Seamless Detection of Cutoff Lows and Preexisting Troughs

SATORU KASUGA,^a MEIJI HONDA,^b JINRO UKITA,^b SHOZO YAMANE,^c HIROAKI KAWASE,^d AND AKIRA YAMAZAKI^e

^a Graduate School of Science and Technology, Niigata University, Niigata, Japan

^b Faculty of Science, Niigata University, Niigata, Japan

^c Department of Environmental Systems Science, Doshisha University, Kyotanabe, Japan

^d Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan

^e Application Laboratory, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

(Manuscript received 6 August 2020, in final form 9 June 2021)

ABSTRACT: We propose a new scheme based on geopotential height fields to detect cutoff lows starting in the preexisting trough stage. The intensity and scale derived from the proposed scheme will allow for a better understanding of the cutoff low life cycle. These cutoff lows often accompany mesoscale disturbances, causing adverse weather-related events, such as intense torrential rainfall and/or tornadoes. The proposed scheme quantifies the geometric features of a depression from its horizontal height profile. The height slope of a line intersecting the depression bottom and the nearest tangential point (optimal slope) locally indicates the intensity and scale of an isolated depression. The strength of the proposed scheme is that, by removing a local background height slope from a geopotential height field, the cutoff low and its preexisting trough are seamlessly detected as an identical depression. The distribution maps for the detected cutoff lows and preexisting troughs are illustrated along with their intensities, sizes, and local background flows estimated from snapshot height fields. We conducted climatological comparisons of cutoff lows to determine the utility of the proposed scheme.

SIGNIFICANCE STATEMENT: We propose a new automated numerical scheme for upper-tropospheric cyclones (cutoff lows) and their earlier developmental stage as troughs (preexisting troughs). Cutoff lows are frequently associated with much smaller-scale hazardous phenomena at the surface, such as tornadoes. The proposed scheme can extract locations with transitions that are as smooth as possible and estimate their intensities, sizes, and even the local background flows behind them using nonpreprocessed (snapshot) basic weather data consisting of geopotential height fields.

KEYWORDS: Atmospheric circulation; Cutoff lows

1. Introduction

Cutoff lows are cold-core cyclones in the upper troposphere that are typically identified as local minima of geopotential height fields in the 500–200-hPa range (Nieto et al. 2008; Pinheiro et al. 2017; Muñoz et al. 2020). Cutoff lows grow from troughs in the westerlies. These troughs are also cyclonic depressions without local height minima. Some troughs occasionally extend toward lower latitudes and are separated from the polar airmass region. Such troughs have been described as preexisting cold troughs (Palmén and Newton 1969; Kentarchos and Davies 1998). Here, they are called preexisting troughs. Most cutoff lows have synoptic spatial and temporal scales on the order of hundreds of kilometers and several days (Kentarchos and Davies 1998;

Nieto et al. 2005; Fuenzalida et al. 2005; Singleton and Reason 2007a; Muñoz et al. 2020).

Cutoff lows often accompany mesoscale disturbances that can cause adverse weather-related events, such as intense torrential rainfall that leads to flash floods (Griffiths et al. 1998; Singleton and Reason 2007b; Schumacher and Johnson 2008), landslides due to heavy rain (Hirota et al. 2016), thunderstorms (Tsuboki and Ogura 1999; Mohr et al. 2020) with hail (Zhao and Sun 2007), and tornadoes (Davies 2006; Homar et al. 2001; Seko et al. 2015). To explore potential relationships between cutoff lows and mesoscale disturbances, the location, intensity, and size of cutoff lows (and preexisting troughs) may be a useful proxy for hazardous weather. This information could be obtained from global climate model simulations, where mesoscale phenomena are not resolved.

The cutoff low detection schemes proposed in previous studies fall into one of the four groups based on the following two criteria:

- Whether a scheme uses variables based on geopotential height or relative/potential vorticity (PV)-based variables. We regard a Laplacian of geopotential height as a vorticity-based variable because it is proportional to the relative vorticity under geostrophic approximation.
- Whether a scheme explicitly uses a local extremum point (extremum-searching schemes) or a closed contour around the extremum point (contour-searching schemes).

Denotes content that is immediately available upon publication as open access.

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/MWR-D-20-0255.s1>.

Corresponding author: Meiji Honda, E-mail: meiji@env.sc.niigata-u.ac.jp

DOI: 10.1175/MWR-D-20-0255.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

Height-based schemes with local minimum searching have been used in many studies to identify cutoff lows (e.g., Kentarchos and Davies 1998; Nieto et al. 2005; Zhang et al. 2008; Favre et al. 2012; Yamashita et al. 2017; Wen et al. 2018; Pinheiro et al. 2019, 2020; see Nieto et al. 2008; Pinheiro et al. 2017 for reviews). The scheme proposed by Nieto et al. (2005) has been widely used with additional conditions imposed on it (Nieto et al. 2007; Porcù et al. 2007; Nieto et al. 2008; Ndarana and Waugh 2010; Reboita et al. 2010; Abatzoglou 2016; Barbero et al. 2019; Muñoz et al. 2020). Bell and Bosart (1989) used a closed-height contour-searching scheme to construct the climatology of 500-hPa closed circulation centers. For other height-based schemes, the intensities of cutoff lows were represented by height anomalies from either the climatological mean (Grumm and Hart 2001) or the zonal mean (Pinheiro et al. 2019, 2020). Thus, schemes could be influenced by analysis periods and extreme events. Some height-based schemes have detected the troughs or frontal structures as axes (Knippertz 2004; Bueh and Xie 2015). Li et al. (2018) and Schemm et al. (2020) used the curvature of the geopotential height to detect troughs and ridges. Some trough detection schemes obtain the tilts of the axis (e.g., Bueh and Xie 2015; Schemm et al. 2020), which are essential for trough life cycles up to wave-breaking events (Thorncroft et al. 1993). The scheme of Nieto et al. (2005) contains a condition to check whether a cutoff low has a frontal structure with a thermal frontal parameter (Renard and Clarke 1965), which was originally designed to detect surface thermal fronts. Temporal wind changes have also been used to detect fronts focusing on the physical aspects of fronts (Simmonds et al. 2012; Rudeva and Simmonds 2015; Rudeva et al. 2019). These two types of approaches were discussed in detail by Schemm et al. (2015).

Pinheiro et al. (2017) proposed a vorticity-based scheme that searched 300-hPa relative vorticity minima in the Southern Hemisphere. Their scheme successfully detected cutoff lows and their intensities, classifying the cyclone's full detachment from the westerlies based on three additional criteria: temperature, PV, and wind. After investigating the sensitivity, they proposed a wind criterion, which allows for a more realistic detection of cutoff lows (Pinheiro et al. 2019). These schemes could not differentiate between the preexisting trough and cutoff low stages but tracked those lows for a long time (up to 8 days), including their early development stages (preexisting trough stages). This is consistent with the inheritance of the vortex-like structures within troughs (Hakim 2000). Other vorticity extremum-searching schemes have been used to detect troughs; however, they have not been used for cutoff lows (Gaza and Bosart 1990; Lefevre and Nielsen-Gammon 1995; Dean and Bosart 1996).

PV-based contour-searching schemes have also been used to detect cutoff lows (Sakamoto and Takahashi 2005; Wernli and Sprenger 2007; Kew et al. 2010; Tsuji and Takayabu 2019) since anomalously high PV areas often correspond to cutoff lows (e.g., Hoskins et al. 1985). A PV-based contour-searching scheme introduced by Wernli and Sprenger (2007) identified PV streamers (open narrow contours) and PV cutoffs (closed contours). Most cutoff lows are thought to be formed from

these streamers through Rossby wave breaking (Thorncroft et al. 1993; Ndarana and Waugh 2010). Nieto et al. (2008) compared the climatological frequency distributions of PV cutoffs obtained from the scheme of Wernli and Sprenger (2007) and cutoff lows obtained from the scheme of Nieto et al. (2005) and confirmed that they are generally consistent. Kew et al. (2010) proposed a scheme to detect PV cutoffs in the lower stratosphere and defined their intensity as PV differences between the closed contour with a subsynoptic area ($10 \times 10^6 \text{ km}^2$) and the peak value within the closed contour. Their scheme successfully quantified the intensity from snapshot fields. Recently, Portmann et al. (2021) modified the scheme of Wernli and Sprenger (2007) and provided the first comprehensive global three-dimensional PV cutoff climatology by adapting a Lagrangian perspective of parcel trajectories.

Extratropical cyclone detection schemes have been developed for a wider range of research purposes (Neu et al. 2013; Ulbrich et al. 2013; Rudeva et al. 2014). The Melbourne University numerical cyclone tracking scheme (hereafter called the Melbourne scheme) was developed by Murray and Simmonds (1991a,b), Simmonds and Murray (1999), Simmonds et al. (1999), Lim and Simmonds (2007), and Pezza et al. (2012). The Melbourne scheme was adopted for detecting Southern Hemispheric upper-level cyclones and cutoff lows (Keable et al. 2002; Fuenzalida et al. 2005). The Melbourne scheme can objectively distinguish between "closed" and "open" depressions. Closed and open depressions are distinguished by the presence of a local maximum of the Laplacian of height within a small distance. Sinclair (1994, 1997) also developed his detection scheme (see section 5b).

The PV-based Wernli and Sprenger (2007) and Melbourne and Sinclair's schemes can detect and distinguish cutoff lows and preexisting troughs with intensity information. However, PV is not always available in recent climate simulation datasets such as the Coupled Model Intercomparison Project, phase 6 (CMIP6). The Melbourne and Sinclair's schemes were originally designed for extratropical cyclones at the surface, where the background flow is generally weak, which is different from the conditions for cutoff lows. Vorticity-based schemes consist of multiple derivative steps for calculating the Laplacian of height or relative vorticity/PV. Since these steps tend to provide fine structures, some spatial and/or temporal filtering (e.g., Sinclair 1997; Simmonds et al. 1999) or additional conditions for other variables (e.g., Pinheiro et al. 2017) are often required to detect the location and to evaluate the intensity and size of cutoff lows.

