Dynamics and Geometry of Extratropical Cyclones in the Upper Troposphere by a Neighbor Enclosed Area Tracking Algorithm

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ABSTRACT

This study shows that the morphological characteristics of upper-tropospheric extratropical eddies are closely related to the background flow in the Northern Hemisphere winter. Enclosed surfaces of 300-hPa relative vorticity are identified by using the neighbor enclosed area tracking algorithm, and the periphery of these surfaces are approximated by ellipses. Eddies are classified into five categories according to the approximate ellipse. Eddies having an oblateness of less than 0.6 are classified as near circle, or are otherwise classified as northeast–southwest (NE–SW), northwest–southeast (NW–SE), north–south, or west–east, according to the direction of the major axis. In the wintertime climatology, NE–SW-oriented cyclones are collocated with the jet stream, while NW–SE-oriented cyclones mostly reside north of the jet. In interannual variability, moreover, the frequency of NE–SW cyclones is slightly correlated with the Arctic Oscillation (AO) index, while the frequency of NW–SE cyclones is highly anticorrelated with the AO index. This is consistent with positive feedback between horizontally slanted eddies and background flow, as has been shown in many previous studies.

1. Introduction

There are many baroclinic disturbances in the extratropics that have horizontal extents of thousands of kilometers. The paths that these disturbances prefer are called storm tracks and are located in the North Pacific and North Atlantic in the Northern Hemisphere (NH) winter (Chang et al. 2002). Extratropical cyclones have been studied in terms of morphological description, conceptual model, and dynamical diagnosis (Shapiro et al. 1999). The morphology of extratropical cyclones was historically pioneered by the Norwegian model (Bjerknes and Solberg 1922), with the modern model of cyclones later bringing profound insight into the distinct differences between the dynamics of the two cyclone life cycles named LC1 and LC2 (Thorncroft et al. 1993). LC1 cyclones develop into a T-bone, bent-back, warm-frontal system under a background of no barotropic shear and take on a horizontally slanted structure with a northeast–southwest (NE–SW) orientation in their mature stage with wave activity flux that radiates southeastward. In contrast, LC2 cyclones mature into a Bergeron’s occluded system under a background of cyclonic barotropic shear and possess a horizontally slanted structure with a northwest–southeast (NW–SE) orientation throughout their life cycle with wave activity flux that radiates north-eastward. Several idealized experiments and data analysis have recently suggested a close relationship between the type of cyclone life cycle and the Rossby wave breaking (RWB) system: LC1 cyclones break up into upper tropospheric cutoff vortices near the jet stream through the barotropic decay process, while LC2 cyclones wrap up cyclonically far north of the jet (see Thorncroft et al. 1993; Appenzeller et al. 1996). The former cyclones tend to develop more rapidly and to have a longer lifetime because of the suppressed energy conversion (James 1987; Thorncroft et al. 1993).

Studies on cyclone life cycle and RWB have indicated that they have an important role in climate variation (Holton 1995; Appenzeller et al. 1996). RWBs are closely related to cutoffs detached from the polar vortex narrow filaments stretched from it. Concisely, LC1 or anticyclonic RWB is characterized by a NE–SW orientation of eddy, while LC2 or cyclonic RWB is characterized by a NW–SE orientation. Modern morphological techniques for identifying cutoffs and filament-like streamers in the isentropic potential vorticity (PV) field have revealed
extensive statistics of RWB events. Wernli and Sprenger (2007) found that climatological streamer and cutoff frequency exhibit maxima at the downstream end of the storm track near the tropopause. Another classification of streamers is according to their orientation, with NE–SW-oriented streamers preferring the positive phase of the North Atlantic Oscillation (NAO) over Europe (Feldstein 2003; Benedict et al. 2004; Franzke et al. 2004; Watanabe 2009) and NW–SE-oriented streamers preferring a positive Pacific North American (PNA) index (Martius et al. 2007). Another RWB classification according to meridional wave activity flux and diffluent flow field suggested a similar result to that described above (Gabriel and Peters 2008). This is consistent with previous studies in which life cycle or RWB type has been found to be closely related to the low-frequency background flow in an aquaplanet model (Lee and Feldstein 1996; Esler and Haynes 1999). Mizuta et al. (2011) suggested an increase in LC1-type cyclones and a decrease in LC2-type cyclones in a global warming climate.

