The global distribution of atmospheric eddy-length scales

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ABSTRACT

The correlation lengths of vorticity anomalies from temporal averages are examined in the ERA-40 Reanalysis dataset. It is shown that in the annual mean, eddies in the Southern Hemisphere are significantly larger than those in the Northern Hemisphere. The eddy vorticity lengths exhibit a strong seasonal cycle, with the largest scales occurring in the winter season. The maximum zonal eddy lengths closely follow the contours of the strong upper-level winds, while the maximum meridional lengths are found in jet exit regions and in the stratosphere.
1. Introduction

Eddies play an important role in defining the large-scale circulation, and their scale predominantly determines their propagation and dissipation (Hoskins et al. 1983). Kidston et al. (2010) demonstrated that the CMIP3 general circulation models (Meehl et al. 2007) exhibit a robust increase in zonal eddy-length scale in future climates, and they suggest that this increase contributes to the predicted poleward migration of the midlatitude jets with increased greenhouse gases. Barnes and Hartmann (2011) present an alternative possibility, demonstrating that a poleward shift of the midlatitude jet can cause an increase in eddy-size in a barotropic model, consistent with spherical Rossby-wave theory.

Understanding eddy scales is clearly important to understanding future atmospheric circulation changes and pinpointing cause and effect. Chang and Yu (1997); Chang (1999) performed in-depth studies of wave packets at 300 mb in the midlatitudes with a focus on propagation characteristics of zonally-propagating storm track disturbances (e.g. phase speed, period, group velocity estimations). Here, our focus is purely one of eddy scale throughout the atmosphere, and we present a three-dimensional picture of observed eddy vorticity scales as a reference point for understanding eddy scales more completely.

2. Data

The data consists of 44 years (1958-2001) of 2.5°×2.5° latitude-longitude gridded daily (1200 UTC) relative vorticity and zonal wind from the European Centre for the 40-yr Medium Range Weather Forecasts Re-Analysis (ERA-40) (Uppala et al. 2005).
We denote daily anomalies as \((\cdot)^{'}\) and they are calculated by first subtracting the mean seasonal cycle at each grid point. The mean seasonal cycle is a smooth curve computed as the climatological mean plus the first four Fourier harmonics of the daily climatology for all seasons over the 44 years of data. Finally, to remove interannual variability, we remove the individual yearly means or individual seasonal means depending on whether we are analyzing annual- or seasonal-mean quantities.

We note that we have also analyzed the data by removing the daily zonal-mean instead of defining temporal anomalies, as well as retained the seasonal cycle and interannual variability and in all cases the results are similar. We present results for DJF and JJA, however, we have also analyzed the shoulder seasons. Results for these seasons depict the atmosphere transitioning between extremes during winter and summer and are not shown here for brevity.

3. Calculation of eddy-length scale

We describe the zonal and meridional lengths of the vorticity anomalies by calculating the e-folding lengths of the one-point vorticity correlation plots. This is done by defining a base point (latitude-longitude pair) and correlating the time series of the anomalous vorticity at the base point with the anomalous vorticity at every grid point on that pressure level. This results in a one-point correlation map centered on the base point. We repeat this calculation for all possible base points (all grid points) and all pressure levels (15 levels, 1000 mb to 50 mb).

Fig. 1 shows the correlation map at \((55^\circ\ N/S, 0^\circE)\) for the Southern and Northern Hemisphere calculations. The correlations at the anomaly centers are identically equal to
one since this represents the correlation of the base point with itself. From this plot alone, it is evident that the Southern Hemisphere vorticity anomalies are larger in the zonal direction than those in the Northern Hemisphere, an observation also made by Chang (1999).

To quantify the size of the anomalies, we slice the correlation plots through the base point and along the zonal and meridional axes (see dashed black lines in Fig. 1). These curves are interpolated to a 0.01°×0.01° grid, and the average meridional distance and average zonal distance between the base point and the point where the correlations drop below 1/e are defined as the vorticity-length scale in the meridional and zonal directions respectively. Near the pole, where the correlations in the meridional direction may never drop to 1/e, we designate the eddy-length as “not defined”.

Other studies define the eddy-length scale as a zonal scale derived from the Fourier decomposition of meridional velocity (Kidston et al. 2010). We have chosen to use correlation e-folding lengths instead as it allows us to easily calculate a meridional scale of the eddies as well as locally define a length scale in sectors of the globe. However, for comparison, we have analyzed vorticity and meridional velocity using Fourier decomposition. To do this, we roughly follow Kidston et al. (2010) and calculate the power-weighted average Fourier zonal wavenumber at each latitude,

$$\overline{k}(\theta) = \frac{\sum_{k} k \times |\tilde{X}(k)|^2}{\sum_{k} |\tilde{X}(k)|^2},$$

where $\tilde{X}$ is the Fourier component of the anomalous vorticity ($\zeta'$) or meridional wind ($v'$). The Fourier zonal eddy length at each latitude $\overline{X}(\theta)$ is then defined as $2\pi a \cos \theta / \overline{k}(\theta)$, where we only plot results equatorward of 80° N/S to avoid spurious values near the poles.
4. Results

