Assessing the Reliability of Global Monsoon Low Pressure System Track Datasets for the East Asian Monsoon

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Research Article

Keywords: monsoon low pressure system track datasets, regions affected by East Asian monsoon, reliability

Posted Date: December 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-999669/v1>

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Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on February 17th, 2022. See the published version at <https://doi.org/10.1007/s00704-022-03980-2>.

Abstract

Limited by the lack of atmospheric observation data over the ocean and the absence of a comprehensive set of track data for monsoon low pressure systems (MLPSs), an in-depth understanding of the activity of East Asian MLPSs has not been acquired. In recent years, advancements in satellite remote sensing and data assimilation techniques have enabled the creation of numerous high-resolution global reanalysis datasets. Additionally, with the improvement of tracking algorithms, two sets of global MLPS track data (HB2015 and VB2020) have been published. This study seeks to understand the fidelity of the two datasets with respect to the East Asian monsoon. The genesis location, movement path, and three-dimensional structure of the East Asian MLPSs obtained using HB2015 and VB2020 are compared, and the atmospheric circulation conditions of typical MLPSs are analyzed. The results show that both datasets are able to generate MLPSs with identical structure for the East Asian Monsoon, and they provide similar results in terms of the location and monthly frequency. Compared to the HB2015, the VB2020 adopts a more stringent set of thresholds for the determination of the MLPS genesis and extinction and a more rigorous tracking algorithm. Therefore, it yields a lower count of MLPSs with significantly shorter lifetimes. However, the MLPSs identified by the VB2020 all have cyclonic circulations in the proximity of their central areas as they continue their movement. In this sense, the results generated by the VB2020 are more consistent with the observed MLPSs and hence are more reliable. However, the tracking can end prematurely with this dataset.

1 Introduction

Tropical monsoon low pressure systems (MLPSs) are synoptic-scale weather systems formed by tropical circulations. Depending on the mean sea level pressure anomaly and the maximum wind speed near their centers, MLPSs are classified into three types with different intensities: monsoon lows, monsoon depressions, and deep depressions. Monsoon depressions are MLPSs with maximum wind speeds of $8.5\text{--}13.5\text{ ms}^{-1}$ and mean sea level pressure anomalies of $4\text{--}8\text{ hPa}$ near the center of the monsoon's activity (IMD, 2003). Early studies of MLPSs were mainly performed in regions affected by the Indian monsoon because the Indian MLPSs often form north of the Bay of Bengal and constitute the main weather system affecting the precipitation in India, and it frequently causes serious floods (Frank, 1970; Reed et al., 1977). The Indian Meteorological Department (IMD) places great importance on MLPSs and has established long-term track observation records spanning over 100 years (Sikka, 2006; India Meteorological Department, 2011). Many scholars have studied the Indian MLPSs and have systematically determined their structures, energy distributions, and genesis mechanisms (Daggupaty and Sikka, 1977; Godbole, 1977; Shukla, 1978; Chen et al., 2005; Boos et al., 2015; Hunt and Parker, 2016; Diaz and Boos, 2019). In fact, in addition to the regions affected by the Indian monsoon, MLPSs occur in West Africa, Australia, the Southwest Indian Ocean, and East Asia. These depressions play an important role in local weather and climate (Yoon and Chen, 2005; Berry et al., 2012). China is located in the southeastern part of Asia and is jointly influenced by the East Asian and South Asian monsoon circulations. Thus, the East Asian monsoon depressions (EAMDs) are important weather systems that

affect the precipitation in Southern China. However, although more research attention has been directed to tropical cyclones because of their greater strength, not many studies have been conducted on the EAMDs, and long-term observations and records of track data, such as those available for the Indian MLPSs, have not been established. In the 1980s and 1990s, the South China Sea monsoon depressions caused severe damage in South China. Chinese meteorologists conducted preliminary studies of this type of weather system, but they mostly focused on the development processes of specific depressions (Feng, 1980; Rong et al., 1985; Liang and Liu, 1988, 1989; Jiang et al., 2008). Liang et al. (1985, 1993) used the *Tropical Cyclone Yearbook* and historical weather maps to manually identify and compile over ten years of data for the South China Sea monsoon depressions, and they performed statistical analysis of these data. Their results indicate an average formation of about four depressions per year, which have an approximate lifetime of 3 days and complex movement paths. Overall, the data used in these studies cover only a short period of time and include only a handful of monsoon depressions, potentially undermining the conclusions of these studies.