It is therefore certain that RWB events may, more or less, contribute to the meridional flux of PV as above. However, cyclones do not always experience typical nonlinear RWB events, and we often observe many cyclones without any breaking events but with a significant meridional PV transport. Moreover, although RWB accompanied by distortion of isentropic PV contours was found to characterize the NE–SW or NW–SE eddy orientation of small-scale streamers or cutoffs (Wernli and Sprenger 2007), these events were identified by using a complicated tracking algorithm or by applying contour dynamics. The work of Martius et al. (2007) was instrumental in extending traditional meteorological dynamics using modern climate dynamics in terms of RWB events. When the action of atypical cyclones on the low-frequency background state is considered, a more straightforward analysis of eddy geometry in relation to the background flow is thought to be worthwhile. Because this kind of direct approach to eddy morphology has not been attempted, there is no direct evidence that horizontally slanted eddies observed in the extratropics are actually related to the jet stream. The corresponding elliptical stratospheric polar vortex may provide hints for identifying the eddy morphology of enclosed areas (Waugh and Randel 1999; Mitchell et al. 2011).

Recently, Inatsu (2009) developed a neighbor enclosed area tracking (NEAT) algorithm (see section 2 for full details) offering much simpler parameter tuning but more plentiful outputs than conventional neighbor point tracking (NPT). Most conventional NPT algorithms identify a cyclone center point by searching for a local extremum point in the vorticity or sea level pressure field in every time frame and optimally concatenate them into a temporal sequence by minimizing some cost function [an example in the Southern Hemisphere (SH) was shown in Keable et al. (2002), and other examples in the NH were shown in Hoskins and Hodges (2002) and Simmonds and Rudeva (2012)]. In contrast, the NEAT algorithm unifies the cyclone identification and cyclone tracking processes by concatenating overlapped enclosed surfaces that satisfy some criteria. The NEAT algorithm is able to evaluate merging and splitting of cyclones without any additional processing. Inatsu (2009) found a frequent-merge region in the western Pacific and a frequent-split region in the eastern Pacific. The splitting in the eastern Pacific may be related to the interaction between eddies and mean flow. Satake et al. (2013) applied this algorithm to detect tropical cyclones (TCs) in a gridded dataset and successfully picked out more than 85% of the typhoons in the western North Pacific from the Japanese 25-year Reanalysis Project (JRA-25) and Japan Meteorological Agency Climate Data Assimilation System (JCDAS; data available from http://jra.kishou.go.jp/JRA-25/index_en.html) (Onogi et al. 2007). They also estimated the extratropical transition of TCs (see Evans and Hart 2003) by focusing on the geometry of the enclosed area and furthermore attempted to calculate the Lagrangian heat transport by TCs. Since the NEAT algorithm is capable of detecting the influential regions of cyclones without performing any postprocessing, it can easily estimate the dynamical and material transport by eddies. It is noted that the NEAT algorithm could be applied to cloud satellite images, oceanic mesoscale eddies, and atmospheric frontal-zone tracking. The NEAT algorithm now joins an international tracking intercomparison project called Intercomparison of Mid Latitude Storm Diagnostics (IMILAST; Neu et al. 2013).

The purpose of the study is to present direct evidence that horizontally slanted high-frequency eddies are related to the background westerly flow in the upper troposphere by using the NEAT algorithm to identify the equivalent ellipses of the enclosed surfaces. We sketch out the climatology of horizontally slanted eddies and compare the geographical distribution with the westerly jet stream. In our analysis of interannual variability, we pay special attention to the relationship with the Arctic Oscillation (AO), which is the leading mode of sea level

\[1\] NAO is a seesaw pattern between Icelandic low and Azores high and shifts the Atlantic jet stream; PNA pattern aligns pressure anomalies across the Pacific to North America and is related to meandering of the Pacific jet stream.
pressure north of 20°N, in order to ensure consistency with previous studies that have suggested the importance of the NAO to RWB or the cyclone life cycle. We use the AO index simply for one of the indices in a global climate pattern, though there are many debates on the physical reality of the AO (Ambaum et al. 2001; Itoh 2008). This paper also attempts to evaluate the westerly meridional transport inside the upper tropospheric eddies by following the method of Satake et al. (2013). The remainder of this paper is organized as follows: the data, tracking method, and evaluation of the shape of cyclone images are described in section 2; climatology and interannual variability for cyclones classified into each shape are shown in section 3; and the summary is given in section 4.

