicate the frequency of maximum spectral power for cases where the spectral peak is statistically different from the red-noise fit at the 95% level (Section 2). The black vertical line indicates the frequency of maximum spectral power for zonal-mean EKE$_{40-60^\circ S}$ (i.e., the maximum in the spectrum shown in Fig. 2a).

As indicated in Fig. 1d, the power spectrum of EKE$_{40-60^\circ S}$ does not exhibit coherent periodicity at a fixed longitude. Likewise, the power spectrum does not indicate coherent periodicity following the flow at a rate comparable to the wave packet (~25 m/s), when the peak in the spectrum is at the lowest resolvable frequency. Rather, the power spectrum of EKE$_{40-60^\circ S}$ only exhibits significant periodicity on the scale of individual grid
boxes at flow speeds between ~5-15 m/s. The reasons for this are visually apparent in Figs. 4 and 5. The negative EKE anomalies that peak around lag +12 days do not evolve at a fixed longitude. Nor do they emerge along the path of the wave packet. Rather, they emerge in the wake of the wave packet as it propagates to the east. Note that the largest amplitudes in the spectra occur at frequencies comparable to the frequency of maximum spectral power for zonal-mean EKE$_{40-60^\circ S}$ (roughly 0.04 cycles/day) regardless of the eastward rate used to sample the flow.

In the following section, we provide a physical interpretation of the unique time/longitude pattern of the alternating positive and negative EKE anomalies associated with SH wave packets.

4. A simple model of periodicity in the extratropical circulation

In Thompson and Barnes (2014) we argued that the periodicity in SH-mean eddy kinetic energy arises from two-way interactions between wave activity and the baroclinicity. The argument is based on two physical relationships: 1) From baroclinic instability theory, periods of anomalously high baroclinicity lead to increases in wave activity, and vice versa; and 2) From the thermodynamic energy equation, periods of anomalously high wave activity (and thus anomalously poleward heat fluxes) lead to decreases in baroclinicity, and vice versa. Similar feedbacks between the baroclinicity and baroclinic wave activity underlie early theories of the “zonal-index cycle” (Rossby and Willett 1948) and more recent analyses of periodic behavior in the North Atlantic storm track (Ambaum and Novak 2014; Novak et al. 2015).
In this section, we develop a simple model of two-way feedbacks between the baroclinicity and wave activity in the SH storm track. The model is analogous to that developed in Thompson and Barnes (2014) but for one primary difference: it is not zonally symmetric and thus includes zonal advection of the baroclinicity and wave activity by the zonal-mean, time-mean flow. The model is developed in Section 4a and used to interpret the observations in Section 4b.

a. Developing the simple model

The model includes two equations: 1) a prognostic equation for baroclinicity and 2) a prognostic equation for wave activity. Both equations are averaged over the meridional scale of the SH storm track region (assumed here to be 40°-60°S) but are not averaged zonally. Hence the model includes zonal but not meridional advection.

The prognostic equation for baroclinicity is predicated on three assumptions. First, we assume that the amplitude of wave activity is closely linked to the eddy fluxes of heat. Using the eddy heat fluxes allows us to use a simplified version of the thermodynamic energy equation. Second, we assume that the eddy fluxes of heat are diffusive, so that the time rate of change of the baroclinicity can be modeled as linearly proportional to the amplitude of the heat fluxes. Third, we assume that the damping of the baroclinicity by both adiabatic and diabatic processes can be modeled as linear damping. Applying the above assumptions to the thermodynamic energy equation and linearizing about a basic state with time-mean, zonal-mean flow \( \langle U_b \rangle \) yields:
\[ \frac{\partial}{\partial t} \langle b \rangle + \langle U_b \rangle \frac{\partial}{\partial x} \langle b \rangle = \beta \langle H \rangle - \frac{\langle b \rangle}{\tau_b} \]

where the brackets \( \langle \cdot \rangle \) denote a quantity averaged meridionally over the band 40\(^\circ\)-60\(^\circ\)S, \( \langle b \rangle \) is the baroclinicity, \( \langle U_b \rangle \frac{\partial}{\partial x} \langle b \rangle \) denotes the eastward advection of the baroclinicity, \( \langle H \rangle \) denotes the eddy fluxes of heat, \( \beta \) is a linear regression coefficient analogous to the eddy diffusivity, and \( \tau_b \) is the damping timescale of the baroclinicity.