In recent years, with the emergence of high-resolution reanalysis datasets and the development of tracking algorithms, some scholars have carried out research on the construction of new track datasets for MLPSs. With the 850 hPa relative vorticity as a variable, Hurley and Boos (2015) used the ERA-Interim reanalysis dataset and the TRACK algorithm (Hodges, 1994, 1995) to establish an MLPS track dataset (HB2015). They compared their results with previous results obtained for Indian MLPSs (Godbole, 1977; Sikka, 2006; Krishnamurthy and Ajayamohan, 2010) and West African MLPSs (Thorncroft and Hodges, 2001). Although differences were found in terms of the genesis location and average track length, the HB2015 provided an accurate description on the structure of the Indian MLPSs and was deemed highly reliable. Hu et al. (2019) used the HB2015 to discuss the climate characteristics of the EAMDs in detail and reached interesting conclusions. Recently, Vishnu and Boos (2020) used the optimized TempestExtremes tracking algorithm (Ullrich and Zarzycki, 2017), and with the stream function of the 850 hPa horizontal wind as a variable, they optimized the identification thresholds of MLPSs and established a new set of MLPS track data (VB2020). The matching degree between this dataset and the long-term observation records of Indian MLPSs (Sikka, 2006) was evaluated based on the critical success index (Di Luca et al., 2015). It was found that in regions affected by the Indian monsoon, better results were obtained using the 850 hPa stream function as the variable than using the 850 hPa relative vorticity. The genesis locations, numbers, and track lengths of the MLPSs obtained were also fairly consistent with the observations. However, the lifetime of the MLPSs identified using the VB2020 was longer.

In conclusion, the credibilities of both the HB2015 and VB2020 with respect to the Indian monsoon have been confirmed. However, due to the lack of long-term observation data for East Asian MLPSs, the reliability of these datasets for the East Asian monsoon has not been established, which leads to questions regarding the results for EAMDs obtained using these datasets. In this study, the EAMDs identified using the VB2020 were compared with the results obtained by Hu et al. (2019) in order to understand the similarities and differences in their genesis locations, movement paths, and three-dimensional structures. The atmospheric circulation conditions of the typical depressions were also analyzed to assess the agreement between the identified EAMD and the observations. In this way, a clear

understanding of the credibility of the two MLPS track datasets (HB2015 and VB2020) for the East Asian monsoon was obtained.

2 Data And Methods

2.1 Data

(1) The ERA-interim high-resolution reanalysis data for 1979–2018 have a spatial resolution of $0.75^{\circ} \times 0.75^{\circ}$ and a time step of 6 hours. The following elements are included: horizontal wind speed, relative vorticity, vertical velocity, temperature, potential vorticity, divergence, and specific humidity.

(2) The HB2015 MLPS track dataset obtained from <http://worldmonsoons.org/global-monsoon-disturbance-track-dataset/> has a spatial resolution of $0.7^{\circ} \times 0.7^{\circ}$ and a time step of 6 hours;

(3) The VB2020 MLPS track dataset obtained from <https://zenodo.org/record/3890646> has a spatial resolution of $0.75^{\circ} \times 0.75^{\circ}$ and a time step of 6 hours.

2.2 Comparison of the MLPS identification and tracking methods of two datasets

Both the HB2015 and VB2020 use ERA-Interim reanalysis as their source data. Other than this similarity, great differences exist in the MLPS identification criteria, tracking algorithms, and intensity classifications of the two datasets. In this sense, they are two sets of completely different MLPS track data.