2. Data and method

a. Data

The data used are the 6-hourly JRA-25/JCDAS reanalysis dataset (Onogi et al. 2007). The input to the NEAT algorithm is 300-hPa relative vorticity; this is estimated from a spatial finite difference of zonal and meridional winds and is not a standard product from the reanalysis. The horizontal grid mesh is 1.25° × 1.25°. The period is from 1979 to 2010 and the analysis is limited to the NH winter [November–March (NDJFM)]. A high-pass filter with a period of <10 days is applied before tracking (Duchon 1979). We also use the AO index defined as the leading principal component of sea level pressure based on the JRA-25/JCDAS data (see Thompson and Wallace 2000).

b. NEAT algorithm

This section fully documents the NEAT algorithm (Inatsu 2009; Satake et al. 2013), the program of which can be freely downloaded from the NEAT website (http://recca-hokkaido.sci.hokudai.ac.jp/~inaz/neat/).2 Cyclone identification in the NEAT algorithm requires the connected component labeling technique (see Samet 1989 for the technical details). We will give an idealized example for cyclone identification. Now fixing a single time frame and thinking of rounded integer values of relative vorticity divided by 10^{-2}s^{-1} in a block with eight grids in longitude and eight grids in latitude (Fig. 1a), the NEAT algorithm converts this image into a binary, as in Fig. 1b, by using a condition on relative vorticity that will be called the enclosed surface criterion C. We set the value of 1 (black in Fig. 1b) where relative vorticity is

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2 Our code is written in Fortran 90 without pointers.
greater than or equal to 1 in Fig. 1a and set the value of 0 (white in Fig. 1b) elsewhere. A label is finally assigned, as in Fig. 1c, in order to identify cyclones as an independent enclosed surface and to distinguish different cyclones in the subsequent process. This cyclone identification process is taken for every time frame throughout the period.

The cyclone tracking in the NEAT algorithm directly evaluates the temporal neighboring, which is to say the overlap, of the equivalently labeled images produced in cyclone identification (Fig. 1c). Logically, there are six possible cases in the temporal neighboring (Table 1): genesis, lysis, single connection, merge, split, and group connection. Genesis here refers to when a particularly labeled cyclone with its intensity $>10^{-4} \text{s}^{-1}$ of relative vorticity at 300 hPa is first emerged throughout the period, which is defined in NEAT as the case when no image in one time frame overlaps a single image in the next time frame. Lysis here refers to when a particularly labeled cyclone is extinct, which is defined as the case when a single image in one time frame overlaps no images in the next time frame. Single connection refers to a cyclone moving without any merges or splits, which is defined as the case when a single image in one time frame overlaps a single image in the next time frame. Merge refers to more than two cyclones coalescing in an isobaric surface, which is defined as the case when multiple images in one time frame overlap a single image in the next time frame. Split refers to a single cyclone breaking into two or more cyclones, which is defined as the case when a single image in one time frame overlaps multiple images in the next time frame. Group connection refers to all other cases. Each track in the NEAT algorithm is output as a time sequence of two-dimensional images. We then filter out tracks where the lifetime, defined as the period from genesis to lysis, is less than H, the size of the equivalently labeled area is less than A, or the size of overlap is less than O. Note that conditions C, H, A, and O must all be satisfied (see schematic in Fig. 2). We set the parameters for condition C to 300-hPa relative vorticity of $10^{-4} \text{s}^{-1}$, condition H to 12 h, condition A to 20 000 km$^2$, and condition O to 10 000 km$^2$. The sensitivity of tracking results to these parameters was thoroughly discussed by Satake et al. (2013).