Schemm et al. (2020)'s scheme captures not only trough and ridges but also cutoff lows for single height fields and further distinguish between cutoff lows and preexisting troughs. Schemm's and our proposed schemes have different features and have their own merits (see section 5c).

In this study, we propose an extremum point-searching scheme applied to the geopotential height to extract an isotropic depression embedded in a background flow, which is designed for a seamless detection of cutoff lows and preexisting trough life cycles. The proposed scheme provides information on the location of cutoff lows, such as their intensity, size, and background gradient, in a consistent and integrated manner.

FIG. 1. Horizontal distributions of the 200-hPa geopotential height (m) at 1200 UTC 13 Apr 2015. Contour interval is 100 m. The A–A' line denotes a latitudinal line at 32.5°N between 90° and 150°E.

The remainder of this paper is organized as follows. The basic concept of the proposed scheme is presented in section 2 and explained with idealized fields in section 3. Section 4 presents the cutoff low climatology. Section 5 provides a detailed discussion of comparisons with other schemes. Finally, section 6 presents the summary.

2. Methodology

We introduce a new scheme for cutoff low detection while applying it to the 200-hPa geopotential height field at 1200 UTC 13 April 2015, when a cutoff low is over the Yellow Sea (Fig. 1). The basic concept of the proposed scheme is described using a longitudinal one-dimensional (1D) geopotential height profile and is expanded for two-dimensional (2D) height fields. The geopotential heights used in this study are from the Japanese 55-year Reanalysis (JRA-55) of the Japan Meteorological Agency (Kobayashi et al. 2015; Harada et al. 2016). Table 1 summarizes the symbols used in the following text.

a. Basic concept

The proposed scheme searches a bottom point of height depression based on the horizontal slope of geopotential height. Figure 2a shows a longitudinal profile of the 200-hPa geopotential height (bold black curve) along the A–A' line in Fig. 1, which crosses the cutoff low. If the bottom point of the depression x_b (120°E) is known, we can draw a series of lines from x_b to other points on the height profile that are 200–2100 km (at 100-km intervals) away from x_b as shown by the solid gray lines. We define the height slopes, $S(r)$, as a function of the distance r from the bottom x_b , i.e.,

$$S(r) = \frac{Z(x_b + r) - Z(x_b)}{r}, \quad (1)$$

where $Z(x)$ is the longitudinal profile of the geopotential height at a certain level and latitude and $Z(x_b + r)$ is calculated using linear interpolation with the nearest two grid points. As shown

TABLE 1. List of symbols used in the text

Symbol	Description
x, y	Longitudinal and latitudinal positions
r	Radial searching variable (200–2100 km, 100-km intervals)
Z	Geopotential height (m)
$S(r)$	Eastward slope as a function of r [m (100 km)^{-1}], defined in Eq. (1)
$AS(x; r)$	One-dimensional averaged slope function [m (100 km)^{-1}], defined in Eq. (3)
$AS(x, y; r)$	Two-dimensional averaged slope function [m (100 km)^{-1}], defined in Eq. (6)
AS^+	Upper envelope of AS [m (100 km)^{-1}], equal to $\max_r AS$
AS^-	Lower envelope of AS [m (100 km)^{-1}], equal to $\min_r AS$
S_o	Optimal slope [m (100 km)^{-1}], given by the local maximum value of AS^+
r_o	Optimal radius (km), given by r corresponding to S_o
D_o	Optimal depth (m), equal to $S_o r_o$
x_b, y_b	Bottom location of depression, given by position with a local maximum of AS^+
m	Zonal local background slope [m (100 km)^{-1}], defined in Eq. (9)
n	Meridional local background slope [m (100 km)^{-1}], defined in Eq. (10)
S_{BG}	Local background slope [m (100 km)^{-1}], equal to $\sqrt{m^2 + n^2}$
α	Angle of local background gradient from the east, equal to $\arctan(n/m)$
SR	Slope ratio of S_{BG} to S_o

in Fig. 2a, the height slope $S(r)$ reaches its maximum (steepest) when the line is closest to the tangent to the height profile (i.e., when it is intersecting the curve but not crossing at any point; red line in Fig. 2a). Here, we call such an intersection a “tangential point” for simplicity. The steepest slope can serve as a measure of cutoff low intensity because it can be recognized as a horizontal height gradient (which is proportional to the geostrophic wind) at the tangential point or a height difference normalized to its horizontal scale. Thus, the steepest slope of S relates the intensity and the horizontal scale of the depression. We call the steepest slope the *optimal slope* S_o . The horizontal width between x_b and the tangential point is called the *optimal radius* r_o (horizontal green line with arrows). The height difference between x_b and the tangential point is called the *optimal depth* D_o (vertical black arrow line with arrows). The depression can be characterized by these optimal parameters. The relation of the parameters is expressed as

$$S_o = \frac{D_o}{r_o} = S(r_o) \geq S(r). \quad (2)$$

The concept of S_o is similar to that of the “openness” of geodesy in the elevation models introduced by Yokoyama et al. (2002).

The range of radius r and its interval for searching r_o depend on the horizontal scale of the phenomenon of interest, the

FIG. 2. (a) Zonal profile of the 200-hPa geopotential height Z (thick black curve; m) along the A–A' line in Fig. 1. The bottom of the profile is at $x_b = 120^\circ\text{E}$. Solid gray lines from the bottom indicate slopes S in Eq. (1) for r ranging from 200 to 2100 km with a 100-km interval. The red line represents the steepest slope of S , termed the optimal slope S_o . The green horizontal line with arrows indicates the optimal radius r_o . The black vertical line with arrows indicates the optimal depth D_o . (b),(c) The height profile is shown as gray curves. (b) Illustration of slopes for the one-dimensional (1D) average slope function AS for $r = 600$ km at three locations, $x_1 = 105^\circ\text{E}$, $x_2 = 120^\circ\text{E}$, and $x_3 = 135^\circ\text{E}$. Red and blue lines indicate positive and negative slopes, respectively. (c) Longitudinal distributions of 1D AS [m (100 km)^{-1}] for r ranging from 200 to 2100 km (with a 100-km interval) are denoted with multiple gray curves. The solid green curve indicates AS for $r = 1300$ km, which has the highest value of AS at $x = 120^\circ\text{E}$. The black solid curve indicates AS for $r = 600$ km, as shown in (b). The red dashed curve indicates AS^+ from Eq. (4). The symbols X and Y denote local maxima of AS^+ for $r = 200$ km and $AS^+ < 0 \text{ m (100 km)}^{-1}$, respectively.

horizontal resolutions of the reanalysis datasets, and the available computational resources. In this study, we chose 200 km as the smallest radius, which is about twice the horizontal resolution of the JRA-55 datasets (a $1.25^\circ \times 1.25^\circ$ grid spacing and 2100 km as the largest radius, which sufficiently covers the typical cutoff low scale of 300–900 km in radius (Kentarchos and Davies 1998; Singleton and Reason 2007a). The interval of r is set to 100 km.

b. Depression searching scheme for 1D height fields

We describe the procedure for searching the bottom point x_b , which was assumed to be known in the previous subsection. First, we consider a pair of slopes, which extend west and east from a point x , assuming that the distance r is fixed at 600 km. Figure 2b shows the pairs of slopes at three longitudinal points of $x_1 = 105^\circ\text{E}$, $x_2 = 120^\circ\text{E}$, and $x_3 = 135^\circ\text{E}$. The signs of the two slopes are both negative at x_1 , opposite at x_2 , and both positive at x_3 . The difference between the two slopes at x_2 , the bottom point, is larger than those at the other points. If we flip the sign of the west slope, add its value to the east slope, and conduct this operation for every grid point of x , then the bottom point x_b could be found as a local maximum of the added values.

We define the 1D averaged slope function, $AS(x; r)$, as

$$AS(x; r) = \frac{1}{2r} [Z(x-r) - 2Z(x) + Z(x+r)], \quad (3)$$

which is the average of the eastward slope $[Z(x+r) - Z(x)]/r$ and the westward slope $[Z(x-r) - Z(x)]/r$. This is similar to the Laplacian finite difference operator; however, the denominator of Eq. (3) is not the square of r . The difference between AS and the Laplacian operator is discussed in section 5a. Figure 2c shows a longitudinal profile of $AS(x; r)$ for each distance r by a thin gray curve with r changed from 200 to 2100 km in increments of 100 km. Applying two-step maximization to $AS(x; r)$ with respect to r first and then x , we obtain the depression bottom point. We call the maximum values of $AS(x; r)$ with respect to r the upper envelope $AS^+(x)$:

$$AS^+(x) = \max_r AS(x; r). \quad (4)$$

The upper envelope $AS^+(x)$ indicated by the red dashed curve in Fig. 2c has a local peak at the bottom point of 120°E . Once the bottom point x_b is identified, the optimal slope S_o and the optimal radius r_o for the point are obtained immediately from the following relation:

$$S_o = AS^+(x_b) = AS(x_b; r_o) \geq AS(x; r). \quad (5)$$

For the height profile in Fig. 2, $x_b = 120^\circ\text{E}$, $S_o = 31.37 \text{ m (100 km)}^{-1}$, and $r_o = 1300$ km.