The HB2015 uses the automated TRACK algorithm (Hodges, 1995, 1999), in which the 850 hPa relative vorticity is used as the variable. The extremum in the 850 hPa relative vorticity with a value of greater than $0.5 \times 10^{-5} \text{ s}^{-1}$ is identified as the MLPS center. The movement path of the MLPS is tracked by minimizing the cost function of its center along its velocity and movement direction using reanalysis data with a 6 h time step. In contrast, the VB2020 employs the TempestExtremes tracking algorithm (Ullrich and Zarzycki, 2017). The 850 hPa stream function is used as a variable, and its minima are identified as candidate MLPS centers. For each candidate center, the existence of a closed contour in the stream function is tested within a radius of a 10° great-circle distance, and the magnitude of this closed contour must exceed the minimum at the center by at least $12.5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$. An MLPS is present if this criterion is fulfilled. After confirming the MLPS's existence, tracking is performed using reanalysis data with a 6 h time step. To do this, new candidate points are searched at each time point using the same criteria within a 3° great-circle distance from of the previous center. If no candidate point meeting the criteria is found within 12 h, the tracking is considered to be complete. Two additional conditions are included in the VB2020. (1) An average value of 85% is used for the 850 hPa relative humidity within a 3° great circle distance from the MLPS center; and (2) this value is maintained for at least 24 h in order to eliminate thermal lows.

A second difference exists in the intensity classification of the MLPS used by the two datasets. The HB2015 classifies MLPSs into different intensity categories based on the maximum sea level pressure anomaly (relative to the 21-day moving average) and the maximum surface wind speed within 500 km of the MLPS's center. The VB2020 use the same criteria for the intensity classification, but it defines them differently. The pressure difference between the MLPS center and the closed contour of the sea level pressure field within a 3° great-circle distance from the center and the maximum surface wind speed both need to fall within a prescribed value range (4–10 hPa for the sea level pressure anomaly, and 8.5–13.5 m s⁻¹ for the maximum surface wind speed). These conditions need to last for at least 6 h. The HB2015 uses the maximum average summer temperature at 850 hPa to define the regions affected by the MLPS, and it continues to track the MLPS after it has moved out of the affected zone while no longer considering its intensity changes. The VB2020 limits the range of the MLPS activity to 35°S–35°N, beyond which tracking is not performed.

2.3 Analyzing MLPSs via dynamic synthesis

Monsoon depressions are dynamic systems formed by atmospheric circulations, and they have their own circulation structures. For the different monsoon depressions sampled and any particular monsoon depression at different time points, the longitude and latitude of the circulation center will change with the position of the system. Hence, the dynamic synthesis of the depression center as a reference point is used for the analysis. In this method, the position of the monsoon depression's center at each time point is taken as moving coordinates and as the center of the dynamic region. The sample average value of a physical quantity is computed at specific time points and coordinates within a region.

3 Results And Analysis

3.1 Comparison of climate characteristics and synthesized three-dimensional structures

Following Hu et al. (2019), the 0–20°N, 100–160°E region was defined as the active zone of the East Asian tropical monsoon. The MLPSs passing through this region (with at least one point in its track point falling in this zone) were defined as East Asian MLPSs. East Asian MLPSs with different intensities were selected from the VB2020 for May–October 1979–2018. Figure 1 shows the density distribution of the different intensities of the MLPSs formed. The monsoon lows formed were evenly distributed in the South China Sea and Pacific region, with areas of higher distribution density found in the south and close to the Equator (Figure 1a). The monsoon depressions were mainly formed in the South China Sea region, but a small number were formed in the Northwest Pacific region. Compared to monsoon lows, they are generally formed farther to the north (Figure 1b). The formation density of the deep depressions was similar to that of the monsoon depressions in the north-south direction, but the former was more concentrated in the Northwest Pacific region than in the South China Sea (Figure 1c). The above density distribution pattern for the MLPSs formed agrees with the results obtained from the HB2015 (Hu et al., 2019).

The VB2020 identified 267 EAMDs during the 40-year period from 1979 to 2018, while the HB2015 identified 313 during the 34-year period from 1979 to 2012. A significantly higher number of monsoon depressions was identified using the HB2015. This could be due to two reasons. (1) A more stringent set of identification criteria is adopted by the VB2020, resulting in some monsoon depressions not being identified using this dataset. (2) The change in the MLPS classification standard causes some systems classified as monsoon depressions by the HB2015 to be labeled as monsoon lows or deep depressions by the VB2020. As is indicated by the monthly count of the EAMDs formed in May–October identified by the VB2020 (Figure 2), fewer monsoon depressions formed in May–June than in July–October. This is consistent with the results of Hu et al. (2019). The lifetimes of the East Asian MLPSs with different intensities identified by the VB2020 were also statistically analyzed (Figure 3). The results show that most of the EAMDs had lifetimes of 3–9 days, with an average of about 6 days. This deviates significantly from the 10-day average lifetime given by the HB2015 (Hu et al., 2019). This may be due to the inclusion of closed contours as one of the identification criteria of the VB2020, which causes the identified monsoon depression's genesis to lag behind. The VB2020 also limits the activity of the monsoon depressions to the 35°S–35°N zone. This may lead to an early ending of the monsoon depressions identified. These two factors together result in the shorter lifetimes of the monsoon depressions identified by the VB2020.

