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Lizhi JIANG , Shenming FU & Jianhua SUN

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New method for detecting extratropical cyclones: the eight-section slope detecting method

JIANG Lizhi[a,b], FU Shenming[c] and SUN Jianhua[a]

[a]Key Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; [b]College of Earth and Planetary Science, University of Chinese Academy of Sciences, Beijing, China; [c]International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT

An algorithm for identifying extratropical cyclones (ECs) on the basis of gridded data is proposed in this study. The algorithm, which is named the eight-section slope detecting (ESSD) method, has five key procedures to identify an EC by using the mean sea level pressure (MSLP) or geopotential height. They are: (i) finding the location of every minimum of the MSLP/geopotential-height; (ii) establishing a targeted box for each minimum; (iii) dividing the targeted box into eight sub-regions; (iv) calculating eight relative slopes within the eight sub-regions; (v) confirming an EC only if all eight relative slopes are above an appropriate threshold. Based on the 0.75° × 0.75° ERA-Interim reanalysis field, comparisons show that the ESSD method performs better in identifying ECs than the other three previous EC detection algorithms, as it can lower the error caused by mistaking a trough for an EC. Moreover, a test of detecting ECs in the Northern Hemisphere using the ESSD method repeated 500 times (randomly distributed across 40 years) shows that the accuracy of this method varies from 79% to 91%, with an annual mean accuracy of ~85%. This means that the ESSD method can provide credible results with respect to EC identification.

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关键词
温带气旋; 气旋识别; ERA-Interim

一个识别温带气旋的新方法:八区域斜率法

摘要

本文提出了一种用于格点数据识别气旋 (EC) 的算法—八区域斜率法 (ESSD) 。该方法基于平均海平面气压 (MSLP)/位势高度场, 主要步骤如下: (1) 搜索MSLP/位势高度场极小值的位置; (2) 在极小值位置周围建立一个矩形关键区; (3) 将关键区划分成八个子区; (4) 计算各子区变量的相对斜率; (5) 如果所有子区的斜率均超过给定阈值, 则识别为气旋。基于0.75° × 0.75° ERA-Interim资料与其他三种方法的比较显示, ESSD方法可以减少将槽误识别成气旋的情况。此外, 在北半球区域, 在40年间随机选取500个时次, 对该方法进行测试, 结果显示准确率在79%到91%之间波动, 其中平均准确率约为85%。这表明ESSD方法对气旋进行的识别效果是可信的。

1. Introduction

An extratropical cyclone (EC) is a synoptic-scale weather system characterized by a closed low-pressure center and remarkable cyclonic wind field (Holton 2004). ECs can form everywhere in the midlatitude regions of the Earth, and they are capable of producing almost all types of weathers from fog, cloudiness and showers to heavy gales, torrential rainfall, hail, intense cold waves, blizzards, and even tornadoes (Markowski and Richardson 2010). Moreover, in the balance of atmospheric energy, moisture and mass, ECs play a key role in transporting meridional heat/moisture, and redistributing air mass (Holton 2004; Hu, Guan, and Li 2014). Therefore, investigating the behaviors/activities of ECs, and then showing their related key characteristics, is of great importance to the atmospheric sciences (Lu 2017).

To investigate the behaviors/activities of ECs (e.g., climatological and statistical studies on ECs, research into their storm tracks, etc.), the first step is to identify this type of system correctly (Hoskins and Hodges 2002; Zhang, Ding, and Li 2012). Therefore, EC detection is of crucial importance, as it can affect the reliability of the final conclusion (Allen, Pezza, and Black 2010; Neu et al. 2013). In earlier studies, synoptic charts were used to detect ECs manually (Sanders and Gyakum 1980; Murty, McBean, and McKee 1983). This method can guarantee a high level of accuracy in EC detection, but it needs a huge amount of manual work when the study period is long (Fu et al. 2015, 2016). With the rapid development of observational technologies and numerical models, increasingly more data can be used for identifying ECs. As such, identifying ECs manually is inefficient, and thus

CONTACT Shenming FU fusm@mail.iap.ac.cn

detecting them using an effective algorithm is imperative (Lim and Simmonds 2002; Allen, Pezza, and Black 2010; Lu 2017).