To remove depressions outside our target and erroneous signals, we impose the following two constraints with respect to r_o and S_o : (i) When r_o is the outermost part of the 200–2100-km range (i.e., 200 or 2100 km), the detected depression is rejected because it may have a much smaller or larger size. One example is denoted by the symbol X in Fig. 2c. (ii) When S_o is negative, the corresponding signal is removed since it indicates a small-scale feature embedded within a large-scale ridge rather than synoptic depressions, of which example is the symbol Y in Fig. 2c.

c. Depression searching scheme for 2D height fields

Here, the 1D AS is expanded to obtain a 2D averaged slope function $AS(x, y; r)$ as

$$AS(x, y; r) = \frac{1}{4r} [Z(x+r, y) + Z(x-r, y) + Z(x, y+r) + Z(x, y-r) - 4Z(x, y)], \quad (6)$$

FIG. 3. Horizontal distributions of the 200-hPa geopotential height Z (contours; m) and AS^+ [shading; $m (100 km)^{-1}$], which indicates fields of AS maxima with respect to r at all grid points defined in Eq. (7) at (a) 1200 UTC 11 Apr, (b) 1200 UTC 13 Apr, and (c) 0000 UTC 15 Apr 2015. The negative regions of AS^+ have been omitted to focus on depressions. Blue triangles denote the locations of local height minima, and solid circles colored according to the optimal slopes S_o [$m (100 km)^{-1}$] denote the bottoms of extracted depressions. Green circles represent circles of optimal radius r_o (km). Thick arrows denote the direction of local background slopes, with colors representing the magnitude of S_{BG} [$m (100 km)^{-1}$]. The B–B' line in (b) denotes a longitudinal line at 120°E between 20° and 45°N. The two red dots in (c) indicate the locations of two tornadoes. Some extracted depressions were removed following the noise reduction scheme described in section 2b.

where x and y are the longitudinal and latitudinal coordinates of the gridded height field Z , respectively. The 2D AS averages the four slopes directing eastward $\{[Z(x+r, y) - Z(x, y)]/r\}$, westward $\{[Z(x-r, y) - Z(x, y)]/r\}$, northward $\{[Z(x, y+r) - Z(x, y)]/r\}$, and southward $\{[Z(x, y-r) - Z(x, y)]/r\}$ for each grid point (x, y) . The four directions are selected for the ease of access and handling of gridded data. The sensitivity of AS to the number of slope directions, e.g., eight or more, will be tested in the future work. By analogy to the 1D AS , the upper envelope AS^+ is defined as

$$AS^+(x, y) = \max_r AS(x, y; r) \quad (7)$$

and the bottom point (x_b, y_b) , optimal radius r_o , and optimal slope S_o for each depression are determined by a spatial local maximum of AS^+ , i.e.,

$$S_o = AS^+(x_b, y_b) = AS(x_b, y_b; r_o) \geq AS(x, y; r). \quad (8)$$

Note that these parameters are extracted assuming an isotropic depression since the distance r is independent of the direction in Eq. (6). Here, AS^+ is considered to have a spatial local maximum if AS^+ at a point exceeds those at the surrounding eight grid points. The local height minimum is defined in the same way.

Figure 3b shows the horizontal distribution of AS^+ with the shading for the snapshot geopotential height fields shown in Fig. 1. The bottom location with a local AS^+ maximum is indicated by a small solid-colored circle over a thick arrow, which can identify the location of the cutoff low over the Yellow Sea. The color of the small circle represents the value of AS^+ (i.e., S_o). The arrow indicates the direction of the local background slope explained in the next paragraph. The green circle with a radius of r_o represents an approximate horizontal extension of the depression. For the cutoff low over the Yellow Sea, $S_o = 32.70 m (100 km)^{-1}$ and $r_o = 1100 km$. A small locational gap is observed between the local AS^+ maximum point and local height minimum point (blue triangle). Hereafter, we regard the detected depressions as cutoff lows if a local height minimum point exists within the circle r_o , and otherwise as preexisting troughs. Figure 3c shows the evaluated parameters for the cutoff low two days later, just before two tornadoes, ranked F1 on the Fujita scale (Fujita 1971), were spawned on the main island of Japan (two red points). Figure 3a shows a preexisting trough that grew to the cutoff low. It is worth noting that a preexisting trough is also extracted as an isotropic depression embedded in a background gradient in the proposed scheme. We expect it to work on the detection of a precursor of cutoff low.

After the detection process, a local background slope is estimated for each depression, which is shown by thick colored arrows in Fig. 3. Figure 4 shows a meridional geopotential height profile of the cutoff low along the B–B' line in Fig. 3b. The meridional height slope of a local background flow can be estimated as

$$n = \frac{Z(x_b, y_b + r_o) - Z(x_b, y_b - r_o)}{2r_o}. \quad (9)$$

FIG. 4. Meridional profile of the 200-hPa geopotential height Z (thick black curve; m) along the B–B' line in Fig. 3b. The red point at 32.5°N indicates the bottom of the extracted depression. The two green lines with arrows at both ends indicate the optimal radius r_o (=1100 km). The solid blue line indicates the meridional background slope n [$=-22.09$ m (100 km) $^{-1}$] calculated from Eq. (9).

This slope n is called the *meridional local background slope* (blue line in Fig. 4). A *zonal local background slope* m is also estimated as

$$m = \frac{Z(x_b + r_o, y_b) - Z(x_b - r_o, y_b)}{2r_o}, \quad (10)$$

and the 2D *local background slope* S_{BG} , which is the magnitude of the slope, and angle α (from the east) for the slope direction are, respectively, expressed as

$$S_{BG} = \sqrt{m^2 + n^2}, \quad (11a)$$

$$\alpha = \arctan \frac{n}{m}, \quad (11b)$$

where $-\pi \leq \alpha \leq \pi$ by using signs of m and n . Under the geostrophic approximation, S_{BG} corresponds to the strength of background flow around the depression. For the cutoff low over the Yellow Sea shown in Fig. 3b, $n = -22.09$ m (100 km) $^{-1}$, $m = 2.62$ m (100 km) $^{-1}$, $S_{BG} = 22.25$ m (100 km) $^{-1}$, and $\alpha = -1.45$ rad (-83.23° from the east).

Figure 5 shows the tracking and life cycle of the cutoff low shown in Fig. 1, from its first appearance (1200 UTC 11 April 2015) until just before its disappearance (1200 UTC 16 April 2015). The tracking is conducted by finding overlapping circles with radii r_o . Green and blue circles indicate the horizontal extension of preexisting trough and cutoff low, respectively. A red circle indicates the cutoff low just before the tornado (0000 UTC 15 April 2015; Fig. 3c). The earliest preexisting trough is detected over Mongolia as a depression with a relatively large size ($r_o = 1400$ km) and weak intensity [$S_o = 15.86$ m (100 km) $^{-1}$] at 1200 UTC 11 April 2015 (green circle; same as that in Fig. 3a). It moved southward, decreasing in size and increasing in intensity, to form a cutoff low 18 h later (blue circle). The cutoff low moved southeastward and continued to strengthen, reaching about twice its initial intensity at 0600 UTC 13 April. This period of a steady increase in S_o corresponds to the developing stage of the cutoff low life cycle. The developed cutoff low then moved eastward slowly

FIG. 5. Tracking of the extracted depression from development (1200 UTC 11 Apr 2015) until just before its disappearance (1200 UTC 16 Apr 2015) with a 6-h interval. Solid colored circles and arrows are similar to those in Fig. 3. The accompanying numbers show the day of the month at 0000 UTC. Green, blue, and red circles indicate the optimal radius of preexisting troughs, cutoff lows, and cutoff lows just before the occurrence of tornadoes (0000 UTC 15 Apr 2015), respectively. We refer to the extracted depression as a cutoff low (preexisting trough) when a local height minimum is present (absent) within the circle of r_o . The two red dots indicate the locations of the tornadoes.

for about a day and half, maintaining its intensity and size. It had a maximum intensity of $S_o = 33.91$ m (100 km) $^{-1}$ with a size of $r_o = 1100$ km at 0000 UTC 14 April. After the mature stage, the cutoff low moved northeastward, decreasing in intensity, considered as the decaying stage, to end and become a trough with a small size ($r_o = 600$ km) and weak intensity [$S_o = 18.10$ m (100 km) $^{-1}$] at 1200 UTC 16 April, just before the disappearance. The direction of the background slopes, indicated by thick arrows, moved counterclockwise throughout the cutoff low life cycle.

3. Verification with idealized height fields

We examined the performance of our AS⁺-based detection with idealized height fields focusing on the detection of a preexisting trough and the displacement of a local height minimum point from a bottom point. As Sinclair (1994) has illustrated a surface cyclone as a superposition of a pure vortex and a parallel background, the idealized height field consists of a negative bell-shaped function (representing a pure vortex) and a linearly sloped surface (representing parallel background flow). For the bell-shaped function, we select the 2D Gaussian function G , which was adopted by earlier studies on extratropical cyclones (Schneider et al. 2010; Schielicke et al. 2016):

$$G(x, y) = -a \exp\left(-\frac{x^2 + y^2}{2b^2}\right). \quad (12)$$

Here, a and b are coefficients of the amplitude and horizontal scale of G , respectively. The linearly sloped surface is defined by

$$L(x, y) = mx + ny, \quad (13)$$

FIG. 6. Horizontal distributions of idealized height fields Z^* from Eq. (14) (contours) and the upper envelope of the averaged slope function AS^+ (shading) for (a) a pure vortex, (b) a cutoff low, (c) a preexisting trough, and (d) a weaker trough. Here, the two parameters of Z^* are fixed as $b = 1/3$ and $m = 0$, and the other two, a and n , vary according to the types of depression, as denoted in the top-right corner of each panel. The red points indicate local AS^+ maxima, i.e., bottom locations $[(x_b, y_b) = (0, 0)]$, and the green circles indicate $r_o = 0.55$ in all cases. The blue triangles in (a) and (b) indicate local height minima. SR denotes the slope ratio S_{BG}/S_o in Eq. (16).

where m and n are the coefficients of the eastward and northward slopes corresponding to Eqs. (9) and (10), respectively. The idealized height model Z^* is expressed as

$$Z^*(x, y) = G(x, y) + L(x, y). \quad (14)$$

By replacing Z in Eq. (6) with Z^* in Eq. (14), AS can be formulated as

$$AS(x, y; r) = \frac{1}{4r} [G(x+r, y) + G(x-r, y) + G(x, y+r) + G(x, y-r) - 4G(x, y)]. \quad (15)$$

The terms of L are canceled out, then AS depends only on G , not L (see the online supplemental material). Therefore AS has a local maximum at the bottom of G , the origin (0, 0).