The movement paths of all 267 EAMDs identified by the VB2020 for May–October 1979–2018 were analyzed (Figure 4). Most of the monsoon depressions moved westward. Some of them were not able to move onto land and were extinguished at sea right after they were formed there. Those that eventually reached land had an impact on Southern China and the Indochina Peninsula. A few very exceptional ones reached India after passing over the Indochina Peninsula and the Bay of Bengal. Because of the limitations imposed by the VB2020 regarding the region where MLPSs can occur (35°S–35°N), the northernmost point reached by the EAMDs in their movement paths was only around 35°N (Figure 4), while the monsoon depressions identified by the HB2015 reached as far north as 50°N (Hu et al., 2019). This could lead to the premature ending of the tracking in the VB2020 and could also be one of the reasons for the shorter movement paths and lifetimes of the EAMDs identified by the VB2020. Using the classification standard of Hu et al. (2019) for the movement paths of EMADs, the paths of such systems generated by the VB2020 were classified. Compared to the results given by the HB2015, a significantly higher number of depressions identified by the VB2020 exhibited westward movement, with fewer following other movement paths. A large decrease in the number of eastward moving depressions (EMD) and those that changed direction (CDD) was observed. The number of depressions with unclassified paths (UCD) also increased (Table 1). The primary reason for this is the shorter movement paths of the EAMDs generated by the VB2020. Some systems did not meet the classification standard because of their short movement paths, and some of the northwestward moving depressions (NWMD) and those that changed direction were categorized as westward moving depressions (WMD) because their movement paths were cut off in the middle.

Table 1
Comparison of the numbers of EAMDs with different movement paths

	EMD	WMD	NWMD	CDD	UCD
VB2020	4	97	33	18	115
HB2015	32	64	51	53	60

Dynamic synthesis was performed on the EAMDs identified by the VB2020. The synthesized vertical structures of the monsoon depressions were obtained (Figure 5). As is shown in Figure 5, the relative vorticity is symmetrically distributed about the central axis of the monsoon depressions, with almost no skew. The positive vorticity extends upward to 200 hPa, and the maximum vorticity occurs at 850 hPa. The specific humidity exhibits a positive anomaly above the centers of the EAMDs, with the maximum occurring at 700–800 hPa (left column in Figure 5). The temperature increases with the geopotential height, with a warm zone above 850 hPa and a cold zone below. The center of the warm zone is located at 400 hPa, and that of the cold zone is located near the ground. The center of the relative vorticity is located at the intersection of the cold and warm zone. Two zones with large potential vorticities are present in the potential vorticity field. The one near 500 hPa is the strongest, and it is located below the center of the warm zone. The potential vorticity at 750 hPa is the second strongest (middle column in Figure 5). These results are consistent with those obtained by Hu et al. (2019) using the HB2015. The divergence field shows convergence in the lower level and divergence in the upper level. The convergence center is located at 950 hPa, and the divergence center is located at 150 hPa. This is different from the conclusions of Hu et al. (2019); that is, the convergence center is symmetrical about the depression center. The convergence centers of the EAMDs generated by the VB2020 are located to the southwest of the depressions' centers. Vertical upward movement primarily occurs in the depression center, while weak subsidence occurs around it, which is consistent with the divergence field. The maximum upward movement also occurs to the southwest of the depression's center (right column in Figure 5). This is different from the symmetry in vertical motion the about the depression center observed by Hu et al (2019).

The above comparisons show that the EAMDs identified by the two sets of MLPS track data share similarities in many aspects, such as their genesis locations, counts, movement paths, and synthesized three-dimensional structures. However, differences also occur, and they are likely to affect their credibility when the two datasets are applied to the East Asian tropical monsoon. To validate their credibility and understand the causes of any possible differences, further comparison and analysis are needed.