Many previous studies have attempted to develop EC identification algorithms. In these algorithms, the process of EC detection is mainly based on the mean sea level pressure (MSLP), pressure, geopotential height, vorticity, and/or other derivative variables from these four factors (Lambert 1988; Murray and Simmonds 1991; Hodges 1994; Simmonds and Keay 2000; Lim and Simmonds 2002; Flaounas et al. 2014; Fu et al. 2015, 2016; Qin, Lu, and Li 2017). As the temporal and spatial resolution of the data used for identification is important for the accuracy of EC detection (Raible et al. 2008; Allen, Pezza, and Black 2010; Neu et al. 2013), many studies interpolate the original data to a higher temporal and/or spatial resolution before beginning the process of EC detection, particularly those studies carried out in the relatively earlier years (Murray and Simmonds 1991; König, Sausen, and Sielmann 1993; Sinclair 1997). Because of the spatial noise of relative vorticity and the Laplacian of MSLP/geopotential height, spatial smoothing has tended to be applied to remove the noise (Murray and Simmonds 1991; Sinclair 1997; Flaounas et al. 2014). The common method for identifying an EC's center is through finding the minimum MSLP/pressure/geopotential height (König, Sausen, and Sielmann 1993; Sinclair 1997; Rudeva and Gulev 2007; Allen, Pezza, and Black 2010; Qin, Lu, and Li 2017; Lu 2017), the maximum cyclonic vorticity (Zhao and Fu 2007; Flaounas et al. 2014; Fu et al. 2015, 2016), or the maximum of the Laplacian of MSLP/pressure (Murray and Simmonds 1991; Simmonds and Keay 2000; Lim and Simmonds 2002). After identifying an EC's center, several methods are then used to determine an EC's range. For instance, Sinclair (1997) used the radial search method to determine the boundary of a surface flow. Wernli and Schwierz (2006) proposed a method that uses the outermost closed isobaric contour to represent the boundary of an EC, based on an isoline search at a given interval. Rudeva and Gulev (2007) estimated the size of an EC by using the radial gradient. This method has been further used to analyze the cyclonic structure (Rudeva and Gulev 2011; Fu et al. 2015, 2016). Qin, Lu, and Li (2017) and Lu (2017) proposed a method to determine the outline of an EC by using a triangular mesh and connected component labeling.

As mentioned above, previous studies have developed many useful algorithms for EC identification. However, thus far, no EC identification algorithm can guarantee a rate of accuracy near to 100%. A large proportion of the errors in detecting ECs are caused by mistaking a trough for an EC. Reducing this type of error in detection algorithms is an effective way to improve the accuracy rate of EC identification. Therefore, in this study, we introduce the eight-section slope detecting (ESSD) method for identifying ECs. It shows a higher accuracy rate in EC detection than previous traditional methods by lowering the error rate caused by mistaking a trough for an EC.

2. Data and methods

2.1. Data

Six-hourly ERA-Interim data with a horizontal resolution of 0.75° × 0.75° (Simmons et al. 2007) are used for the EC detection in this study. Considering that ECs are classed as synoptic-scale systems, the horizontal resolution of 0.75° is high enough for EC detection (Allen, Pezza, and Black 2010; Fu et al. 2015, 2016).

2.2. The ESSD method

The ESSD method has five key procedures:

(i) A domain (e.g., the Northern Hemisphere) is determined within which the algorithm finds all the local minimum values in terms of MSLP or geopotential height.

(ii) For each of the local minimum values, a box ($A_1A_2A_3A_4$), centered in A_c, is established (as Figure 1 shows, A_c is the location of the local minimum value, and the box, $A_1A_2A_3A_4$, is similar in size to the typical size of the cyclone that is being detected), which is then split evenly into four parts using lines A_5A_7 and A_6A_8 (Figure 1). The box size should be comparable in size to the target system (in this study, ECs). As we focus on synoptic-scale ECs, the box size is determined as 13 × 13 points (9° × 9°), which can cover the central region of an EC (tests from 8 × 8 points to 16 × 16 points also indicate the above selection has the best performance).

(iii) Eight sub-regions (A_i) are determined relative to the total box (where the subscript 'i' is the ordinal number of the sub-region), as follows: A_1– Ⅰ (the northeastern quadrant); A_2– Ⅱ (the northwestern quadrant); A_3–Ⅲ (the southwestern quadrant); A_4 –Ⅳ (the southeastern quadrant); A_5– Ⅰ+Ⅱ (the top section); A_6– Ⅱ+Ⅲ (the western section); A_7 –Ⅲ+Ⅳ (the bottom section); and A_8– Ⅰ+Ⅳ (the eastern section).

