Using the Local Deepening Rate to Indicate Extratropical Cyclone Activity

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Abstract

The “Local deepening rate (LDR)”, the local surface pressure tendency, which is normalized by the sine of latitude and similar to the definition of an explosive cyclone, is introduced to extratropical cyclone activity analysis. The LDR has the advantage of being much simpler than conventional methods such as cyclone tracking and time filtering. The time average of positive LDR, which implies cyclone deepening, captures not only individual explosive cyclone’s deepening but also the mid-latitude storm track climatology. The probability of explosive deepening, defined as LDR ≥ 1 hPa h⁻¹ and based on ensemble forecasts, accurately represents the deepening potential and provides information regarding the influence area of storms—analogous to the strong wind area used in typhoon forecasts. The LDR can also be used to assess the quality of storm tracks in reanalysis products. In the 20th-century reanalysis, the storm track activity, calculated from ensemble mean surface pressure, is too weak before 1910 in the North Pacific, and in the South Pacific low activity is observed up to the end of the 20th century, because of large ensemble spread due to few surface pressure observations.

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1. Introduction

Extratropical cyclones have been investigated as one of the major targets in modern meteorology because they often cause weather disasters as well as being water resources and energy transporters in global circulation. Cyclone tracking is a traditional analysis method for extratropical cyclones as well as tropical cyclones (Murray and Simmonds 1991; Hodges 1995; Inatsu 2009). Originally, Tor Bergeron defined the normalized deepening rate using central pressure change based on cyclone tracking (as discussed in Sanders and Gyakum 1980). Because the cyclone tracking can provide information of cyclone characteristic such as actual start and end points, storm intensity, lifetime, and cyclone structures (Catto et al. 2010), many tracking methods have been suggested. However, they exhibit different differences from each other, especially weak cyclones (Neu et al. 2013). The differences are due to cyclone definition, detection and selection of connection and merger, some of which depend on spatial and temporal data resolution. In addition it is not easy to understand the detail and code of tracking methods which require long and complicated programs. The uncertainty and the complexity of the methods may prohibit the progress of cyclone tracking analysis.

Another commonly used method is time-filtering for local time series. A band pass filter in time (e.g. for 2–8 day period disturbances) is used to detect synoptic time scales, including both extratropical cyclones and anticyclones, and the root-mean-square of these fluctuations calculated at each point is referred to as a storm track (Blackmon et al. 1984). This method is useful to analyze the collective effect of storm track on large-scale circulation (Nakamura 1992). However, this method is difficult to correlate with individual cyclones.

Recently, Fink et al. (2012) introduced a diagnostic equation of local pressure tendency to analyze explosive cyclones. They suggested that the pressure tendency analysis can easily be applied to a large number of cyclones because of simple methods using Eulerian calculations, and they used the method to analyze tracked cyclones.

The present study suggests a new index of extratropical cyclone activity using the local surface pressure tendency. It is useful to survey deepening cyclone events and to analyze the climatology, annual cycle and inter-annual variability of extratropical cyclone activity. Although the index cannot directly detect the cyclone track of individual cyclones, it can be complementary to tracking methods.

2. Method and data

This study suggests a normalized surface pressure tendency, “Local Deepening Rate (LDR)”, as follows:

\[
\text{LDR} = -\frac{\partial p(t)}{\partial t} \frac{\sin 60^\circ}{\sin \theta}
\]

where \(p\) is the surface pressure, \(t\) is the time, \(\theta\) is the latitude of the grid point. The normalization by latitude is analogous to the explosive cyclone definition (Sanders and Gyakum 1980). The surface pressure is used instead of the sea-level pressure (SLP) to avoid artificial noise over high mountains. The pressure tendency can be estimated by several differences. Because the 6-h and 12-h differences include shorter time-scale pressure tendencies such as diurnal cycle and cumulus convection, in this study, the LDR estimated by the 24-h central difference (LDR24, in hPa h⁻¹) is used to analyze synoptic-scale cyclones, as follows:

\[
\text{LDR24} = -\frac{p(t+12h) - p(t-12h)}{24} \frac{\sin 60^\circ}{\sin \theta}
\]

This value is similar to the 24-hour difference filter in Wallace et al. (1988). To analyze cyclone deepening, time averages of positive LDR24 are used here. LDR24P0 is the time average of positive LDR24, with all other values of LDR24 set to zero, and LDR24P1 is the time average of LDR24 ≥ 1, again with all other values of LDR24 set to zero, to analyze explosive deepening. Note that the time averages include the zero values.