3.2 Case study of a typical year

Figure 6 shows the annual variation in the cumulative number of EAMDs during May–October generated by the HB2015 and VB2020. Substantial differences were observed in the annual variations in the numbers of EAMDs given by the HB2015 and VB2020. The HB2015 generally gives a higher number of monsoon depressions than the VB2020, and the difference is quite large for some years. As can be seen

from Figure 6, the number of EAMDs identified by the HB2015 was the highest in 1986 and 1992 (14 depressions). For the VB2020, the numbers of EAMDs in these two years were 9 and 5, respectively. To ensure a sufficient number of cases was used, 1986 was chosen as the typical year for the comparative analysis of the EAMDs.

Figure 7 shows the genesis locations of the EAMDs given by both datasets for 1986. Similar patterns were found in the genesis location distributions of the monsoon depressions identified using both datasets. The EAMDs mainly formed over the South China Sea and the tropical West Pacific, with scattered occurrences along the east coast of the Bay of Bengal. Figure 8 shows the movement paths of the EAMDs given by the two datasets for 1986. After careful comparison, the paths of 8 depressions were found to overlap to some degree (depressions 1–8 in Table 2). However, their paths were not entirely identical. In most cases, the movement paths of the monsoon depressions identified by the HB2015 were longer than those identified by the VB2020. For the other 6 monsoon depressions identified by the HB2015 (depressions 9–14 in Table 2), some were classified as other types of MLPSs (2 lows and 1 deep depression) by the VB2020, and the others were not classified (3 systems). The remaining one monsoon depression identified by the VB2020 (#15 in Table 2) was classified as a monsoon low by the HB2015. In terms of the lifetimes of the EAMDs in 1986, the average lifetime given by the HB2015 was 10.54 days, while that given by the VB2020 was 6.75 days. This is consistent with the results obtained in the previous section on EAMDs during the entire study period.

Table 2
Comparison of the EAMDs generated by the two datasets for 1986 (shown in Universal Time)

No.	HB2015			VB2020		
	Start time	End time	Path	Start time	End time	Path
1	00Z05May	12Z15May	EMD	06Z08May	12Z10May	UCD
2	12Z17May	12Z29May	EMD	12Z15May	18Z27May	CDD
3	18Z30Jul	18Z03Aug	UCD	06Z30Jul	12Z03Aug	CDD
4	18Z05Aug	12Z14Aug	UCD	06Z08Aug	06Z12Aug	WMD
5	06Z16Aug	00Z02Sep	CDD	18Z17Aug	06Z26Aug	UCD
6	18Z11Sep	12Z23Sep	WMD	06Z20Sep	00Z23Sep	UCD
7	06Z02Oct	18Z08Oct	CDD	18Z27Sep	00Z07Oct	NWMD
8	06Z11Oct	00Z25Oct	NWMD	18Z13Oct	12Z23Oct	NWMD
9	06Z25Jun	12Z04Jul	CDD			
10	18Z08Jul	06Z14Jul	WMD			
11	12Z09Jul	18Z27Jul	UCD			
12	18Z11Jul	12Z24Jul	CDD			
13	18Z08Aug	12Z13Aug	UCD			
14	18Z13Oct	12Z23Oct	CDD			
15				18Z03Oct	12Z09Oct	WMD

The movement paths of the monsoon depressions in East Asia are rather complex. The movement paths of the monsoon depressions identified by the VB2020 and HB2015 were classified using the standard of Hu (2019). As can be seen from Table 2, large differences occur in the movement paths of the EAMDs identified by the two datasets. To understand the causes of these differences and to determine the reliabilities of both datasets, the relative vorticity, stream function, and wind field at 850 hPa were compared and analyzed for the EAMDs identified by the two datasets at different times in 1986 along the movement paths of the depressions.