4.1 Zonally-averaged eddy-length scales

Fig. 2a shows the zonally-averaged correlation e-folding lengths of the 200 mb vorticity anomalies ($\zeta'$) for all days, where the y-axis denotes both negative and positive latitudes to allow for easy comparison of the two hemispheres. From this figure, it is evident that the vorticity anomalies in the Southern Hemisphere are larger than those in the Northern Hemisphere in both zonal and meridional extent, verifying what was seen in Fig. 1. Performing the same calculations for even and odd years separately results in similar hemispheric differences. Also, in the mid- and polar-latitudes, the zonal and meridional length-scales appear to be similar in both hemispheres, indicating that the vorticity anomalies are isotropic, while in the subtropics and tropics the eddies are zonally elongated.

Focusing on the zonal scales, both hemispheres display a peak in zonal-eddy vorticity scale near 25°. However, in the midlatitudes, the zonal-eddy scale in the Southern Hemisphere is nearly constant, while the zonal lengths of the eddies in the Northern Hemisphere continue to shrink. In the meridional direction, the Southern Hemisphere exhibits a peak in the meridional length of the eddies in the midlatitudes. In the Northern Hemisphere however, the meridional scale of the eddies gradually increases with latitude at 200 mb with no obvious maximum.

Fig. 2b shows the zonally-averaged zonal length scales of the vorticity anomalies defined using the Fourier method. The actual lengths are much larger than those calculated using the e-folding correlation scale, which is expected since the Fourier scales correspond to an entire wavelength of the wave. To see that the two methods described similar scales, we can explic-
itly relate the autocorrelation of a cosine wave to its Fourier transform. The autocorrelation and the power-spectral density are a Fourier Transform pair (Wiener-Khinchin Theorem), and so the autocorrelation of the cosine wave \( Y(x) = \cos(2\pi x/L) \) is \( R(x) = \cos(2\pi x/L) \). Thus, we can relate the e-folding length scale \( x_e \) of the autocorrelation function to the wavelength \( L \) by

\[
e^{-1} = \cos(2\pi x_e/L)
\]

\[
x_e = 0.19L.
\] (2)

Looking at Fig. 2b, the maximum Fourier zonal length scale in the Southern Hemisphere is approximately 4500km. Plugging this into (2) yields a correlation e-folding distance of 850 km, very similar to what we see in Fig. 2a. Thus, the Fourier decomposition method yields similar results to those obtained using the correlation method.

We perform the same calculations using the meridional velocity at 200 mb instead of the relative vorticity, and show the results in Fig. 2c,d. The main difference between the vorticity and meridional velocity results is that the meridional velocity shows much larger meridional length scales compared to vorticity. As with vorticity, the Southern Hemisphere zonal and meridional eddy length scales are larger than those in the Northern Hemisphere in the midlatitudes. In addition, we see similar results to those of Chang (1999), where he found using one-point correlation maps of meridional velocity that the zonal scales of the wave packets decrease toward the poles.

For the rest of this analysis, we focus solely on the length scales of relative vorticity. We choose this variable because it is a scalar quantity that is straightforward to interpret in the context of large-scale dynamics. In addition, recent findings using satellite data
show that the cloud scales in the Southern Hemisphere are larger than those found in the Northern Hemisphere (Roger Marchand, personal communication). In this context, vorticity emphasizes the smaller scales that are more directly associated with precipitation.

b. Pressure-latitude cross-sections of seasonal length-scales

Fig. 3 displays the zonally-averaged zonal and meridional DJF (December-February) and JJA (June-August) eddy-length scales as a function of pressure and latitude. Overlaid on these panels is the seasonal-mean zonal-mean zonal wind. The distributions show a strong seasonal cycle, with each hemisphere displaying its largest length scales during winter. In terms of the vertical distribution, the maximum length scales appear above 150 mb since smaller synoptic scale waves cannot propagate into the stratosphere (Charney and Drazin 1961; Matsumo 1970).

In the winter hemisphere, the zonal scales above 300 mb roughly follow the strongest zonal winds, while below they align with the equatorward flank of the jet. In both DJF and JJA, a band of upper-level easterlies exists near the equator, and the largest zonal scales appear to peak in the winter hemisphere and terminate at the latitude of easterlies in the summer hemisphere.

Interestingly, we see that the largest meridional scales do not necessarily align with the largest zonal scales, but rather they are located in the midlatitude-stratosphere, extending downward into the upper-troposphere with the largest lengths found in the Southern Hemisphere during JJA.
c. Seasonal length-scales on isobaric surfaces

We now present latitude-longitude maps of the correlation length scales. Fig. 4 depicts global maps of 200 mb eddy vorticity scales in DJF and JJA. As seen in the zonal-average, the distributions show a strong seasonal cycle and the largest zonal scales clearly follow the strongest zonal winds. The meridional scales do not align with the upper-level jets, but rather, the maximum meridional scales tend to occur near the jet exit regions (e.g. the Gulf of Alaska and south of Australia). In addition, the smallest meridional scales appear in the Indian Ocean basin, which is a region of strong easterlies in JJA.