Two reanalyses are used in this study to compare the cyclone activity between sophisticated and simpler reanalyses. The first dataset is JRA-55 (Ebita et al. 2011; Kobayashi et al. 2015), the latest reanalysis data produced by the Japan Meteorological Agency with spectral triangular truncation 319 with linear grid (TL319) in horizontal resolution and 60 levels (L60) of a sigma-pressure hybrid coordinate in vertical, and 4 dimensional variational data assimilation. It assimilates most available observations. The 1.25-degree data from January 1958 to February 2014 are used. The second dataset is the 20th Century Reanalysis version 2 (20CR; Compo et al. 2011). It is the longest reanalysis dataset with T62 (200 km) L28 resolution and ensemble Kalman filter assimilation with 56 members. Note that only surface pressure is assimilated in 20CR. The ensemble mean, ensemble analysis spread and each ensemble member with 2-degree data from January 1871 to December 2012 are used. Six-hourly data are used in both reanalyses. LDR24 is calculated using the 6-hour surface pressure in the reanalysis data.

To compare with cyclone tracking methods, explosive cyclone track data from the Explosive Cyclone Information Database provided by Kyushu University (http://fujin.geo.kyushu-u.ac.jp/).
meteol_bomb/index.php) are used. The track data are based on Yoshiike and Kawamura (2009) with JRA-25 (Onogi et al. 2007) and Japan Meteorological Agency Climate Data Assimilation System (JCDAS) extended by the JRA-25 system.

In this study, for comparison with LDR, the normalized deepening rate (NDR, in Bergeron) is defined as:

$$NDR = \frac{P(t+12h) - P(t-12h)}{24} \sin 60^\circ \sin \theta,$$

where $P$ is the sea-level pressure at the cyclone center and $\theta$ is the latitude at the cyclone center. The NDR shows Lagrangian deepening rate at the cyclone center unlike the Eulerian LDR.

For comparison with LDR24P1, additional common indices such as the frequency of NDR $\geq 1$ (NDR1) counted within 1.25-degree grids used all the NDR values not just the maximum in each cyclone’s lifetime, the transient eddy heat flux at 850 hPa (VT850):

$$VT850 = v^'t^'$$

where $v^'$ and $t^'$ are the 6-h meridional velocity temperature with 8-day high-pass filtering, respectively, the Eady growth rate (EGR, Lindzen and Farrell 1980):

$$EGR = \frac{0.31}{N} \frac{dV}{dZ},$$

where $f$ is Coriolis parameter, $N$ is the Brunt-Väisälä frequency, $V$ is the velocity and $Z$ is the height, and the eddy kinetic energy (EKE, Chang et al. 2002):

$$EKE = \frac{1}{2} (u^2 + v^2),$$

are calculated using the 6-hourly track and JRA-55 data.

To apply the LDR to probability forecasts using ensemble forecast data, ensemble forecasts are conducted by the atmosphere general circulation model for the Earth Simulator version 3 (AFES; Ohfuchi et al. 2004, 2007; Enomoto et al. 2008; Kuwano-Yoshida et al. 2010). The initial conditions of ensemble forecasts are provided by AFES–Local Ensemble Transform Kalman Filter (LETKF) experimental ensemble reanalysis 2 (ALER2A; Enomoto et al. 2013). ALER2A has T119L48 resolutions with 63 members. Ensemble forecasts are conducted with the same resolutions from 63 members for 10 days.

3. Results

Figure 1 shows the LDR and SLP regarding the explosive and non-explosive cyclone cases around Japan using JRA-55 as an example. The explosive cyclone appears south of Japan at 1800 UTC 13 January 2013 (Fig. 1a), moving northeastward with explosive development at 1200 UTC 14 January 2013 (Fig. 1b). The non-explosive cyclone also appears south of Japan at 0000 UTC 11 February 2011 (Fig. 1c), moving northeastward with weak development at 1800 UTC 11 February 2011 (Fig. 1d). In both cases, the positive LDR appears downstream and the negative LDR upstream of the cyclones as expected from Eq. 2. Because the cyclones move with development, the magnitudes and horizontal extents of positive and negative LDR are asymmetric, especially in the explosive cyclone.