Figure 6 shows the distributions of Z^* and AS^+ in a nondimensional horizontal space with 201×201 grid points for four

cases: (Fig. 6a) a pure vortex, (Fig. 6b) a cutoff low, (Fig. 6c) a preexisting trough, and (Fig. 6d) a weaker trough. The parameters a and n are changed in the four cases. Their values are indicated in the top right corner of each panel. The parameters b and m are fixed as $b = 1/3$ and $m = 0.0$. AS^+ are calculated with the radius r ranging from 0.15 to 0.95 with an interval of 0.20. The bottom point for the depression and the corresponding optimal parameters are obtained. As is expected, AS^+ has a local maximum at the origin for each case. The distribution of AS^+ and the extracted parameters for the depression are exactly the same in Fig. 6a, the pure vortex case, and Fig. 6b, the cutoff low case, since these two cases have the same Gaussian parameters. We obtained that the optimal radius r_o is the same in all cases ($r_o = 0.55$; green circles) and the optimal slope S_o decreases as the amplitude of G decreases (Figs. 6a–c). An investigation of the relationship between the Gaussian parameters and the optimal parameters showed that

FIG. 7. Occurrence histogram of cutoff lows (blue bars) and preexisting troughs (green bars) with respect to SR, calculated from 6-h, 200-hPa geopotential heights for 9 years (2010–18) in midlatitudes in both hemispheres (75° – 15° S and 15° – 75° N). The red dashed vertical line indicates $SR = SR_p \sim 1.34$, which is an upper limit for the existence of a local height minimum in Z^* (see supplemental material). The total numbers of cutoff lows and preexisting troughs are 142 480 and 181 918, respectively.

r_o is proportional to b and that S_o is proportional to a/b (see the online supplemental material).

Figure 6 shows the displacement of a local height minimum point from the bottom point of G (Fig. 6b) and its disappearance (Figs. 6c,d) as the amplitude of G decreases. Similar behaviors are observed as the background gradient increases (Sinclair 1994), which corresponds to increasing S_{BG} . These behaviors can be expressed with a ratio of S_{BG} to S_o :

$$SR \equiv \frac{S_{BG}}{S_o}, \quad (16)$$

where SR is the *slope ratio*. The values of SR are shown in the bottom right corner of Fig. 6. An upper limit of SR for the existence of a local height minimum, SR_p , can be obtained as about 1.34 for the idealized height field Z^* (supplemental material).

To examine the availability of SR in the real atmosphere, we applied our depression searching scheme to the 6-hourly 200-hPa geopotential height fields for nine years (2010–18) at midlatitudes in both hemispheres (75° – 15° S and 15° – 75° N) and identified 142 480 cutoff lows and 181 918 preexisting troughs. SR was calculated with the optimal parameters for each detected depression. Figure 7 shows histograms of cutoff lows (blue bars) and preexisting troughs (green bars) with respect to SR. As SR increases, most depressions gradually switch from cutoff lows to preexisting troughs around $SR = SR_p \sim 1.34$ (red vertical dashed line). In the real atmosphere, the depressions do not have exact Gaussian shapes. The background flows are not as simple as the idealized ones, and the interactions with neighboring depressions cannot be ignored. However, the slope ratio SR may be a useful index to distinguish between cutoff lows and preexisting troughs.

As the slope ratio SR increases, an extracted depression becomes obscured in the height contour map (e.g., Fig. 6d) suggesting the use of SR as another constraint to remove negligible troughs. We impose the following condition on the proposed search scheme:

$$SR < 3.0, \quad (17)$$

FIG. 8. As in Fig. 3, but for (a) 1800 UTC 20 Feb and (c) 1800 UTC 13 Aug 2015. (b),(d) Obtained by applying a noise reduction scheme to (a) and (c), respectively. Here, we regard the extracted depressions with $SR > 3.0$ as being noise. Numbers denoted at the extracted points are their respective SR values.

where the critical value of 3.0 is determined based on whether noisy ripples (Simmonds et al. 1999) in strong wintertime westerlies are removed. Figure 8 shows the effects of SR constraint on depression detection for 200-hPa snapshot geopotential height fields at 1800 UTC 20 February 2015 (winter; Figs. 8a,b) and 1800 UTC 13 August 2015 (summer; Figs. 8c,d). The extracted parameters in Fig. 8 are illustrated similarly to those in Fig. 3; however, SR values are added to the top right of the extracted points. The depressions with relatively high SR values are identified in the strong wintertime westerlies, especially over the Tibetan Plateau in the southern part of Eurasia (Fig. 8a). These ripple-like depressions are removed by the SR constraint (Fig. 8b). Several depressions in the summer over the Pacific Ocean at lower latitudes (15° – 30° N) remain, though their intensity S_o is relatively weak (Fig. 8d).

FIG. 9. (a),(b) Climatologies for the annual frequencies of cutoff lows detected at each grid point at 200 hPa (shading) and 500 hPa (contours) for (a) the Northern Hemisphere and (b) the Southern Hemisphere. (c) Climatologies for the probability of preexisting trough detection (blue shading; %) and mean geopotential height (contours; 5200–5800 m with 100-m intervals) for extended winter (November–March) at 500 hPa.

This is because S_{BG} values are comparable to S_o values for these depressions. Such weak cutoff lows over the Pacific Ocean in the lower latitudes during the summer are known as tropical upper-tropospheric trough cells (e.g., Sadler 1976). It has been reported that they move westward and affect the early developmental stages of tropical cyclone life cycles (e.g., Wei et al. 2016; Fudeyasu and Yoshida 2019). Besides, they are accompanied by torrential rainfalls when they interact with a lower-level warm and moist air (Tsuboki and Ogura 1999; Hirota et al. 2016; Tsuji and Takayabu 2019). The significant and hazardous cutoff lows and preexisting troughs can be properly extracted from the snapshot height distribution maps with the SR constraint.

4. Climatology

Applying the proposed scheme to the 6-hourly JRA-55 geopotential height fields for 40 years (1979–2018), we have extracted the locations of cutoff lows and preexisting troughs with their optimal slope S_o and radius r_o , and made the climatology maps for the frequencies of their occurrence. Here, the cutoff lows and preexisting troughs are chosen as those having S_o values greater than 10 and 5 m (100 km) $^{-1}$, respectively. These thresholds of S_o are determined through several calibration approaches so that the obtained climatology maps can be compared with those provided by other studies.

Figures 9a and 9b show the cutoff low climatology obtained by the proposed scheme for the Northern and Southern Hemisphere, respectively. The unit is the frequency per year for the occurrence of the detected points (local maxima of AS^+) with the nine grid point smoothing. The areas are confined to 50°–20°S and 20°–70°N, and the excluded areas are shaded in gray to compare with Figs. 10a and 10b in Muñoz et al. (2020), whose climatology is based on the period of 39 years (1979–2017). Local maximum regions are observed over the northeastern Atlantic Ocean, southwestern Europe, northeastern Eurasia, the Gulf of Alaska, the northeastern Pacific Ocean, and western and northeastern North America in the Northern Hemisphere (Fig. 9a), and over eastern Australia, northwestern New

Zealand, South America, and southern Africa in the Southern Hemisphere (Fig. 9b). These features are consistent with those in Muñoz et al. (2020). Besides, the frequencies for the Southern Hemisphere at 500 hPa (Fig. 9b) and 300 hPa (not shown) are also consistent with those analyzed by Keable et al. (2002), Fuenzalida et al. (2005), and Pinheiro et al. (2019). The number of the detected cutoff lows at 500 hPa is comparable to that at 200 hPa in our analysis. However, Muñoz et al. (2020) extracted more cutoff lows at 500 hPa than at 200 hPa. The frequency of cutoff low for the Southern Hemisphere is lower than that of the Northern Hemisphere, which can also be seen in the PV cutoff climatology (Portmann et al. 2021). The difference in frequency between both hemispheres is found in Muñoz et al. (2020); however, it is less prominent than ours. One of the reasons for the inconsistency may be that the adjusted criteria for the cutoff low detection are applied to the Southern Hemisphere in Muñoz et al. (2020), while the same criteria are applied to both hemispheres in our analysis.

Figure 9c shows the extended winter (November–March) climatology for the occurrence probability of preexisting trough (blue color shadings) and mean geopotential height (contours) at 500 hPa in the Northern Hemisphere. We count the number of occurrences, assuming that each trough event occurs in an inner area within the circle of r_o , which may allow a qualitative comparison to the trough climatology provided through the area-based scheme in Schemm et al. (2020), whose analysis period was the same as ours. The probability distribution in Fig. 9c shows maximum regions over North America, the Far East, Gulf of Alaska, and eastern Europe, which resembles that of Schemm et al. (2020). This resemblance indicates that the proposed scheme's results are consistent with other schemes.

5. Discussion

a. Comparison to the Laplacian of geopotential height and potential vorticity

The finite difference approximations of the second-order partial derivative of the geopotential height (Z) fields with respect to x and y can be formulated as

FIG. 10. As shown in Fig. 3b, but for (a) the Laplacian of geopotential height at 200 hPa ($\nabla^2 Z$; 10^{-10} gpm m^{-2}), (b) $\nabla^2 Z$ with a 5° latitude $\times$ 5° longitude moving average (10^{-10} gpm m^{-2}), and (c) the potential vorticity on a 320-K isentropic surface. Green curves indicate contours of $\nabla^2 Z = 0$ in (b) and $PV = 2$ PVU ($1 \text{ PVU} = 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ K kg}^{-1}$) in (c).

$$\frac{\partial^2 Z}{\partial x^2} = \frac{1}{\delta_x^2} [Z(x - \delta_x, y) - 2Z(x, y) + Z(x + \delta_x, y)],$$

$$\frac{\partial^2 Z}{\partial y^2} = \frac{1}{\delta_y^2} [Z(x, y - \delta_y) - 2Z(x, y) + Z(x, y + \delta_y)],$$

where δ_x and δ_y are the grid sizes on the x and y axes, respectively. Assuming $\delta_x = \delta_y = \delta$, the Laplacian of Z , $\nabla^2 Z$, can be formulated by

$$\nabla^2 Z = \frac{1}{\delta^2} [Z(x + \delta, y) + Z(x - \delta, y) + Z(x, y + \delta) + Z(x, y - \delta) - 4Z(x, y)], \quad (18)$$

which is also shown in earlier studies [e.g., Eq. (3) in Simmonds et al. 1999]; $\nabla^2 Z$ evaluates concave and convex patterns in the Z field at a fine resolution. The average slope function AS in Eq. (6) is similar to Eq. (18). However, the order of r in the denominator is reduced to one, and r is adaptively determined. Figure 10a shows the horizontal distributions of $\nabla^2 Z$ for the 200 hPa geopotential height field shown in Fig. 1. Compared with the AS^+ field in Fig. 3b, where the negative regions of AS^+ are omitted to focus on depressions, it is found that $\nabla^2 Z$ gives multiple local maxima in the area of cutoff low (Fig. 10a), whereas AS^+ gives a single local maximum (Fig. 3b). The $\nabla^2 Z$ fields could have a local maximum for each synoptic depression through a smoothing procedure, such as a moving average with 5° latitude $\times 5^\circ$ longitude kernels (about $555.7 \text{ km} \times 392.9 \text{ km}$ at 45°N), as shown in Fig. 10b. We can confirm that AS^+ provide the field similar to the smoothed $\nabla^2 Z$ field. It indicates that AS^+ depends little on the data resolution (see the appendix).