Two eastward moving monsoon depressions (#1–2) identified by the HB2015 are presented in Table 2, while the VB2020 did not identify any eastward moving monsoon depressions. Through careful comparison, it was found that monsoon depression 1 formed at 00:00, May 5 (Universal Time, same below) according to the HB2015. This depression overlaps with the one formed at 06:00, May 8 according to the VB2020. Figure 9a shows the relative vorticity and stream function at 850 hPa for the monsoon depressions identified by the HB2015 at the time of their genesis (00:00, May 5). The identified

depression center (blue dot) is located in a zone of high relative vorticity and exceeds the specified threshold ($0.5 \times 10^{-5} \text{ s}^{-1}$). Although closed stream function contours can be observed near the center, this system does not meet the classification criteria of the VB2020 for eastward moving depressions. Distinguishable cyclonic circulations are also absent near the depression's center in the 850 hPa flow field at the same time point (Figure 9b). At 06:00, May 8 (Figure 9c), the monsoon depression was identified by the VB2020. At this time, the locations of the depression centers generated by the two datasets were slightly different, but nevertheless they were both located in the zone of high relative vorticity and the area enclosed by the closed stream function contours. Concurrently, discernable cyclonic circulations appeared at the depression centers (Figure 9d). The monsoon depression identified by the VB2020 only lasted for a short period of time, and its movement was essentially northward. Hence, it did not meet the criteria for an eastward moving depression. This depression reached the Indochina Peninsula at the end of its movement (Figure 9e, 06:00, May 10), and cyclonic circulations were still observed (Figure 9f). Figure 9g shows the relative vorticity and stream function at one time step (12:00, May 10) after the end of the monsoon depression's movement identified by the VB2020. The relative vorticity near the center of the depression identified by the HB2015 still met the identification criteria, but the stream function around it no longer exhibited closed contours. In the corresponding 850 hPa flow field, the closed circulations had transformed to a trough (Figure 9h).

Another monsoon depression identified as eastward moving by the HB2015 (#2 in Table 2) was determined to have undergone changes in its path direction by the VB2020. Compared to the HB2015, the VB2020 gave an earlier genesis time for this depression. This monsoon depression formed in the Northwest Pacific monsoon trough. Initially, the West Pacific subtropical high (WPSH) strengthened and extended westward, and this depression moved to the west with the easterly flow present to the south of the WPSH and increased its strength. Later, when the WPSH weakened and retreated to the east, this depression shifted northeastward with the Southwest Monsoon. The cyclonic circulations eventually weakened and dissipated, but the vorticity was maintained at a value above the threshold of the HB2015. In addition, the path of this depression ended early in the VB2020 (figure not included). The other six monsoon depressions with overlapping paths (#3–8 in Table 2) all formed in July–October (the paths of the depressions generated by both datasets for June do not overlap) in the South China Sea and Northwest Pacific region. Depressions 3–5 formed in the Northwest Pacific monsoon trough during July–August. Depression 3 had a short lifetime, which is consistent across both datasets. Its movement paths given by the two datasets are also identical. It is labeled as unclassified by the HB2015 and as having experienced direction changes by the VB2020. The VB2020 recognized its genesis 12 h before the HB2015 did, while both datasets recognized its extinction simultaneously. The tracking of depressions 4–5 started earlier and ended later in the HB2015 than in the VB2020. The paths of the depressions given by the VB2020 coincide with those given by the HB2015 when the depressions were strong. Figure 10 shows the movement path of depression 5 in mid-August and its circulation conditions at typical times. As is shown in Figure 9, errors exist in the identification of the monsoon depression's genesis by the HB2015, i.e., the relative vorticity near the center reaches the threshold, but a closed center is not present in the stream function (Figure 10a), nor are cyclonic circulations present as is the case for actual monsoon

depressions (Figure 10b). The monsoon depressions identified by the VB2020 all feature centers with closed stream function contours around them at their genesis (Figure 10c) and extinction (Figure 10e). Clear cyclonic circulations were also found in the 850 hPa wind field (Figures 10d, f). At the conclusion of tracking in the VB2020, the depression centers tracked by the HB2015 no longer have closed stream function contours in their proximity (Figure 10g), and the cyclonic circulations in the 850 hPa wind field are also dissipating (Figure 10h).