Figure 2 displays LDR24P0 and LDR24P1 averaged for 24 hours, including 4 time steps of 6-h data, during deepening of the two cases. In the explosive case, LDR24P1 shows cyclones move with rapid deepening along the south coast of Japan with a maximum east of Japan (Fig. 2a). The LDR24P0 and LDR24P1 peaks extend along the Lagrangian track, and the LDR24P1 maximum tends to appear downstream of NDR. The criterion of LDR $\geq 1$ appears adequate for explosive deepening. Indeed LDR24P1 is small in non-explosive case (Fig. 2b). Notably, LDR24P0 and LDR24P1 demonstrate the horizontal extent of cyclone deepening. For example, LDR24P0 shows that the deepening area extend to the Sea of Japan and the Sea of Okhotsk not only over the northwestern Pacific, and LDR24P1 suggests that explosive deepening extends south of the cyclone not only near the cyclone center of the explosive case (Fig. 2a). This additional information is useful for identifying the sphere of influence of extratropical cyclones, analogous to the strong wind radius of tropical cyclones, although it is difficult to separate for cyclones close together.

The horizontal extent of the LDR is also useful for probabil-
ity forecasts using ensemble forecast data. Figure 3 shows the LDR24 of JRA-55 and ensemble forecasts by AFES initialized by ALERA2 at 1200 UTC 14 January 2013. In JRA-55 explosive deepening (LDR24 ≥ 1) appears over the northwestern Pacific east of Japan (Fig. 3a). The 5-day forecast well captures the explosive cyclogenesis distribution with 90% probability, which means that 90% of ensemble forecast members indicate LDR24 ≥ 1 at the grid (Fig. 3b). Although the explosive cyclogenesis area in the 7-day forecast is predicted farther south than the reanalysis, the area with a probability of explosive deepening over 10% covers the reanalyzed explosive cyclogenesis area (Fig. 3c). The 9-day forecast minimally captures explosive deepening near Japan (Fig. 3d).

To estimate how the LDR can be used as a climatological index of extratropical cyclone activity, LDR24P1 is compared with common indices using climatologies of DJF from 1996 to 2014. LDR24P1 and the negative horizontal Laplacian of LDR24P1 are presented in Fig. 4a. As used for pressure in tracking methods (Lim and Simmonds 2007) and climatological analysis (Minobe et al. 2008), the negative Laplacian can pick up the area around the peaks working as a spatial high-pass filter. The negative Laplacian is relatively consistent with NDR1 east of Japan (Fig. 4b), whereas LDR24P1 itself shows a broad distribution and the maximum appears around 170E, 43N. The LDR24P1 distribution is similar to VT850 (Fig. 4c) and EKE at 300 and 500 hPa (Fig. 4d). EGR at 850 hPa apparently corresponds to the negative Laplacian of LDR24P1 and NDR1 (Fig. 4c). The results suggest that LDR24P1 indicates the accumulated results of cyclone development (similar to EKE and VT850), whereas the negative Laplacian of LDR24P1 capture the feature of cyclone development (similar to EGR).

Figure 5 displays the global distribution of LDR24P0 and LDR24P1. The average of 0 ≤ LDR ≤ 1 (LDR24P0-1) is also shown only for winter to estimate weak cyclone activity (Figs. 5c, d). The cyclone activity climatology is similar to previous studies based on cyclone tracking and time-filtering methods (Nakamura 1992; Lim and Simmonds 2002; Allen et al. 2010), whereas a positive LDR tends to show maxima more downstream than the tracking method as shown in Fig. 4, because the LDR24P0 and LDR24P1 include the effects of cyclone movement and expansion of the deepening area, and not only the central pressure deepening. As shown in Fig. 1, the deepening area tends to extend downstream associated with an increased LDR. The analysis reveals that explosive deepening accounts for approximately one-half of the total deepening amplitude in the Northern Hemisphere (Figs. 5f, 6f).
5a, c), whereas explosive deepening in the Southern Hemisphere is weak, especially over the Pacific sector (Figs. 5b, d). This finding suggests that the weakness of explosive deepening contributes to the zonal asymmetry of storm tracks (Inatsu and Hoskins 2004; Hoskins and Hodges 2005). They suggest that weaker SST gradients in the Pacific make the zonal asymmetry. LDR24P0-1 is large equatorward and up/downstream of LDR24P1 in winter (Figs. 5c, d).