The second equation is based on two assumptions. First, we assume that the growth rate of baroclinic waves - and thus their heat fluxes - is linearly proportional to the baroclinicity. The assumption follows from baroclinic instability theory and the Eady growth rate (e.g., Lindzen and Farrell 1980). Second, we assume that the sink of the heat fluxes (due to Rossby wave radiation and breaking) is well-modeled as linear damping. Linearizing about a time-mean, zonal-mean flow of \( \langle U_n \rangle \) yields the following expression for the time rate of change of the heat fluxes:

\[ \frac{\partial}{\partial t} \langle H \rangle + \langle U_n \rangle \frac{\partial}{\partial x} \langle H \rangle = \alpha \langle b \rangle - \frac{\langle H \rangle}{\tau_H} \]

where \( \langle U_n \rangle \frac{\partial}{\partial x} \langle H \rangle \) denotes the eastward advection of the heat fluxes, \( \alpha \langle b \rangle \) reflects the linear relationship between the baroclinicity and the wave fluxes of heat, and \( \alpha \) is a
linear regression coefficient. The coefficient $\tau_\mu$ is the damping timescale for the eddy fluxes of heat.

The parameters of the model are listed in Table 1 and are found as follows. The linear regression coefficient $\beta$ is derived from observations by regressing zonal-mean values of anomalous $\frac{\partial}{\partial t} \langle b \rangle$ onto zonal-mean values of $\langle H \rangle$, where $\langle b \rangle$ is defined as the meridional temperature gradient at 700 hPa averaged 40°-60°S and $\langle H \rangle$ is defined as the eddy fluxes of heat at 700 hPa averaged 40°-60°S. Similar results are obtained for the temperature gradient and heat fluxes at other pressure levels. In principal, the baroclinicity is the ratio of the meridional and vertical gradients in temperature; in practice, variations in the static stability play a secondary role in determining the parameters of the model. The regression coefficient $\beta$ is positive, consistent with poleward (negative) heat fluxes leading to a reduction in the baroclinicity (a decrease in the difference in temperature between 40°S and 60°S).

The linear regression coefficient $\alpha$ is derived from observations in a similar manner by regressing zonal-mean values of anomalous $\frac{\partial}{\partial t} \langle H \rangle$ onto $\langle b \rangle$. The regression coefficient is negative, consistent with anomalously positive baroclinicity (an increase in the difference in temperature between 40°S and 60°S) leading to anomalously poleward (negative) heat fluxes.

The linear damping coefficients are the e-folding timescales of observed $\langle H \rangle$ and $\langle b \rangle$ time series.
The model is initiated with a Gaussian pulse in $\langle H \rangle$ centered at 0° longitude with amplitude and zonal-scale that mimics those of the observed eddy fluxes of heat at 700 hPa: the amplitude is defined as the zonal-mean of the standard deviation of the eddy fluxes of heat at 500 hPa averaged 40°-60°S ($27 \text{ K} \frac{m}{s}$); the Gaussian RMS width is 12° longitude. The model is integrated for 100 days.

b. Applying the simple model

We will apply the model to three different configurations of the time-mean, zonal-mean flow: 1) no zonal advection; 2) identical eastward zonal advection in the baroclinicity and heat fluxes; and 3) different eastward advection in the baroclinicity and heat fluxes. In all cases, the model is run with the parameters given in Table 1.

Case 1. $U_b = U_H = 0$

In this case, Equations 1 and 2 reduce to the zonally symmetric model considered in Thompson and Barnes (2014). The time series of $\langle H \rangle$ consists of a damped oscillator that - by construction - remains fixed in longitude throughout the integration. The Gaussian pulse in $\langle H \rangle$ decays rapidly over the first several days of the integration (Fig. 7, top), reaches peak negative amplitude on roughly day 10, and exhibits weak positive values that peak again around day 20 (results beyond day 12 not shown). The power spectrum of $\langle H \rangle$ is characterized by a spectral peak centered ~20 days that is identical whether $\langle H \rangle$ is sampled at a single longitude, or is zonally averaged over all longitudes.
(the spectrum of zonal-mean $\langle H \rangle$ is shown in Fig. 8). The period of oscillation in the heat fluxes in the idealized model is somewhat shorter than that found in the observed eddy-kinetic energy (~20 days for the model versus ~25 days for the observations). Nevertheless, as discussed in more detail in Thompson and Barnes (2014) for a range of model parameters, the idealized model provides a remarkably close approximation of the simulated peak despite its simplicity.