Several studies used PV fields for detecting cutoff lows (e.g., Sakamoto and Takahashi 2005; Portmann et al. 2017, 2021; Tsuji and Takayabu 2019). We examined the PV fields for the cutoff low shown in Fig. 1 and obtained that the cutoff low is detected in the area of 2 PVU (PV units; $1 \text{ PVU} = 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ K kg}^{-1}$) or larger on the 320-K surface as shown by the green closed contours in Fig. 10c. For a qualitative comparison with a PV-based scheme, the proposed scheme is applied to a case of cutoff low analyzed by Portmann et al. (2017).

Figure 11 shows the tracking of the depression extracted by our scheme from the 300-hPa geopotential height fields. The

300-hPa level is chosen for a better agreement with the tracking shown in Portmann et al. (2017), who have used PV mainly on the 310-K surface. They indicated that a cutoff low is formed over Scandinavia and then traveled over Europe before dissipating over the Black Sea, showing the track for 10 days from 1200 UTC 18 April to 0600 UTC 28 April 2015. Our scheme can detect the similar track and also provide the preexisting trough stage starting at 1800 UTC 16 April 2015 and decaying over the Caspian Sea at 1800 UTC 29 April 2015, which is 42 h earlier and 36 h longer, respectively. Portmann et al. (2017) have shown that the amplitude of the depression decreased by half over the Alps between 0000 UTC 23 April and 0000 UTC 24 April (a period they termed “PHASE II”), and the size of the depression expanded by a factor of 2 over the Alps between 0000 and 0600 UTC 24 April 2015. In our results, S_o for the detected depressions decreased from 32.7 to $22.19 \text{ m (100 km)}^{-1}$ during PHASE II, and their r_o values expanded from 300 to 600 km between 1200 and 1800 UTC 24 April 2015. Thus, the intensities and scales extracted with the PV-based scheme and our AS^+ -based scheme are consistent.

b. Comparison to the Melbourne and Sinclair schemes

The depression parameters extracted using the proposed scheme have certain similarities with those of other sophisticated surface cyclones detection schemes such as the Melbourne scheme (Murray and Simmonds 1991a,b; Simmonds and Murray 1999; Simmonds et al. 1999; Lim and Simmonds 2007; Pezza et al. 2012) and the Sinclair schemes (Sinclair 1994, 1997). The Melbourne scheme distinguished between closed (cutoff low) and open (trough) depressions by checking whether a height minimum point exists near the center. The Sinclair schemes continuously used the local extremum of gradient wind vorticity for both depression types. Comparing these schemes with the proposed schemes, it seems that there are some similarities and differences in horizontal extension, background flow, and the physical interpretation of intensity as follows.

1) HORIZONTAL EXTENSION

The optimal radius r_o is adaptively determined through the maximization process of AS (or AS^+). In contrast, both the Melbourne and Sinclair schemes determine the radius R by estimating a perfect circle with the same area within a closed

FIG. 11. As in Fig. 5, but for a long-lived cutoff low at 300 hPa from 1800 UTC 16 Apr to 1800 UTC 29 Apr 2015, which was analyzed by Portmann et al. (2017). Tracking begins at 1800 UTC 17 Apr over the North Atlantic and ends at 1200 UTC 29 Apr over the Caspian Sea. Here, r is set from 200 to 4100 km.

contour of $\nabla^2 Z = 0$ (the green contours in Fig. 10b). Its calculation is schematically illustrated in Fig. 1b of Lim and Simmonds (2007). In the case of Gaussian-shaped depression, the relationship between r_o and R is simple, i.e., r_o is proportional to R ($r_o/R \sim 1.12$; supplemental material).

2) BACKGROUND FLOW

The strength of the local background flow around each depression can be estimated from S_{BG} , which is defined in Eq. (11a). Sinclair (1994) suggested that the background flow is essential for the surface depression life cycles. This would be more critical for the cutoff low in the upper troposphere, where the background flow is stronger within the troposphere. Quantifying S_{BG} for each depression may have the following advantages:

- The slope ratio SR ($=S_{BG}/S_o$) can be used to distinguish between the cutoff low and the preexisting trough (Fig. 6) and reject negligible troughs (Fig. 8).
- S_{BG} can be used to estimate the steering of depression movements. For example, the background geostrophic wind evaluated from S_{BG} is generally consistent with the depression's actual movements for the cutoff low shown in Fig. 11. This idea is similar to the area-averaged geostrophic wind (geostrophic wind obtained by the area-averaged pressure gradient) over 5° - and 3° -latitude circles around a cyclone, as adopted by the Melbourne and Sinclair schemes, respectively.

3) PHYSICAL INTERPRETATION OF INTENSITY

The eastward slope S_o in Eq. (2) is proportional to the northward geostrophic wind at the tangential point on the height curve shown in Fig. 2a. Similarly, S_o originating from the 2D AS in Eq. (8) is also proportional to an average of four circular-oriented geostrophic winds, i.e.,

$$S_o \propto \overline{V_g}, \quad (19)$$

where $\overline{V_g}$ is an average of geostrophic winds evaluated from four (northward, westward, southward, and eastward) directional slopes, and corresponds to the geostrophic tangential

wind on a circle with a radius r_o . Using the circulation around a circle of radius r_o and Stokes's theorem, $\overline{V_g}$ can be expressed as

$$\overline{V_g} = \frac{\oint_{r_o} \mathbf{V_g} \cdot d\mathbf{l}}{\oint_{r_o} d\mathbf{l}} = \overline{\zeta_g} r_o / 2, \quad (20)$$

where $\mathbf{V_g}$ is the geostrophic wind, $d\mathbf{l}$ is a displaced vector locally tangent to the circle of radius r_o , and $\overline{\zeta_g}$ is the area-averaged geostrophic vorticity within the circle of radius r_o . The circular flow $\overline{V_g}$ has a unit of meters per second, whose dimension is between that of the circulation ($\text{m}^2 \text{s}^{-1}$) and vorticity (s^{-1}). Sinclair (1997) showed that there is an adverse areal bias in estimating the cyclone intensity with either circulation or vorticity and proposed the combination of the two to reduce the bias. The use of S_o (or $\overline{V_g}$) may be also one of the good solutions for reducing the bias. The Melbourne scheme estimates a depth D for a paraboloidal depression of radius R on a flat field, as $D = 0.25 \times \nabla^2 Z \times R^2$ (Simmonds et al. 1999). Using these parameters, we can obtain a quantity similar to S_o , i.e., $S_o \sim D/R = 0.25 \times \nabla^2 Z \times R^2$. The same relation can be obtained from Eqs. (6) and (18), if $\nabla^2 Z$ is estimated with r_o , not δ . It seems that S_o has a simpler formulation to configure both depth and radius comprehensively.

c. Comparison with other feature-based schemes for preexisting trough detection

We compare the proposed scheme with feature-based schemes for Rossby wave breaking (e.g., Wernli and Sprenger 2007) and for troughs or ridges (Schemm et al. 2020). In the detection scheme involving Rossby wave breaking, a "PV streamer" is detected as a breaking event, which is a filament-like area within a 2-PVU contour. The detected PV streamer is a trough or ridge from the synoptic viewpoint. The recent trough and ridge detection scheme of Schemm et al. (2020) searches areas of strong curvature in the geopotential height. These feature-based schemes detect distorted troughs or ridges, especially in the early stage. Another important point is that these two schemes belong to the contour-searching scheme (see section 1), where the identified grid points are masked as a coherent region or object, but not as a point or location.

Our cutoff low and preexisting trough detection scheme is also a feature-based scheme, searching for vortex-like features. In this search scheme, an object (a cutoff low) is identified as a point. The proposed scheme has some similarities with the trough and ridge detection scheme of Schemm et al. (2020); (i) Both schemes require only the geopotential height at a given isobaric surface. (ii) The trough feature is evaluated with second-order derivative: the curvature of geopotential height isolines in Schemm's scheme, and AS in the proposed scheme. (iii) The proposed scheme identifies the cutoff low and the preexisting trough, which are distinguished as "closed trough" and "open trough," respectively, in the Schemm's scheme.