Fig. 3 shows that the largest zonally-averaged zonal eddy scales appear in the stratosphere, and so we plot the length scales at 50 mb in Fig. 5 to give another view of the eddies at upper-levels. The meridional scales peak near both poles in DJF and peak near Antarctica in JJA at 50 mb. The largest zonal scales at 50 mb appear along a somewhat zonally-symmetric band near the equator, aligning well with the summer-hemisphere easterlies.

5. Discussion & Conclusions

In this article, we document the climatological distribution of zonal and meridional eddy-length scales in DJF and JJA. We find that the Southern Hemisphere exhibits larger eddy scales than the Northern Hemisphere and the maximum zonal-eddy scales follow the contours of strong zonal winds, while the longer meridional length scales tend to peak in the jet exit regions.
The fact that the largest zonal vorticity scales at upper-levels follow the strongest zonal winds in the midlatitudes is perhaps not surprising. Consider the zonal phase speed of a Rossby wave linearized about a background zonal flow $\mathcal{U}$:

$$c_{px} = \mathcal{U} - \frac{\beta}{k^2 + \ell^2}, \quad (3)$$

where $k$ and $\ell$ are the zonal and meridional wavenumbers of the wave. Rearranging this equation gives

$$(\mathcal{U} - c_{px})(k^2 + \ell^2) = \beta. \quad (4)$$

Assuming the zonal wind increases more than the phase speed of the wave, if $\mathcal{U}$ increases along a latitude circle (beta is constant), the scale of the wave must increase ($k^2 + \ell^2$ must decrease). Intuitively, larger scales are required so that planetary vorticity advection may balance larger downstream advection by a stronger mean flow. For this reason, one might expect the largest waves in regions of strong zonal wind, which is indeed what we see in Fig. 3 and Fig. 4. Given that the zonal-length scales at the jet level appear to follow the zonal wind, that the Southern Hemisphere has larger eddies than the Northern Hemisphere is not surprising since the Southern Hemisphere has stronger climatological zonal winds (Peixoto and Oort 1992). These findings are consistent with Frierson et al. (2006), where changes in eddy-length scales in a simplified GCM were best predicted by the Rhines scale ($\sqrt{v_{rms}/\beta}$), where $v_{rms}$ is the square root of the eddy kinetic energy.

Although the largest zonal lengths at 200 mb are typically found along the jet-stream axes, another peak in eddy length exists near the equator in the Eastern Pacific during DJF (Fig. 4). This region corresponds to a band of equatorial westerlies and has been shown to act as a duct, allowing waves to propagate from one hemisphere to the other (Webster and
Holton 1982; Waugh and Polvani 2000; Waugh 2005). One point correlation maps from this region give evidence of Rossby waves propagating into this region from the extratropics (not shown). These one-point correlation maps also suggest triggering of equatorial waves, which may be related to the development of convection as these vorticity signals reach the deep Tropics.

Unlike at 200 mb, the zonal lengths at 50 mb are largest at the equator and appear to align with the strong band of easterlies in the summer hemisphere (see Fig. 3 and Fig. 5). These increased eddy-length scales are likely evidence of the inertially unstable flow associated with the strong easterlies there. Knox and Harvey (2005) document regions of inertial instability in the lower stratosphere and find that most occurrences are found within 30° of the equator, with the distribution offset into the winter hemisphere and extending around the globe, as we see here. Consistent with the picture of inertial instability generating waves at the equator, lagged-correlation plots of anomalous vorticity show waves that appear to partially develop locally at the equator and then propagate westward (not shown).

In both hemispheres, on average the zonal eddy-length scales decrease with latitude, while the meridional scales increase slightly with latitude. Basic Rossby-wave propagation theory can potentially explain this observation. Imagine a Rossby wave of zero frequency emanating from the midlatitude jet and propagating equatorward, and suppose that $\beta/\pi$ decreases with latitude. Rossby-wave tracing on the sphere tells us that the frequency and zonal wavenumber will remain constant during propagation and that the meridional wavenumber will increase to satisfy the Rossby-wave dispersion relation (Hoskins and Karoly 1981). In terms of physical eddy lengths, this implies that the zonal length scale will increase and the meridional length will decrease as the wave propagates equatorward. Consistent with this
argument, we see that the meridional scales tend to be smallest in the tropical troposphere while the zonal scales tend to be largest there (see Fig. 2 and Fig. 3).

This work highlights the relationship between the strong zonal wind and the scale of the eddies, demonstrating that observed eddy-vorticity length scales vary regionally and exhibit a clear seasonal cycle. Since the scale of the waves plays a large role in determining their propagation characteristics and ultimate effects on the general circulation, understanding their spatial and seasonal distributions is critical to understanding future circulation changes. These results suggest that a change in wind speed could potentially change the distribution of eddy scales, which through a feedback loop, has the potential to affect the wind profiles themselves.

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REFERENCES


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