Case 2. $U_b = U_H = 25$ m/s

In this case, the model baroclinicity and eddy fluxes of heat are both advected eastward at a rate similar to the observed group velocity of wave packets in the free troposphere, roughly 25 m/s (i.e., see Fig. 3). Conceptually, case 2 is identical to case 1, except that the heat fluxes and baroclinicity interact with each other as they propagate eastward with the wave packet. The power spectrum of the zonal-mean model $\langle H \rangle$ is identical to the power spectrum for case 1 shown in Fig. 8. But by construction, the damped oscillation in the model heat fluxes propagates to the east at 25 m/s (Fig. 7, middle): the Gaussian pulse in $\langle H \rangle$ again reaches peak negative amplitude on roughly day 10, but the largest negative values occur roughly 180 degrees to the east of the original pulse.

For both cases 1 and 2, the simulated power spectra are very similar to the observed power spectrum when the eddy fluxes are zonally averaged. However, neither case correctly captures the zonally-varying structure of the observed eddy kinetic energy, as indicated in Figs. 4 and 5, in which opposite signed EKE anomalies form not at a fixed
longitude, nor along the path of the wave packet, but to the west of the wave packet as it propagates to the east.

Case 3. $U_b = 10 \text{ m/s} ; U_H = 25 \text{ m/s}$

We now consider the case where 1) the heat fluxes propagate to the east at a rate comparable to the group velocity of the wave packet (25 m/s) but 2) the baroclinicity is advected to the east at a rate given by typical flow speeds in the lower troposphere (10 m/s). Conceptually, this implies that 1) the wave packet interacts with and responds to the baroclinicity but 2) the baroclinicity is not part of the wave packet itself. The key assumption in this case is that the wave packet propagates eastward at a faster rate than the advection of the lower tropospheric temperature field.

Applying different advection speeds to the heat fluxes and baroclinicity yields results that bear strong resemblance to the observations (Fig. 7, bottom). The original Gaussian pulse in $\langle H \rangle$ again decays along the path given by 25 m/s, but in contrast to case 2, the opposite signed anomalies in $\langle H \rangle$ form to the west of the wave packet as it propagates to the east. Note that the lagging of the baroclinicity anomalies relative to $\langle H \rangle$ alters the timescale of the anomalies in two ways: 1) The decay timescale of the initial positive pulse in $\langle H \rangle$ is enhanced relative to case 2, since it is not directly affected by the negative baroclinicity anomalies that it generates; and 2) The negative anomalies in $\langle H \rangle$ form more rapidly than they do in case 2, since they form to the west of the region of positive $\langle H \rangle$. The zonal-mean values of $\langle H \rangle$ and its associated power spectrum are identical to those in cases 1 and 2.
5. Conclusions

The ~20-25 day periodicity in SH eddy kinetic energy indicated in Thompson and Barnes (2014) is robust not only on hemispheric scales, but on regional spatial scales as well. As demonstrated for hemispheric scales in Thompson and Barnes (2014), the periodicity in SH eddy kinetic energy is consistent with two-way interactions between the baroclinicity and the wave fluxes of heat. As shown here on regional scales, the periodicity has a rich longitudinal structure that is masked in analyses of the hemispheric-mean.

The periodicity in SH wave activity arises from the development of out-of-phase anomalies in eddy kinetic energy in the wake of decaying extratropical disturbances. As shown in numerous previous studies on the downstream development of extratropical disturbances (e.g., Lee and Held 1993; Chang 1993; Chang and Yu 1999; Chang 1999; Chang 2005), extratropical wave packets propagate to the east in the storm track region at a rate consistent with the Rossby group velocity. The results shown here indicate that - as such wave packets decay in amplitude - opposite signed anomalies in eddy kinetic energy form to the west of the decaying wave packet. The opposite signed anomalies give rise to the observed periodicity in SH-mean wave activity indicated in our previous work (Thompson and Barnes 2014). But they also give rise to a unique pattern of periodicity on regional scales. The periodicity in eddy kinetic energy is not apparent at a fixed location, since the opposite signed anomalies form at a different location than the original wave packet. It is also not apparent along the eastward path of the wave packet, since the opposite signed anomalies form to the west of the original wave packet as it propagates to...
the east. Rather, on regional spatial scales, the periodicity in eddy kinetic energy is most
clearly apparent along an eastward path that lags extratropical wave packets as they
propagate to the east, and is statistically significant at eastward rates between ~5-15 m/s.