(iv) The relative slope of the eight sub-regions is calculated using $S = \frac{\bar{A}_i - A_c}{\bar{A} - A_c}$, where *i* is the area-mean value within sub-region A_i, A_C is the value

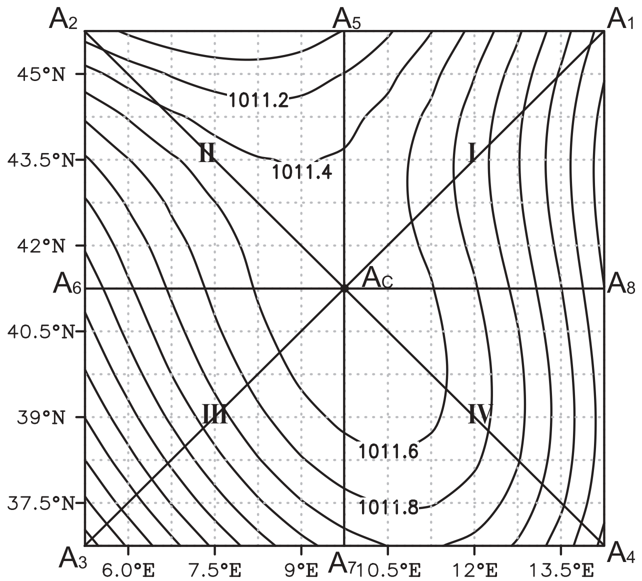

Figure 1. Schematic illustration of the ESSD method, where the solid line is the sea level pressure (units: hPa); point A_C marks the location of the minimum MSLP within the target region; points A_1, A_2, A_3, and A_4 are the four vertices of the box centered in A_C; points A_5, A_6, A_7, and A_8 are the midpoints of the four sides of the box, respectively. Regions I, II, III, and IV are the four quadrants of the box.

at point A_C, and $\bar{A}$ is the area-mean value within the total box $A_1A_2A_3A_4$.

(v) An appropriate threshold value of S is determined using the following procedures: Firstly, give a value of S according to typical ECs; then, modify S iteratively as follows: (a) detect ECs (suggest a sample of at least 500) based on S; (b) verify the detected ECs manually; (c) use valid cyclones to modify S, and then detect ECs again using the modified S; (d) repeat procedures (a) to (c) until the accuracy rate for EC detection is above a specified level (e.g., 85% or more). In this study, the value of S is set to 0.3. If S is above the threshold value within all eight sub-regions, a cyclone is determined; otherwise, no cyclone is detected.

3. Results of different types of EC identification algorithms

The ESSD method can detect EC centers both using MSLP and geopotential height. In order to evaluate its performance, a comparison between this method and three other types of identification algorithms (based on their relatively optimal settings) is conducted (Figures 2 and 3). The four types of methods are the local minimum of MSLP method (hereafter, method M01) (König, Sausen, and Sielmann 1993; Geng and Sugi 2001; Rudeva and Gulev 2007), the ESSD method, the local maximum Laplacian method (hereafter, method M03) (Murray and Simmonds 1991; Simmonds and Keay 2000; Lim and Simmonds 2007), and the local maximum of relative vorticity method (hereafter, method M04) (Zhao and Fu 2007; Flaounas et al. 2014). Detailed information about these methods is provided in Table 1. For M01, following Geng and Sugi (2001), we set the threhold of the difference between the searched point and its surrounding grid points to 0.3 hPa. For M03 and M04, because the vorticity field and the Laplacian of MSLP/geopotential-height are noisy, a smoothing the same as that of ESSD is conducted before the process of detection. For M03, as Lim and Simmonds (2007) suggested, the threshold of the Laplacian of MSLP/geopotential height is set to 0.2 hPa/1.7 gpm. For M04, the threshold of relative vorticity is set to 3×10^{-5} s^{-1}, following Flaounas et al. (2014).

Figure 2 shows a random sample (at 1800 UTC 3 January 1998) of the EC detection results by using MSLP. It is shown that M03 and M04 have a larger error rate in detecting ECs than the other two methods. M01 detects three ECs, with one of them (the easternmost red dot in Figure 2(a) being incorrect. The ESSD method only identifies two ECs (in fact, within this region, only two synoptic-scale ECs can be found), both of which are correct (Figure 2(b)).

Similarly, Figure 3 shows a random sample of the EC detection by using the 500-hPa geopotential height (at 1800 UTC 28 February 1998). From this figure it can be seen that M01, M03 and M04 again mistake a trough (Figure 3(a)) for an EC. The ESSD method detects two synoptic-scale ECs in Figure 3(b), which is correct both in number and location. M04 still has a higher rate in identifying ECs, and this is mainly because a cyclonic-vorticity center does not always correspond to an EC center.