However, there are differences between the scheme of Schemm et al. (2020) and the proposed scheme. Schemm et al. (2020) focus on troughs and ridges with either open or closed features, while we focus on cutoff lows (i.e., closed features)

FIG. 12. As in Fig. 3, but for AS^- [$m (100 \text{ km})^{-1}$] for blocking highs or ridges at 0000 UTC 25 Feb 2004. The red triangle indicates the local height maximum.

with their backgrounds. Also, their scheme involves contour searching, while the proposed scheme is an extremum point search. Both schemes have their own merits. The Schemm scheme provides information on the degree of orientation of the trough and ridge axes. The proposed scheme provides information on the intensity of the closed cutoff lows by means of an extremum point search. Our parameters do not reflect the distorted trough's features; however, they can evaluate the isotropic depression removing the background gradient (S_{BG} , α) regardless of the stages of the cutoff low's life cycles.

d. Application to blocking highs and ridges

Several studies have used a depression identification scheme to document anticyclone behavior by “reversing” the criteria (e.g., Wernli and Schwierz 2006; Wernli and Sprenger 2007; Hatzaki et al. 2014). We obtain that the proposed scheme can also be used for detecting blocking highs and ridges, which are anticyclonic disturbances in the upper troposphere, by simply searching for local minima of AS . Figure 12 shows an example of the application of the proposed scheme to a blocking event over the North Atlantic at a 200-hPa geopotential height at 0000 UTC 25 October 2004. Note that AS^- is the lower envelope of AS . In Woollings et al. (2018), this case was introduced as a typical omega block case, which is easily detected in anomaly fields from a basic state (i.e., the anomaly based method; Barriopedro et al. 2010). The proposed scheme can be

used as an anomaly based method even though a basic state is not required. More detailed comparisons with other blocking indices are under investigation and will be presented in the future.

6. Summary

We propose a new scheme to seamlessly detect cutoff lows and preexisting troughs and verified the scheme with JRA-55 data and idealized height fields. The strengths of the proposed scheme are as follows: the proposed scheme can detect the location of cutoff lows with their intensity, size, and background height gradient in an integrated manner. The quantified intensity depends little on data resolution, and the gradient is evaluated for each cutoff low scale.

The proposed scheme is based on a geometric characteristic of depressions, the optimal slope (S_o); S_o is a height slope of a line intersecting the depression bottom and the nearest tangential point on the geopotential height curve (Fig. 2a). The slope S_o is regarded as the local maximum of AS^+ , which is the upper envelope of AS with respect to r (Fig. 2c). It indicates that depression intensity using a height difference normalized to the depression's horizontal scale or optimal radius (r_o). Assuming the isotropy of a solitary depression, we produced the 2D average slope function AS to extract S_o , r_o , and the location of depression bottoms (x_b , y_b) by searching local maxima of AS^+ [Eq. (8); Fig. 3]. Owing to the detected parameters of r_o and (x_b , y_b), we can define the local background slope S_{BG} using Eq. (11a) (Fig. 4). The detection of life cycles from preexisting troughs to cutoff lows by tracking (x_b , y_b) is also shown (Fig. 5).

We conducted experiments to investigate the proposed scheme's performance. We obtained that S_o is independent of S_{BG} , indicating that a cutoff low and its preexisting trough can be identified by removing a local background flow. Besides, the ratio of S_{BG} to S_o (slope ratio, SR) indicates the transition from a (weak) preexisting trough to a cutoff low (Figs. 6–8). We illustrated some distribution maps for detected depressions with the aid of three inclusive detection constraints: (i) $\min r < r_o < \max r$, (ii) $S_o > 0$, and (iii) $SR < 3.0$. The comparisons of climatology agree with previous studies for both hemispheres at multiple pressure levels in the upper troposphere (Fig. 9).

FIG. A1. (a),(b) As in Figs. 3b and 10a, respectively, but with 2.5°-resolution data made from JRA-55 by skipping every other grid.

TABLE A1. Dependence of cutoff low parameters on data resolution in the case of the cutoff low shown in Fig. 1.

Data resolution	max AS^+ (S_o) [$m (100 km)^{-1}$]	r_o (km)	S_{BG} [$m (100 km)^{-1}$]	SR (—)	max $\nabla^2 Z$ [$10^{-10} gpm (m)^{-2}$]
1.25°	32.73	1100	22.25	0.68	25.44
2.5°	32.66	1100	22.23	0.68	19.36

We discussed the similarities and differences between AS^+ and the traditional parameters of $\nabla^2 Z$ and PV (Fig. 10). Based on a case study of a long-lived cutoff low, the proposed scheme's detected parameters are consistent with those of the PV cutoff analyzed by Portmann et al. (2017) (Fig. 11). Finally, through detailed comparisons with some of the most sophisticated cyclone detection schemes (the Melbourne and Sinclair's schemes) and PV streamer and trough/ridge detection schemes (Wernli and Sprenger 2007; Schemm et al. 2020), the similarities and differences were highlighted. We confirmed that the proposed scheme is sufficient for detecting and classifying cutoff lows. The proposed scheme also has the capability of early stage detection, a snapshot view, the requirement of a single input (geopotential height), and cyclone and anticyclone detection. The applicability for a typical blocking high event was tested (Fig. 12).

The proposed scheme is compatible with some of the most sophisticated tracking schemes for near-surface extratropical cyclones, e.g., the Melbourne scheme (Murray and Simmonds 1991a,b; Simmonds and Murray 1999; Simmonds et al. 1999; Lim and Simmonds 2007; Pezza et al. 2012), TRACK (Hodges 1994, 1995, 1999), and NEAT (Inatsu 2009; Inatsu and Amada 2013; Satake et al. 2013). This is because the proposed scheme defines the center of each depression and estimates its horizontal extension. The life cycles and variability of cutoff lows associated with tornadoes and quality comparisons with previous schemes will be investigated in future work.

Acknowledgments. This work represents a portion of the first author's Ph.D. dissertation at Niigata University. We thank Drs. E. Tochimoto, S. I. Watanabe, H. Hirata, A. Kuwano-Yoshida, W. Yanase, H. Nakano, M. Inatsu, T. Horinouchi, Y. Hirockawa, T. Fukamachi, K. Norisuye, and S. Usui for stimulating discussions and their helpful comments. We would also like to thank Dr. R. McTaggart-Cowan and three anonymous reviewers for helpful comments, which have greatly improved the manuscript. The second, fourth, fifth, and sixth authors are supported by JSPS KAKENHI Grants 17H02067 and 19H05698, Collaborative Research Project (2018-7, 2019-6, 2020-3) of the Research Institute for Natural Hazards and Disaster Recovery, Niigata University, and Arctic Challenge for Sustainability II.

APPENDIX

Dependence on Data Resolution

The smoothing effect of our scheme, described in section 5a, reduces the dependence of the extracted parameters on data resolution. Figure A1 shows the distributions for AS^+ and $\nabla^2 Z$, which are the same as AS^+ in Fig. 3b and $\nabla^2 Z$ in Fig. 10a,

respectively, but for using a dataset with 2.5° resolution generated by skipping every other grid from the original JRA-55 resolution of 1.25°. The distributions with different resolutions are qualitatively consistent. Table A1 shows the respective local maximum values and the corresponding depression parameters for the cutoff low shown in Fig. 1. Note that the local maxima of $\nabla^2 Z$ are sought in an area within 20°–45°N, 105°–135°E. As the resolution has changed from 1.25° to 2.5°, the local maximum value of $\nabla^2 Z$ decreases by $6.08 \times 10^{-10} gpm (m)^{-2}$ (23.9%), while the local maximum value of AS^+ (S_o) decreases by $0.07 m (100 km)^{-1}$ (0.2%). The rate of change in the other parameters is also smaller than that of $\nabla^2 Z$.

REFERENCES

- Abatzoglou, J. T., 2016: Contribution of cutoff lows to precipitation across the United States. *J. Appl. Meteor. Climatol.*, **55**, 893–899, <https://doi.org/10.1175/JAMC-D-15-0255.1>.
- Barbero, R., J. T. Abatzoglou, and H. J. Fowler, 2019: Contribution of large-scale midlatitude disturbances to hourly precipitation extremes in the United States. *Climate Dyn.*, **52**, 197–208, <https://doi.org/10.1007/s00382-018-4123-5>.
- Barriopedro, D., R. García-Herrera, and R. M. Trigo, 2010: Application of blocking diagnosis methods to general circulation models. Part I: A novel detection scheme. *Climate Dyn.*, **35**, 1373–1391, <https://doi.org/10.1007/s00382-010-0767-5>.
- Bell, G. D., and L. F. Bosart, 1989: A 15-year climatology of Northern Hemisphere 500 mb closed cyclone and anticyclone centers. *Mon. Wea. Rev.*, **117**, 2142–2164, [https://doi.org/10.1175/1520-0493\(1989\)117<2142:AYCONH>2.0.CO;2](https://doi.org/10.1175/1520-0493(1989)117<2142:AYCONH>2.0.CO;2).
- Bueh, C., and Z. Xie, 2015: An objective technique for detecting large-scale tilted ridges and troughs and its application to an East Asian cold event. *Mon. Wea. Rev.*, **143**, 4765–4783, <https://doi.org/10.1175/MWR-D-14-00238.1>.
- Davies, J. M., 2006: Tornadoes with cold core 500-mb lows. *Wea. Forecasting*, **21**, 1051–1062, <https://doi.org/10.1175/WAF967.1>.
- Dean, D. B., and L. F. Bosart, 1996: Northern Hemisphere 500-hPa trough merger and fracture: A climatology and case study. *Mon. Wea. Rev.*, **124**, 2644–2671, [https://doi.org/10.1175/1520-0493\(1996\)124<2644:NHHTMA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1996)124<2644:NHHTMA>2.0.CO;2).
- Favre, A., B. Hewitson, and M. Tadross, 2012: Relationships between cut-off lows and the semiannual and southern oscillations. *Climate Dyn.*, **38**, 1473–1487, <https://doi.org/10.1007/s00382-011-1030-4>.
- Fudeyasu, H., and R. Yoshida, 2019: Statistical analysis of the relationship between upper tropospheric cold lows and tropical cyclone genesis over the western North Pacific. *J. Meteor. Soc. Japan*, **97**, 439–451, <https://doi.org/10.2151/jmsj.2019-025>.
- Fuenzalida, H. A., R. Sánchez, and R. D. Garreaud, 2005: A climatology of cutoff lows in the Southern Hemisphere. *J. Geophys. Res.*, **110**, D18101, <https://doi.org/10.1029/2005JD005934>.
- Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Research Paper 91, University of Chicago, 42 pp.