The unique time/longitude evolution of the periodicity is explored in a simple
zonally-varying model of two-way feedbacks between extratropical eddy activity and
baroclinicity. If the eddy activity and baroclinicity are not advected zonally, then the
development of out-of-phase anomalies and thus periodicity in wave activity occurs at a
fixed location. If the eddy activity and baroclinicity are both advected eastward at the
same rate, then the development of out-of-phase anomalies and thus periodicity in wave
activity follow wave packets as they propagate to the east. The observed development of
out-of-phase anomalies in eddy kinetic energy in the wake of decaying disturbances is
only reproducible if the wave activity and baroclinicity are advected eastward at different
rates: the eddy activity at a rate consistent with the group velocity; the baroclinicity at a
slower rate consistent with flow speeds in the lower troposphere.

The results shown here highlight the origins of periodicity in SH extratropical
circulation. They also reveal a novel aspect of extratropical wave packets not appreciated
in previous work: that they are associated with out-of-phase anomalies in eddy kinetic
energy that form to the west of decaying disturbances. To what extent similar behavior is
observed in the Northern Hemisphere storm tracks will be explored in a companion study.

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### Tables

**Table 1. Parameters used in the simple model**

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<td>$\beta$</td>
<td>$3.7 \times 10^{-13}$ (dimensionless)</td>
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<td>$\alpha$</td>
<td>$-24 \text{ m}^2/\text{s}^2$</td>
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<td>$\tau_b$</td>
<td>4 days</td>
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Figure Captions

Figure 1. a) Eddy kinetic energy anomalies at 300 hPa regressed onto the BAM index time series, defined as the leading PC time series of eddy kinetic energy over all levels and latitudes within the domain 1000-200 hPa and 20°-70°S. Solid black lines indicate latitude circles at 40°S and 60°S. b) Power spectrum of the BAM index time series in units cycles per day (cpd). See text for details.

Figure 2. Power spectra of eddy kinetic energy anomalies at 300 hPa averaged 40°-60° latitude. (a) Zonal-mean; (b-d) averages over longitude bands of indicated widths. See text for details.

Figure 3. (left) Hovmöller plot for eddy-kinetic energy anomalies at 300 hPa averaged 40°-60° latitude. Results are found by averaging lag/longitude correlation plots formed for all base longitudes. Longitude 0° indicates the base longitude of the analysis. The lowest contour value corresponds to correlations that are significant at the 95% level (see Section 2). Contours at -0.02, +0.02 0.06, .... (right) Corresponding lag correlations for zonal-mean eddy kinetic energy. Note that the right panel shows the correlations for zonal-mean EKE_{40°-60°S}, not the the zonal-mean of the composite correlations in the left panel. In practice, results based on both calculations yield effectively identical results.

Figure 4. (left) As in Fig. 3, but results are smoothed with a 30 degree longitude running mean filter and are shown as a series of filled line plots. Note the longitude axis is extended relative to Fig. 3 so that the anomalies can be traced as they wrap around the globe. (right) Corresponding lag correlations for zonal-mean EKE.
Figure 5. As in Fig. 4, but for lags extending from 0 to +30 days. Note the longitude axis in the left panel is shifted to the east of that in Fig. 4 so that the anomalies can be traced as they wrap around the globe.

Figure 6. Power spectra of eddy-kinetic energy anomalies at 300 hPa averaged 40°-60° latitude and following the flow eastward at indicated rates. Open circles denote the frequency of maximum power for each eastward rate for cases where the spectral peak is statistically different from a red-noise fit to the data at the 95% level. The vertical black line denotes the frequency of maximum power for the spectrum of zonal mean eddy-kinetic energy. All spectra are normalized to unit variance. See text for details of the analysis.

Figure 7. Output of the model given by Eqs. 3) and 4) for three different configurations of the time-mean, zonal-mean flow. Left panels indicate results as a function of longitude; right panels indicate the zonal averages of the results. The initial amplitude of the Gaussian pulse is 27 K m/s. See text for details.

Figure 8. Power spectrum of the zonally-averaged output from Fig. 7. The spectrum of the zonally-averaged output is identical for all three configurations of the time-mean, zonal-mean flow.
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wave packet propagates eastward at ~25 m/s

negative EKE anomalies develop in wake of original wave packet

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