In order to evaluate the ESSD method more objectively, we apply it to the detection of synoptic-scale ECs in the Northern Hemisphere, repeated 500 times and randomly distributed across 40 years (using the MSLP). After that, we detect the same 500 instances manually and compare the results with those from the ESSD method. Table 2 shows the annual distribution of the random sampled times of detecting ECs. The accuracy rate of the manually detected ECs relative to the ESSD-detected ECs is shown in Figure 4. It is shown that, for different years, the ESSD method performs differently. A minimum accuracy rate of ~79% appears in 1979, and a maximum accuracy rate of ~91% occurs in both 1990 and 1999. Overall, for the 40 years, a mean accuracy rate of ~85% is reached. In contrast, the mean accuracy rate of M01 is below 80%;

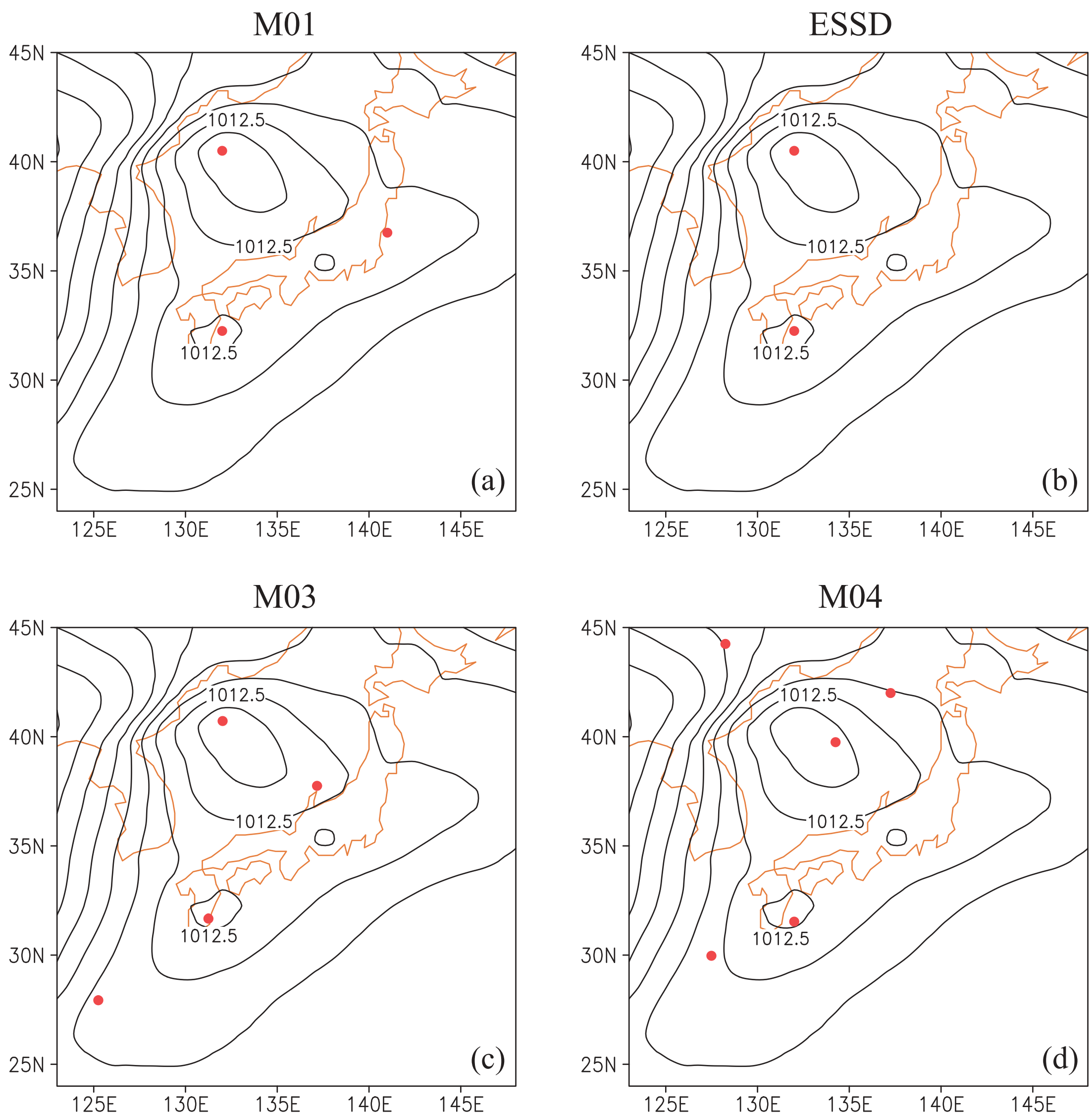

Figure 2. Results of detecting cyclones using the mean sea level pressure (MSLP) (black contours; units: hPa), where panels (a–d) show the results (red dots mark the detected cyclone centers) from the local minimum SLP method (method M01), the ESSD method, the maximum Laplacian method (method M03), and the maximum vorticity method (method M01), respectively. The applied thresholds for the local maximum Laplacian of MSLP and local maximum relative vorticity are 0.2 hPa degree^{-2} and 3×10^{-5} s^{-1}, respectively.

whereas, the mean accuracy of M03 and M04 is lower than 30%. This means the ESSD method can provide a credible EC detection result for studies on EC behavior.

4. Summary and conclusions

In this study, an EC detection algorithm—the ESSD method—which is developed to identify ECs using gridded data, is proposed. This algorithm uses the relative slopes of pressure/geopotential height within eight subregions to identify an EC. A comparison of this method with three previous traditional methods (the local minimum of MSLP/geopotential-height method, the local maximum Laplacian of MSLP/geopotential height method, and the local maximum of relative vorticity method) is conducted. The result shows that, of the four methods, the ESSD method has the lowest error rate in detecting ECs both at the surface level and the 500-hPa isobaric level. In addition, the ESSD method has a similar computational cost to that of the local minimum of MSLP/geopotential height method, both of which are obviously less than those of the other two methods. To evaluate the performance of the ESSD method more objectively, we select 500 instances in the Northern Hemisphere randomly distributed across 40 years from 1979 to 2018. Compared to the manual detection results, it is found that the ESSD method can overestimate the number of ECs (by ~15%). Overall, with the threshold of the relative slope we used in this study, the ESSD method has a mean accuracy rate of