- Gaza, R. S., and L. F. Bosart, 1990: Trough-merger characteristics over North America. *Wea. Forecasting*, **5**, 314–331, [https://doi.org/10.1175/1520-0434\(1990\)005<0314:TMCONA>2.0.CO;2](https://doi.org/10.1175/1520-0434(1990)005<0314:TMCONA>2.0.CO;2).
- Griffiths, M., M. J. Reeder, D. J. Low, and R. A. Vincent, 1998: Observations of a cut-off low over southern Australia. *Quart. J. Roy. Meteor. Soc.*, **124**, 1109–1132, <https://doi.org/10.1002/qj.49712454805>.
- Grumm, R. H., and R. Hart, 2001: Standardized anomalies applied to significant cold season weather events: Preliminary findings. *Wea. Forecasting*, **16**, 736–754, [https://doi.org/10.1175/1520-0434\(2001\)016<0736:SAATSC>2.0.CO;2](https://doi.org/10.1175/1520-0434(2001)016<0736:SAATSC>2.0.CO;2).
- Hakim, G. J., 2000: Climatology of coherent structures on the extratropical tropopause. *Mon. Wea. Rev.*, **128**, 385–406, [https://doi.org/10.1175/1520-0493\(2000\)128<0385:COCSOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0385:COCSOT>2.0.CO;2).
- Harada, Y., and Coauthors, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability. *J. Meteor. Soc. Japan*, **94**, 269–302, <https://doi.org/10.2151/jmsj.2016-015>.
- Hatzaki, M., H. A. Flocas, I. Simmonds, J. Kouroutzoglou, K. Keay, and I. Rudeva, 2014: Seasonal aspects of an objective climatology of anticyclones affecting the Mediterranean. *J. Climate*, **27**, 9272–9289, <https://doi.org/10.1175/JCLI-D-14-00186.1>.
- Hirota, N., Y. N. Takayabu, M. Kato, and S. Arakane, 2016: Roles of an atmospheric river and a cutoff low in the extreme precipitation event in Hiroshima on 19 August 2014. *Mon. Wea. Rev.*, **144**, 1145–1160, <https://doi.org/10.1175/MWR-D-15-0299.1>.
- Hodges, K. I., 1994: A general method for tracking analysis and its application to meteorological data. *Mon. Wea. Rev.*, **122**, 2573–2586, [https://doi.org/10.1175/1520-0493\(1994\)122<2573:AGMFTA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122<2573:AGMFTA>2.0.CO;2).
- , 1995: Feature tracking on the unit sphere. *Mon. Wea. Rev.*, **123**, 3458–3465, [https://doi.org/10.1175/1520-0493\(1995\)123<3458:FTOTUS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1995)123<3458:FTOTUS>2.0.CO;2).
- , 1999: Adaptive constraints for feature tracking. *Mon. Wea. Rev.*, **127**, 1362–1373, [https://doi.org/10.1175/1520-0493\(1999\)127<1362:ACFFT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<1362:ACFFT>2.0.CO;2).
- Homar, V., M. Gaya, and C. Ramis, 2001: A synoptic and meso-scale diagnosis of a tornado outbreak in the Balearic Islands. *Atmos. Res.*, **56**, 31–55, [https://doi.org/10.1016/S0169-8095\(00\)00087-9](https://doi.org/10.1016/S0169-8095(00)00087-9).
- Hoskins, B. J., M. E. McIntyre, and A. W. Robertson, 1985: On the use and significance of isentropic potential vorticity maps. *Quart. J. Roy. Meteor. Soc.*, **111**, 877–946, <https://doi.org/10.1002/qj.49711147002>.
- Inatsu, M., 2009: The neighbor enclosed area tracking algorithm for extratropical wintertime cyclones. *Atmos. Sci. Lett.*, **10**, 267–272, <https://doi.org/10.1002/asl.238>.
- , and S. Amada, 2013: Dynamics and geometry of extratropical cyclones in the upper troposphere by a neighbor enclosed area tracking algorithm. *J. Climate*, **26**, 8641–8653, <https://doi.org/10.1175/JCLI-D-12-00379.1>.
- Keable, M., I. Simmonds, and K. Keay, 2002: Distribution and temporal variability of 500 hPa cyclone characteristics in the Southern Hemisphere. *Int. J. Climatol.*, **22**, 131–150, <https://doi.org/10.1002/joc.728>.
- Kentarchos, A. S., and T. D. Davies, 1998: A climatology of cutoff lows at 200 hPa in the Northern Hemisphere, 1990–1994. *Int. J. Climatol.*, **18**, 379–390, [https://doi.org/10.1002/\(SICI\)1097-0088\(19980330\)18:4<379::AID-JOC257>3.0.CO;2-F](https://doi.org/10.1002/(SICI)1097-0088(19980330)18:4<379::AID-JOC257>3.0.CO;2-F).
- Kew, S. F., M. Sprenger, and H. C. Davies, 2010: Potential vorticity anomalies of the lowermost stratosphere: A 10-yr winter climatology. *Mon. Wea. Rev.*, **138**, 1234–1249, <https://doi.org/10.1175/2009MWR3193.1>.
- Knippertz, P., 2004: A simple identification scheme for upper-level troughs and its application to winter precipitation variability in northwest Africa. *J. Climate*, **17**, 1411–1418, [https://doi.org/10.1175/1520-0442\(2004\)017<1411:ASISFU>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1411:ASISFU>2.0.CO;2).
- Kobayashi, S., and Coauthors, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*, **93**, 5–48, <https://doi.org/10.2151/jmsj.2015-001>.
- Lefevre, R. J., and J. W. Nielsen-Gammon, 1995: An objective climatology of mobile troughs in the Northern Hemisphere. *Tellus*, **47A**, 638–655, <https://doi.org/10.3402/tellusa.v47i5.11558>.
- Li, Q., Y. Huang, Y. Fan, S. Tang, and Y. Hu, 2018: Automatic analysis of trough lines based on curvature tracing. *Atmosphere*, **9**, 88, <https://doi.org/10.3390/atmos9030088>.
- Lim, E., and I. Simmonds, 2007: Southern Hemisphere winter extratropical cyclone characteristics and vertical organization observed with the ERA-40 data in 1979–2001. *J. Climate*, **20**, 2675–2690, <https://doi.org/10.1175/JCLI4135.1>.
- Mohr, S., and Coauthors, 2020: The role of large-scale dynamics in an exceptional sequence of severe thunderstorms in Europe May–June 2018. *Wea. Climate Dyn.*, **1**, 325–348, <https://doi.org/10.5194/wcd-1-325-2020>.
- Muñoz, C., D. Schultz, and G. Vaughan, 2020: A midlatitude climatology and interannual variability of 200- and 500-hPa cut-off lows. *J. Climate*, **33**, 2201–2222, <https://doi.org/10.1175/JCLI-D-19-0497.1>.
- Murray, R. J., and I. Simmonds, 1991a: A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. *Aust. Meteor. Mag.*, **39**, 155–166.
- , and —, 1991b: A numerical scheme for tracking cyclone centres from digital data. Part II: Application to January and July circulation model simulations. *Aust. Meteor. Mag.*, **39**, 167–180.
- Ndarana, T., and D. W. Waugh, 2010: The link between cut-off lows and Rossby wave breaking in the Southern Hemisphere. *Quart. J. Roy. Meteor. Soc.*, **136**, 869–885, <https://doi.org/10.1002/qj.627>.
- Neu, U., and Coauthors, 2013: IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms. *Bull. Amer. Meteor. Soc.*, **94**, 529–547, <https://doi.org/10.1175/BAMS-D-11-00154.1>.
- Nieto, R., and Coauthors, 2005: Climatological features of cutoff low systems in the Northern Hemisphere. *J. Climate*, **18**, 3085–3103, <https://doi.org/10.1175/JCLI3386.1>.
- , and Coauthors, 2007: Interannual variability of cut-off low systems over the European sector: The role of blocking and the Northern Hemisphere circulation modes. *Meteor. Atmos. Phys.*, **96**, 85–101, <https://doi.org/10.1007/s00703-006-0222-7>.
- , M. Sprenger, H. Wernli, R. Trigo, and L. Gimeno, 2008: Identification and climatology of cutoff lows near the tropopause. *Ann. N. Y. Acad. Sci.*, **1146**, 256–290, <https://doi.org/10.1196/annals.1446.016>.
- Palmén, E., and C. W. Newton, 1969: *Atmospheric Circulation Systems: Their Structure and Physical Interpretation*. Academic Press, 603 pp.
- Pezza, A. B., H. A. Rashid, and I. Simmonds, 2012: Climate links and recent extremes in antarctic sea ice, high-latitude cyclones, Southern Annular Mode and ENSO. *Climate Dyn.*, **38**, 57–73, <https://doi.org/10.1007/s00382-011-1044-y>.
- Pinheiro, H. R., K. I. Hodges, M. A. Gan, and N. J. Ferreira, 2017: A new perspective of the climatological features of upper-level cutoff lows in the Southern Hemisphere. *Climate Dyn.*, **48**, 541–559, <https://doi.org/10.1007/s00382-016-3093-8>.