Cyclone quantification using the NEAT algorithm provides a greater abundance of information about the tracks. Genesis, lysis, merge, and split density are calculated using a spherical circle with a radius of $S$ (here 1000 km). The lifetime of the track is the period from genesis (first frame) to lysis (last frame). The track velocity vector is the temporal change in the position vector between centroids at adjacent time frames. The growth rate is the ratio of the size of the enclosed area in the next time frame to that in the previous frame. Although the density is defined as usual, the track frequency is, naturally for NEAT, quantified as the occupying-time fraction in the equivalently labeled images. The track frequency, just like the feature density in Hoskins and Hodges (2002), tends to stress larger, or deeper, cyclones rather than smaller, or weaker, ones.

c. Ellipse evaluation

The ellipses are classified into types by using the following procedure. First, the enclosed surface is transformed into two-dimensional polar coordinates with the center of the surface as the origin in each time frame such that the distance between the center and boundary of the area becomes a function of polar angle $u$ that is estimated from the transformed data (Figs. 3a,b). The distance $r(u)$ is given by

$$r(\theta) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\theta + b_n \sin n\theta),$$

where $a_n$ and $b_n$ are the Fourier coefficients defined as
The fitted ellipse estimated from the Fourier coefficients $a_n, a_2,$ and $b_2$ from Eq. (1).

\[ a_n = \frac{1}{\pi} \int_0^{2\pi} r(\theta) \cos \theta \, d\theta, \quad (2) \]

and

\[ b_n = \frac{1}{\pi} \int_0^{2\pi} r(\theta) \sin \theta \, d\theta, \quad (3) \]

for all nonnegative integers $n$. One possible optimal fitting of an ellipse to the original surface is then given by

\[ E(\theta) = a_0 + a_2 \cos 2\theta + b_2 \sin 2\theta, \quad (4) \]

as shown in Fig. 3c. Of course, Eq. (4) does not represent a true ellipse in the mathematical sense, but we refer to it as an ellipse because of its simple formulation. The major and minor axes of $E(\theta)$ are $a = a_0 + \sqrt{a_2^2 + b_2^2}$ and $b = a_0 - \sqrt{a_2^2 + b_2^2}$, respectively, giving an oblateness of $f = [(a - b)/a]$. We regard a shape to be an ellipse if the oblateness $f = [(a - b)/a] > 0.6$; otherwise, we regard it as a near circle.$^3$ Ellipses are furthermore classified into north–south (N–S), NE–SW, west–east (W–E), and NW–SE orientations if the argument of the major axis falls into the ranges of $\pi/2 \pm \pi/8$, $\pi/4 \pm \pi/8$, $0 \pm \pi/8$, or $-\pi/4 \pm \pi/8$, respectively. The root-mean-square error (RMSE) of $E(\theta)$ is defined as

\[ e = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} |E(\theta) - r(\theta)|^2 \, d\theta}. \quad (5) \]

$^3$In the other words, the minor and major axes are written as $a = a_0(1 + e)$ and $b = a_0(1 - e)$, respectively, where eccentricity $e$ of $E(\theta)$ is given by $e = \sqrt{1 - (b/a)^2}$. We regard a shape to be an ellipse if $e = 0.8$ and a circle otherwise.

The above process is partially similar to Lim and Simmonds (2009), who estimated the mean radius of cyclones from $a_0$ in Eq. (2), and is based on the same idea as that of Waugh (1997) for polar vortex analysis.

Before giving the main result, we would first like to comment on the results when real atmospheric eddies are fit to an ellipse by following the procedure in the previous section. Figure 4 shows a typical eddy moving over North America in mid-January 1979. In the synoptic charts, a low-pressure system moved along the northern edge of the jet stream and rapidly developed over the course of two days from 13 to 15 January (not shown). On 13 January, the cyclone was located in central United States and the labeled image with relative vorticity at 300 hPa exceeding $10^{-4} \text{s}^{-1}$ was elongated west to east. The argument of the major axis of ellipse is $-2.8^\circ$. On 14 January, it moved eastwards and the identified cyclone area is very slanted in the NE–SW direction, with the major-axis angle being 42.6°. On 15 January, the cyclone moved eastward, reaching the east coast of United States, and its image became elongated north to south with the major-axis angle being 67.9°. Moreover, the ellipse successfully approximates the image when fit is based on $E(\theta)$. The RMSE of $E(\theta)$ ranged from 100 to 150 km during this period, with a ratio to the angular-mean radius of less than 0.35. The climatological RMSE of this fit to an ellipse (Fig. 5) is just as large as in this typical case. This guarantees the statistical stability of the ellipse evaluation in this study. Furthermore, the typical case suggests that ellipse evaluation is insensitive to the choice of criterion because the result does not change if the criterion is changed to a greater or a smaller value.
3. Results