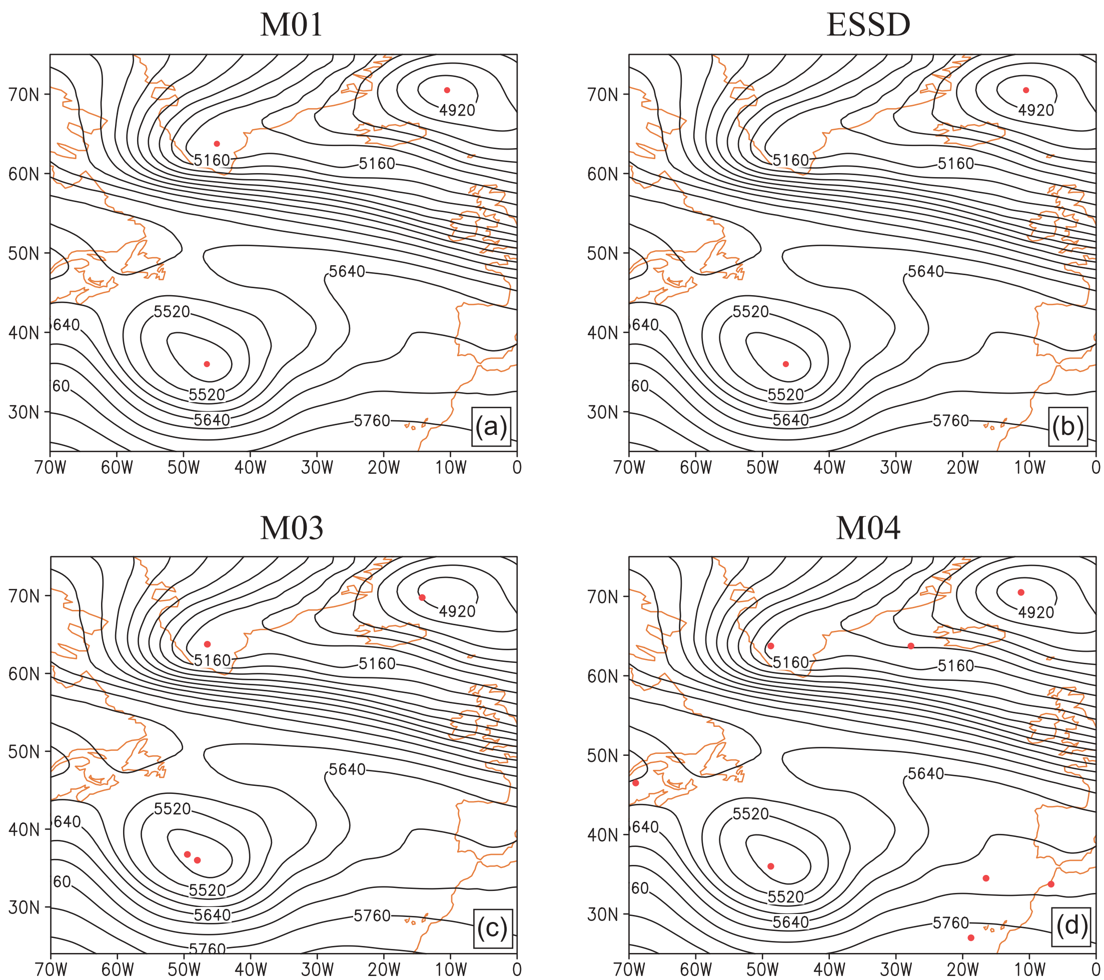

Figure 3. Results of detecting cyclones (at 500 hPa) using the geopotential height (black contours; units: gpm), where panels (a–d) show the results (red dots mark the detected cyclone centers) from the local minimum geopotential height method (M01), the ESSD method, the maximum Laplacian method (M03), and the maximum relative vorticity method (M04), respectively. The applied thresholds for the local maximum Laplacian of geopotential height and local maximum relative vorticity are 1.7 gpm degree^{-2} and 3×10^{-5} s^{-1}, respectively.

Table 1. Key information for the four detection schemes. MSLP, mean seal level pressure; GPH, gopotential height.

Methods	Main references	Variables used
M01	König, Sausen, and Sielmann (1993); Geng and Sugi (2001); Rudeva and Gulev (2007)	MSLP (surface), GPH (pressure levels)
ESSD	–	MSLP (surface) GPH (pressure levels)
M03	Murray and Simmonds (1991); Simmonds and Keay (2000); Lim and Simmonds (2007)	Laplacian of MSLP (surface), Laplacian of GPH (pressure levels)
M04	Zhao and Fu (2007); Flaounas et al. (2014)	Relative vorticity of 850 hPa (surface), Relative vorticity (pressure levels)