- , —, and —, 2019: Sensitivity of identifying cut-off lows in the Southern Hemisphere using multiple criteria: Implications for numbers, seasonality and intensity. *Climate Dyn.*, **53**, 6699–6713, <https://doi.org/10.1007/s00382-019-04984-x>.
- , —, and —, 2020: An intercomparison of subtropical cut-off lows in the Southern Hemisphere using recent reanalyses: ERA-Interim, NCEP-CFRS, MERRA-2, JRA-55, and JRA-25. *Climate Dyn.*, **54**, 777–792, <https://doi.org/10.1007/s00382-019-05089-1>.
- Porcù, F., A. Carrassi, C. M. Medaglia, F. Prodi, and A. Mugnai, 2007: A study on cut-off low vertical structure and precipitation in the Mediterranean region. *Meteor. Atmos. Phys.*, **96**, 121–140, <https://doi.org/10.1007/s00703-006-0224-5>.
- Portmann, R., B. Crezee, J. Quinting, and H. Wernli, 2017: The complex life cycles of two long-lived potential vorticity cut-offs over Europe. *Quart. J. Roy. Meteor. Soc.*, **144**, 701–719, <https://doi.org/10.1002/qj.3239>.
- , M. Sprenger, and H. Wernli, 2021: The three-dimensional life cycles of potential vorticity cutoffs: A global and selected regional climatologies in ERA-Interim (1979–2018). *Wea. Climate Dyn.*, **2**, 507–534, <https://doi.org/10.5194/wcd-2-507-2021>.
- Reboita, M. S., R. Nieto, L. Gimeno, R. P. Da Rocha, T. Ambrizzi, R. Garreaud, and L. F. Krüger, 2010: Climatological features of cutoff low systems in the Southern Hemisphere. *J. Geophys. Res.*, **115**, D17104, <https://doi.org/10.1029/2009JD013251>.
- Renard, R. J., and L. C. Clarke, 1965: Experiments in numerical objective frontal analysis. *Mon. Wea. Rev.*, **93**, 547–556, [https://doi.org/10.1175/1520-0493\(1965\)093<0547:EINOFA>2.3.CO;2](https://doi.org/10.1175/1520-0493(1965)093<0547:EINOFA>2.3.CO;2).
- Rudeva, I., and I. Simmonds, 2015: Variability and trends of global atmospheric frontal activity and links with large-scale modes of variability. *J. Climate*, **28**, 3311–3330, <https://doi.org/10.1175/JCLI-D-14-00458.1>.
- , S. K. Gulev, I. Simmonds, and N. Tilinina, 2014: The sensitivity of characteristics of cyclone activity to identification procedures in tracking algorithms. *Tellus*, **66A**, 24961, <https://doi.org/10.3402/tellusa.v66.24961>.
- , D. Crock, and G. Bosch, 2019: Midlatitude fronts and variability in the Southern Hemisphere tropical width. *J. Climate*, **32**, 8243–8260, <https://doi.org/10.1175/JCLI-D-18-0782.1>.
- Sadler, J. C., 1976: A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.*, **104**, 1266–1278, [https://doi.org/10.1175/1520-0493\(1976\)104<1266:AROTTU>2.0.CO;2](https://doi.org/10.1175/1520-0493(1976)104<1266:AROTTU>2.0.CO;2).
- Sakamoto, K., and M. Takahashi, 2005: Cut off and weakening processes of an upper cold low. *J. Meteor. Soc. Japan*, **83**, 817–834, <https://doi.org/10.2151/jmsj.83.817>.
- Satake, Y., M. Inatsu, M. Mori, and A. Hasegawa, 2013: Tropical cyclone tracking using a neighbor enclosed area tracking algorithm. *Mon. Wea. Rev.*, **141**, 3539–3555, <https://doi.org/10.1175/MWR-D-12-00092.1>.
- Schemm, S., I. Rudeva, and I. Simmonds, 2015: Extratropical fronts in the lower troposphere—global perspectives obtained from two automated methods. *Quart. J. Roy. Meteor. Soc.*, **141**, 1686–1698, <https://doi.org/10.1002/qj.2471>.
- , S. Rüdisühli, and M. Sprenger, 2020: The life cycle of upper-level troughs and ridges: A novel detection method, climatologies and Lagrangian characteristics. *Wea. Climate Dyn.*, **1**, 459–479, <https://doi.org/10.5194/wcd-1-459-2020>.
- Schielicke, L., P. Nvir, and U. Ulbrich, 2016: Kinematic vorticity number—A tool for estimating vortex sizes and circulations. *Tellus*, **68A**, 29464, <https://doi.org/10.3402/tellusa.v68.29464>.
- Schneidereit, A., R. Blender, and K. Fraedrich, 2010: A radius-depth model for midlatitude cyclones in reanalysis data and simulations. *Quart. J. Roy. Meteor. Soc.*, **136**, 50–60, <https://doi.org/10.1002/qj.523>.
- Schumacher, R. S., and R. H. Johnson, 2008: Mesoscale processes contributing to extreme rainfall in a midlatitude warm-season flash flood. *Mon. Wea. Rev.*, **136**, 3964–3986, <https://doi.org/10.1175/2008MWR2471.1>.
- Seko, H., M. Kunii, S. Yokota, T. Tsuyuki, and T. Miyoshi, 2015: Ensemble experiments using a nested LETKF system to reproduce intense vortices associated with tornadoes of 6 May 2012 in Japan. *Prog. Earth Planet. Sci.*, **2**, 42, <https://doi.org/10.1186/s40645-015-0072-3>.
- Simmonds, I., and R. M. Leighton, 1999: A refinement of cyclone tracking methods with data from FROST. *Aust. Meteor. Mag.*, Special Issue, 35–49.
- , R. J. Murray, and R. M. Leighton, 1999: Southern extra-tropical cyclone behavior in ECMWF analyses during the FROST special observing periods. *Wea. Forecasting*, **14**, 878–891, [https://doi.org/10.1175/1520-0434\(1999\)014<0878:SECBIE>2.0.CO;2](https://doi.org/10.1175/1520-0434(1999)014<0878:SECBIE>2.0.CO;2).
- , K. Keay, and J. A. T. Bye, 2012: Identification and climatology of Southern Hemisphere mobile fronts in a modern reanalysis. *J. Climate*, **25**, 1945–1962, <https://doi.org/10.1175/JCLI-D-11-00100.1>.
- Sinclair, M. R., 1994: An objective cyclone climatology for the Southern Hemisphere. *Mon. Wea. Rev.*, **122**, 2239–2256, [https://doi.org/10.1175/1520-0493\(1994\)122<2239:AOCFFT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122<2239:AOCFFT>2.0.CO;2).
- , 1997: Objective identification of cyclones and their circulation intensity, and climatology. *Wea. Forecasting*, **12**, 595–612, [https://doi.org/10.1175/1520-0434\(1997\)012<0595:OIOCAT>2.0.CO;2](https://doi.org/10.1175/1520-0434(1997)012<0595:OIOCAT>2.0.CO;2).
- Singleton, A. T., and C. J. Reason, 2007a: A numerical model study of an intense cutoff low pressure system over South Africa. *Mon. Wea. Rev.*, **135**, 1128–1150, <https://doi.org/10.1175/MWR3311.1>.
- , and —, 2007b: Variability in the characteristics of cut-off low pressure systems over subtropical southern Africa. *Int. J. Climatol.*, **27**, 295–310, <https://doi.org/10.1002/joc.1399>.
- Thorncroft, C. D., B. Hoskins, and M. E. McIntyre, 1993: Two paradigms of baroclinic-wave life-cycle behaviour. *Quart. J. Roy. Meteor. Soc.*, **119**, 17–55, <https://doi.org/10.1002/qj.49711950903>.
- Tsuboki, K., and Y. Ogura, 1999: A potential vorticity analysis of thunderstorm-related cold lows (in Japanese). *Tenki*, **46**, 453–459.
- Tsuji, H., and Y. N. Takayabu, 2019: Precipitation enhancement via the interplay between atmospheric rivers and cutoff lows. *Mon. Wea. Rev.*, **147**, 2451–2466, <https://doi.org/10.1175/MWR-D-18-0358.1>.
- Ulbrich, U., and Coauthors, 2013: Are greenhouse gas signals of Northern Hemisphere winter extra-tropical cyclone activity dependent on the identification and tracking algorithm? *Meteor. Z.*, **22**, 61–68, <https://doi.org/10.1127/0941-2948/2013/0420>.
- Wei, N., Y. Li, D. Zhang, Z. Mai, and S. Yang, 2016: A statistical analysis of the relationship between upper-tropospheric cold low and tropical cyclone track and intensity change over the western North Pacific. *Mon. Wea. Rev.*, **144**, 1805–1822, <https://doi.org/10.1175/MWR-D-15-0370.1>.
- Wen, D., Y. Li, D. Zhang, L. Xue, and N. Wei, 2018: A statistical analysis of tropical upper-tropospheric trough cells over the western North Pacific during 2006–15. *J. Appl. Meteor. Climatol.*, **57**, 2469–2483, <https://doi.org/10.1175/JAMC-D-18-0003.1>.

- Wernli, H., and C. Schwierz, 2006: Surface cyclones in the ERA40 data set (1958–2001). Part I: Novel identification method and global climatology. *J. Atmos. Sci.*, **63**, 2486–2507, <https://doi.org/10.1175/JAS3766.1>.
- , and M. Sprenger, 2007: Identification and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical tropopause. *J. Atmos. Sci.*, **64**, 1569–1586, <https://doi.org/10.1175/JAS3912.1>.
- Woollings, T., and Coauthors, 2018: Blocking and its response to climate change. *Curr. Climate Change Rep.*, **4**, 287–300, <https://doi.org/10.1007/s40641-018-0108-z>.
- Yamashita, Y., M. Takigawa, K. Ishijima, H. Akiyoshi, C. Kodama, H. Yashiro, and M. Satoh, 2017: Resolution dependency of numerically simulated stratosphere-to-troposphere transport associated with mid-latitude closed cyclones in early Spring around Japan. *SOLA*, **13**, 186–191, <https://doi.org/10.2151/sola.2017-034>.
- Yokoyama, R., M. Shirasawa, and R. J. Pike, 2002: Visualizing topography by openness: A new application of image processing to digital elevation models. *Photogramm. Eng. Remote Sens.*, **68**, 257–266.
- Zhang, C., Q. Zhang, Y. Wang, and X. Liang, 2008: Climatology of warm season cold vortices in East Asia: 1979–2005. *Meteor. Atmos. Phys.*, **100**, 291–301, <https://doi.org/10.1007/s00703-008-0310-y>.
- Zhao, S., and J. Sun, 2007: Study on cutoff low-pressure systems with floods over Northeast Asia. *Meteor. Atmos. Phys.*, **96**, 159–180, <https://doi.org/10.1007/s00703-006-0226-3>.