a. Climatology

Figure 6a shows the climatology of cyclone frequency in the NDJFM season based on high-pass-filtered relative vorticity at 300 hPa by the NEAT algorithm. The track frequency is again taken as the duration over which equivalently labeled images occupy each grid. High-frequency areas in the North Pacific and North Atlantic correspond to the storm tracks, where transient eddy activity attains local maxima. Cyclone images occupy points along the storm tracks for about 7% of the total period. This is very similar to a traditional Eulerian estimation by high-pass-filtered eddy kinetic energy (EKE) in the upper troposphere (Fig. 6b; see Chang 1993). Lagrangian track statistics (Fig. 6a) produced a sharper image of midlatitude storm-passage lines than the Eulerian statistics (Fig. 6b), presumably because the former tends to emphasize the cyclone center under condition C (section 2). Storm passages are wider in the meridional direction in the eastern Pacific and Atlantic, but are tighter in the western Atlantic. The storm tracks are located downstream of the strong westerly wind and stationary trough (Fig. 6c), as many previous studies have already pointed out (Chang et al. 2002).

Now we divide the total cyclone frequency (Fig. 6a) into the frequencies of the five types of cyclones: the near-circle (Fig. 7a), NE–SW-oriented (Fig. 7b), NW–SE-oriented (Fig. 7c), N–S-oriented (Fig. 7d), and W–E-oriented cyclones (Fig. 7e). The cyclones are almost equally divided among the first four types, with far fewer of the W–E-oriented cyclones, probably because most of them have lower-frequency spectra (Hoskins et al. 1983) that were eliminated by the numerical filter used in this study. The near-circle and NE–SW-oriented cyclone frequencies have a local maximum ranging from over North American to the western Atlantic. We also found a minor storm track in the Mediterranean from the near-circle and NE–SW-oriented cyclones. In contrast, the N–S- and NW–SE-oriented cyclone frequencies...
have two peaks in the eastern Pacific and eastern Atlantic. Their storm passage routes are broad and in the meridional direction. The NE–SW cyclones (Fig. 7b) reside just above the entrance of the Atlantic jet, while the NW–SE cyclones (Fig. 7d) are mostly located around the exit of the jet in the higher latitudes. The result is quite suggestive of the close relationship between cyclone morphology and background state in the upper troposphere.

Figure 8 shows the meridional location relative to the upstream jet core of horizontally slanted eddies. The zonal wind has a high peak of more than 40 m s$^{-1}$ at 35°N in the Pacific. NE–SW–oriented eddies are frequent at the subtropical jet core, while NW–SE–oriented eddies prefer locations at 55°N, far north of the core. By contrast, the Atlantic jet stream is located in the range of 40°–45°N and has wind speeds that are weaker than the Pacific jet stream. NE–SW eddies are mostly collocated with the jet core. NW–SE eddies are actually located north of the jet, but the distance is less than in the Pacific case. This result suggests that NW–SE eddies are located around the latitudinal circle of 55°N regardless of the location of the jet stream and that NE–SW eddies reside along the jet stream. Considering the eddy-mean flow feedback, the NE–SW–oriented eddies prefer the southern side of the jet and the NW–SE–oriented eddies prefer the northern side. It is suspected that, because the location south of the jet is not under baroclinic instability, the NE–SW cyclone climatology might peak at the jet latitude.
FIG. 7. NDJFM climatology of the number of tracked cyclones having shapes of (a) near-circle and (b) NE–SW–, (c) NW–SE–, (d) N–S–, and (e) E–W–oriented ellipse. The contour interval is $4^\circ_{\text{eq}}$. Light shading denotes ranges of $8^\circ_{\text{eq}}–12^\circ_{\text{eq}}$ and $>24^\circ_{\text{eq}}$, heavy shading denotes $16^\circ_{\text{eq}}–20^\circ_{\text{eq}}$. See text for the eddy shape classification.
Figure 9 shows climatological horizontal $E$ vector by high-pass eddies (Hoskins et al. 1983) according to

$$E = \left( \overline{u_H} \overline{v_H} - \overline{u_H u_H} - \overline{u_H v_H} \right).$$