Depressions 6–8 all formed in the tropical West Pacific region. They were generated to the south of the WPSH in September–October. In this case, the tracking again started earlier and ended later for the HB2015 than the VB2020. Figure 11 shows the evolution of a unique monsoon depression (#7 in Table 2). It is labeled as northward moving (green line) by the VB2020 and as two separate MLPSs by the HB2015: a monsoon low (purple curve) in the early stage and a depression with a path direction change (blue line) in the late stage. At 18:00 on September 27 (Figures 11a, b), the system was recognized by the VB2020 as a monsoon depression, with its center (green dot) located in a zone of relatively high vorticity and surrounded by closed stream function contours. In the 850 hPa wind field, cyclonic circulations were also observed in the vicinity of the depression center. In this stage, the depression center and its subsequent movement path corresponded to a monsoon low (purple line) identified by the HB2015 earlier. In addition, at the time of the monsoon low's genesis as identified by the HB2015, no closed circulation was present at the center in the 850 hPa wind field. Thus, this monsoon low could be a misidentification by the HB2015. Figure 11c shows the distribution of the relative vorticity and the stream function at the onset of the monsoon depression tracking by the HB2015. Compared to Figures 11a and b, the depression had increased in intensity, and the cyclonic circulations at its center had become more prominent (Figure 11d). By comparing the distribution of the relative vorticity and the stream function at 850 hPa at the conclusion of the depression tracking by the VB2020 (Figure 11e) with those one time step (6hr) later (Figure 11g), it was found that this dataset sometimes fails to give a full accounting of the depression's movement path. This could be due to the sudden acceleration in the depression's movement. The distance traveled by the depression in the northward direction in 6 h exceeded the limiting condition set forth in the search for the next candidate point by the VB2020, i.e., within a 3° great-circle distance of the depression center. The fact that the cyclonic circulations were maintained and strengthened at the center of the 850 hPa wind field also confirms the on-going presence of the monsoon depression (Figures 11f, h).

In addition to the above monsoon depressions with overlapping centers and paths, several MLPSs were identified by both the HB2015 and VB2020, but were classified into different intensity categories. For example, two systems identified by the HB2015 as monsoon depressions (#9 and 10 in Table 2) were labeled as lows by the VB2020, and one depression (#13 in Table 2) was labeled as a deep depression. A system identified by the VB2020 as a monsoon depression (#15 in Table 2) was categorized as a monsoon low by the HB2015. This is largely due to the differences in the methods adopted by both datasets for calculating the mean sea level pressure anomaly in their classification of the MLPS intensity. The HB2015 uses the maximum sea level pressure anomaly within 500 km of the MLPS's center (relative to the 21-day moving average), which is a comparison made with respect to time. In the VB2020, the sea

level pressure anomaly is defined as the pressure difference between the MLPS's center and the closed contour of the sea level pressure field within a 3° great-circle distance from the center, which is a comparison made with respect to space. Sometimes large differences occurred between the two methods. For example, at 12:00 on June 29, 1986, depression 9 in Table 2 has developed to its highest strength. The sea level pressure anomaly in the vicinity of the MLPS's center was above 5 hPa, and this system was identified as a monsoon depression by the HB2015 (Figure 12a). However, the sea level pressure anomaly within a 3° great-circle distance from the MLPS's center was less than 3 hPa and did not meet the criteria for a depression. Thus, it was classified as a monsoon low by the VB2020 (Figure 12b). In addition, three systems (11, 12, and 14 in Table 2) identified as monsoon depressions by the HB2015 failed to be classified by the VB2020. This is primarily because the stream function did not form a closed contour or the closed contour formed outside of the latitude range specified in the VB2020, i.e., the MLPS's center was at a latitude of >35°N (figure not included).

In the above comparisons of the monsoon depressions that occurred in 1986, it was found that the monsoon depressions identified by the HB2015 had longer lifetimes and movement paths than those identified by the VB2020. There are two main reasons for this. (1) The HB2015 used a less scrutinized set of conditions to identify monsoon depression formation, and it sometimes identifies a trough as an MLPS when the cyclonic circulations have yet to form. This leads to early onset of the tracking. (2) The HB2015 often cannot make an accurate judgement as to whether an MLPS has weakened to a trough. This results in a late ending of the tracking in the HB2015 compared to the VB2020. Generally speaking, the VB2020 uses a stricter set of identification criteria for MLPS genesis and extinction and a more rigorous tracking algorithm. The monsoon depressions identified are almost guaranteed to have cyclonic circulations near their centers as they continue their movement, which is a feature observed in actual monsoon depressions. In this sense, the VB2020 is a more reliable dataset. However, the tracking performed with this dataset sometimes ends prematurely.