~85% in EC detection (which is appreciably larger than all the other three methods), with a minimum accuracy rate of ~79% occurring in 1979. Since the domain size and threshold S of the ESSD method can be adjusted iteratively

Table 2. Annual number distribution of the random sampled times for cyclone detection.

Year	Number of times for detection	Year	Number of times for detection
1979	9	1999	16
1980	9	2000	8
1981	13	2001	5
1982	17	2002	16
1983	16	2003	14
1984	8	2004	10
1985	10	2005	11
1986	12	2006	18
1987	12	2007	14
1988	14	2008	11
1989	12	2009	11
1990	15	2010	11
1991	11	2011	5
1992	15	2012	13
1993	10	2013	12
1994	12	2014	20
1995	12	2015	11
1996	13	2016	10
1997	10	2017	18
1998	20	2018	16

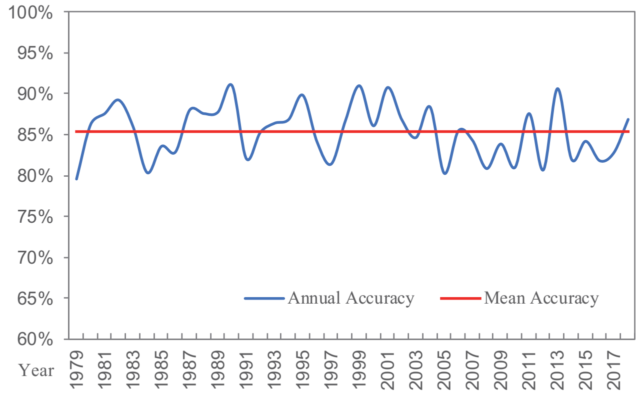

Figure 4. Accuracy rate of the manually detected cyclones in the Northern Hemisphere relative to the ESSD-detected cyclones (blue solid line; units: %) during a 40-yr period, and their total mean accuracy rate (red solid line; units: %).

using valid detected cyclones, the accuracy rate of the ESSD method can still be improved.

Disclosure statement

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