The divergence of this vector field gives the eddy forcing that accelerates the time-mean westerly jet. Here $(u, v)$ is the horizontal wind vector, subscript $H$ means high-pass-filtered quantity, and the overbar denotes time average. The climatological $E$ vector basically points westward in the extratropics and has two maxima of length in the eastern Pacific and Atlantic, where storm activity exhibits local maxima (Figs. 6a,b). The meridional component of the $E$ vector is negative around the subtropical jet and positive in the far north of the jet (Fig. 10a). The eddy forcing therefore acts to accelerate the time-mean jet in the central Pacific and western Atlantic. The NEAT algorithm identifies the enclosed surface that satisfies the vorticity condition in every time frame, so that the surface-average climatic variables can be directly estimated (see Satake et al. 2013 for a similar analysis on the meridional heat transport by TCs). Since the high-pass-filtered meridional momentum flux is generally large in the periphery of the enclosed surface of cyclones, the momentum transport shown in Figs. 10b,c is likely to be substantially underestimated. Although this is indirect evidence, it suggests that horizontally slanted cyclones play a significant role in the poleward westerly transport in the eastern Pacific and Atlantic and in the equatorward westerly transport over North America in the sense of climatological distribution.

The results on the winter climatology of eddy frequency presented in this section support the notion that horizontally slanted eddies dynamically transport westerly momentum in the background flow in the meridional direction. This notion has been established by many previous studies and is widely accepted in dynamic meteorology. By using the NEAT algorithm, this paper shows the feasibility of estimating how many horizontally slanted eddies reside in the extratropics and of comparing their horizontal distribution relative to the position of the jet stream.

b. Interannual variability

Figure 11a displays the interannual variation of cyclone frequency for each of the types classified in this

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**Fig. 8.** Cyclone frequency averaged over the Pacific sector from 150°E to 90°W and zonal wind averaged in its upstream area from 150°E to 150°W. Dashed and dotted lines with left axis label (%) are for NE–SW and NW–SE cyclone frequency, respectively, and solid line with right axis label (m s$^{-1}$) is for zonal wind. (b) Cyclone frequency averaged over the Atlantic sector from 90°W to 30°E and zonal wind averaged in its upstream area from 90° to 30°W.
The correlation coefficient between cyclone frequency and the AO index is summarized in Table 2. The NW–SE or NE–SW cyclone frequency ranges 3–4 and standard deviation is about 0.5. The normalized AO index shown in Fig. 11b is significantly anticorrelated with paper averaged over the extratropics in NH winter. The correlation coefficient between cyclone frequency and the AO index is summarized in Table 2. The NW–SE or NE–SW cyclone frequency ranges 3–4 and standard deviation is about 0.5. The normalized AO index shown in Fig. 11b is significantly anticorrelated with

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<th>CGI</th>
<th>AO index</th>
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<tr>
<td>Total cyclone frequency</td>
<td>0.20</td>
<td>0.15</td>
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<tr>
<td>NE–SW cyclone frequency</td>
<td>0.80</td>
<td>0.39</td>
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<td>NW–SE cyclone frequency</td>
<td>−0.85</td>
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<td>CGI</td>
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NW–SE cyclone frequency, probably because the meridional transport of zonal momentum in high latitudes plays an important role in jet vacillation (Tanaka and Tokinaga 2002). In contrast, it is slightly correlated with NE–SW cyclone frequency. As near-circle cyclone frequency is not completely synchronized with AO (not shown), the correlation coefficient between total cyclone frequency and AO is not statistically significant.

The cyclone ellipses are synchronized with AO as above, which is related to the vacillation of zonal-mean zonal wind in the NH extratropics (Thompson and Wallace 2000).