During summer, when extratropical cyclone activity is weak, LDR24P0 shows storm tracks (Figs. 5e, f). Their peaks shift poleward and the magnitudes become one-half of those during winter. The results suggest that the LDR may capture weak deepening even during summer. The frequency analysis of LDR over each hemisphere suggests that the total frequency of positive LDR in winter is by 20% compared with it in summer, and the frequency of larger LDR more increases especially (not shown).

The reproducibility of cyclone activity in the reanalysis can also be estimated by LDR methods. Figure 6 shows a 13-month running mean of LDR24P0 monthly mean values, between 30°N (S) and 60°N (S) in the Northern (Southern) Hemisphere using ensemble mean and the first eight ensemble mean calculated by the individual ensemble members of 20CR and JRA-55, respectively. LDR24P0 calculated by the 20CR ensemble mean is very small before 1900 in the North Pacific, whereas in the North Atlantic it is almost the same magnitude even before 1900 (Fig. 6a). This difference might be due to more observations in the North Atlantic.

In the Southern Hemisphere, LDR24P0 calculated by the 20CR ensemble member mean further depends on time and location. In the Southern Indian Ocean, LDR24P0 is weak before 1950, and in the Southern Pacific Ocean around 120°W, small values of LDR24P0 persist up to the 2000s (Fig. 6b, contours). The LDR24P0 time series is consistent with an ensemble analysis spread of surface pressure (Fig. 6b, contours) — in other words, the magnitude of analysis error. Confirming this, LDR is effective for estimating storm track reproducibility in other reanalyses without analysis error information. The results are consistent with Compo et al. (2011) and Wang et al. (2012), suggesting that the few surface pressure observations, which are the only assimilated data in 20CR, increase spread and decrease reproducibility of the storm track estimated by ensemble mean. In fact, LDR24P0 calculated by the first eight ensemble members of 20CR is comparable to that of JRA-55, although artificial large value can be seen between 1950 and 1980 in the Southern Hemisphere where the ensemble spread of LDR24P0 is large (Figs. 6c, d, e, f).

4. Conclusion and recommendations

A new cyclone activity index, the LDR, is introduced to analyze extratropical cyclone activity, and it can be applied not only to individual cyclone events but also to cyclone activity climatology. Because the LDR has a horizontal extent, it provides the radius of influence for extratropical cyclones, whereas it is available by tracking methods with additional definition of size (Rudeva and Gulev 2007). The LDR is suited for probabilistic forecasts using ensemble forecast, and can also be used to estimate cyclone activity reproducibility in reanalysis data. The LDR can be calculated with much fewer computational resources compared with conventional cyclone tracking or time-filtering methods. In addition, LDR shows weak dependency on the horizontal resolution of the data, whereas tracking methods can reduce the influence of resolution if they are applied at a common resolution. Although the LDR cannot provide start and end points, lifetimes and intensity

Fig. 6. Monthly LDR24P0 with the 13-month running mean (color, in hPa day$^{-1}$) for (left) the NH averaged between 30°N and 60°N and (right) the SH averaged between 30°S and 60°S calculated by (a) 20CR ensemble mean, (c) (d) the first eight ensemble members of 20CR, and (e) (f) JRA-55. The contour in (a) (b) displays the ensemble spread of surface pressure (in hPa) and that in (c) (d) displays the ensemble spread of LDR24P0 (= 0.1 hPa day$^{-1}$).

Fig. 7. Local tendencies of the geopotential height (contour, in m h$^{-1}$) and temperature (color, in K h$^{-1}$) at 1200 UTC 14 January 2013 (a) at 200 hPa, (b) at 850 hPa, and (c) zonal – vertical cross section along 37°N.
history of individual cyclones provided by tracking methods, the climatology and variations of LDR may easily be used as a storm track index in inter-comparison of climate models for reproducibility and future projections, complementing results of tracking methods. The tendency analysis and time average of positive/negative LDR values can be expanded to other variables in the future. For example, the geopotential height and temperature tendencies during a cyclone development at 1200 UTC 14 January 2013 are shown in Fig. 7. The geopotential height tendency shows westward-tilted structure and the temperature tendency shows warming around surface cyclone and upper troposphere, which is similar to a typical cyclone structure.

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