Based on the hypothesis that horizontally slanted eddies effectively have the action of zonal mean flow through the westerly momentum transport in the meridional direction, we define the cyclone geometry index (CGI) as the difference between NE–SW and NW–SE cyclone frequency. The time series of CGI is highly correlated with that of the AO index (Fig. 11b; Table 2), and the regression map for CGI is almost the same as that for AO. The total cyclone frequency regressed with respect to CGI (Fig. 12a) seems a bit noisy but is positive along the Atlantic jet stream (Fig. 6c) and negative in the higher latitudes. The former positive signal can be explained by the regression of the NE–SW cyclone frequency (Fig. 12b), while the latter negative signal is brought about by the regression of the NW–SE cyclone frequency (Fig. 12c). Statistically significant signals in horizontally slanted cyclone frequency (Figs. 12b, c) are mostly found in the Atlantic. In contrast, the near-circle cyclone frequency does not have much effect on the CGI, or the AO index (not shown), perhaps consistent with the argument that the “frequency” of infinitesimally small eddies that are likely to be circularly shaped is probably independent of the background flow (see Inatsu and Terakura 2012).

The regressions of eddy, mean flow, and the interaction between them as shown in Fig. 13 can be reconsidered in the context of the relationship between eddy geometry and background flow. Naturally, they are quite similar to the AO projection (see Wettstein and Wallace 2010). The EKE at 300 hPa regressed with respect to the CGI brings an even smoother map than the Lagrangian track frequency (Fig. 12a) with a positive signal along the Atlantic jet (Fig. 6c). The background flow regressed with respect to the CGI just resembles the AO pattern itself, or a combination of the NAO and PNA patterns, and exhibits a significant poleward shift of the jet stream, especially in the Atlantic and eastern Pacific. Analysis of eddy action [Eq. (1)] with respect to the CGI (Fig. 12c) clearly shows mean flow acceleration in the north of the jet stream and mean flow deceleration in the south of the jet stream. This is related to the

![Fig. 12. (a) Regression of total cyclone frequency with respect to CGI. Color shading (units are $^\circ$) follows the legend at the right. The contour line represents where the correlation coefficient between CGI and total cyclone frequency has a statistical significance of 5%. (b) As in (a), but for NE–SW cyclone frequency. (c) As in (a), but for NW–SE cyclone frequency.](http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00379.1)
southeastward Rossby wave flux anomaly along the jet
stream and is consistent with the anticyclonic circulation
anomaly in the background flow (Fig. 13b). Once the
anticyclonic circulation anomaly has been generated just
above the jet stream, the eddies propagating along the
jet tend to slant in the NE–SW direction (Fig. 12b). Since
the NE–SW eddies transport the westerly momentum to
the north, the given anticyclonic anomaly is expected to
be maintained against damping by many restoring pro-
cesses, including surface drag and the Newtonian cool-
ing effect. Moreover, we note that the N–S cyclone
frequency is almost synchronized with the NE–SW cy-
cclone frequency (not shown), which contributes to the
eastward Rossby wave flux. This effect, usually called
downstream development (Chang 1993), probably shifts
the eddy mean flow feedback effect eastward.

4. Summary

This study shows that eddy geometry is closely related
to the background state in terms of the geographical
distribution of climatology and in terms of the inter-
annual variability in the NH extratropics in winter. First,
the NEAT algorithm (Inatsu 2009) was used to identify
enclosed surfaces having relative vorticity \( >10^{-2}\) s\(^{-1}\),
and the cyclones in each time frame were classified as
near-circle, NE–SW-, NW–SE-, N–S-, or W–E-oriented
cyclones. It was found that NE–SW-oriented cyclones
tend to be collocated with the jet stream, while NW–SE
cyclones often reside north of the jet. This is consistent
with many previous studies on cyclone life cycle or
RWB, many of which have correlated NE–SW-oriented
cyclones with LC1 or breaking under anticyclonic shear
flow and NW–SE-oriented cyclones with LC2 or breaking
under cyclonic shear (e.g., Thornicroft et al. 1993). The
NE–SW- or NW–SE-oriented cyclones probably con-
tributed to the meridional transport of the westerly
momentum, as was expected. Analysis of interannual
variations found that NE–SW cyclone frequency is slightly
anticorrelated with the AO index, while NW–SE cyclone
frequency is significantly correlated with AO. This result
also supports the notion that horizontally slanted eddies
effectively transport the westerly momentum in the me-
ridional direction in the upper troposphere.

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