4 Discussion And Conclusions

EAMDs are one of the most important weather systems driving summer precipitation in East Asia. These systems are weaker than typhoons and do not have as large an impact. They receive less attention as a research topic. Due to the absence of long-term observation records on MLPS paths, previous studies have mostly involved case-by-case analysis. Thus, our understanding of EAMDs is far from comprehensive and systematic. In recent years, the emergence of high-resolution reanalysis datasets and the development of tracking algorithms have made the establishment of MLPS track datasets such as the HB2015 and VB2020 possible. Comparison of the results yielded by these datasets with the long-term observation data for Indian monsoon depressions confirms their reliability with respect to the Indian monsoon, but their reliability regarding the East Asian monsoon needs to be validated. In this study, the genesis locations, movement paths, and three-dimensional structures of the EAMDs generated by the HB2015 and VB2020 were compared and the atmospheric circulation conditions of typical depressions were analyzed in order to gain a clear understanding of the credibility of these datasets with respect to the East Asian monsoon.

Based on the results of this study, the VB2020 identified 267 EAMDs during May–October 1979–2018. Most of these depressions formed in the South China Sea and the West Pacific region in July–October, with an average lifetime of around 6 days. Their genesis locations and monthly genesis frequencies exhibit the same variations as those identified by the HB2015, but the total number of monsoon depressions identified by the VB2020 was significantly lower, and their lifetimes were significantly shorter. In terms of their movement path directions, a larger number of EAMDs were identified as westward moving by the VB2020, while the number of depressions with the other three path directions (eastward moving, northwestward moving, and with direction changes) were lower. This is particularly true for the eastward moving type and those with direction changes, and some depressions could not be classified into any type using the standard criteria. The comparison revealed that EAMDs identified by both the HB2015 and the VB2020 have identical synthesized vertical structures, except for the asymmetry in the vertical motion at the centers of the monsoon depressions identified by the VB2020. By comparing the paths and atmospheric circulation conditions of the EAMDs in 1986, two factors were found to be responsible for the longer lifetimes and movement paths of the monsoon depressions identified by the HB2015. (1) The HB2015 uses a set of more lenient conditions for the recognition of monsoon depressions. Sometimes a trough is identified as an MLPS before the cyclonic circulations have formed. This leads to early onset of the tracking. (2) The HB2015 often cannot tell if an MLPS has weakened to a trough. This leads to delayed ending of the tracking compared to the VB2020. Overall, the VB2020 uses a stricter set of criteria for the identification of MLPS genesis and extinction and a more rigorous tracking algorithm. The monsoon depressions identified all had cyclonic circulations at their centers as they continued their movement. This is consistent with the observed depressions, and thus, the VB2020 is a more reliable dataset for studying the East Asian monsoon. However, it also suffers from incomplete tracking since the tracking can end prematurely.

In the case analysis, it was also found that some of the MLPSs were identified by both the HB2015 and VB2020, but they were classified into different intensity categories. This is because the two datasets use different methods to calculate the mean sea level pressure anomaly in their classification of the MLPS intensity. The HB2015 uses the maximum sea level pressure anomaly within 500 km of the MLPS's center (relative to the 21-day moving average), which is a comparison made with respect to time. In the VB2020, sea level pressure anomaly is defined as the pressure difference between the MLPS's center and the closed contour of the sea level pressure field within a 3° great-circle distance from the center, which is a comparison made with respect to space. Sometimes large differences occurred between the two methods, and their status as the better candidate for MLPS identification and classification requires further investigation.

Declarations

Acknowledgments We thank the European Centre for Medium-Range Weather Forecasts for providing the ERA-Interim data, Dr. William R. Boos for providing global track dataset of monsoon low pressure systems (HB2015 and VB2020).

Funding This research is supported by the National Key R&D Program of China (2019YFC1510104) and the National Natural Science Foundation of China (No. 41775060)

Author contribution **Yanhong Zhang:** Data curation, Formal analysis, Visualization, Software, Writing-Original draft preparation. **Xiaohui Shi:** Conceptualization, Methodology, Writing- Reviewing and Editing. **Min Wen:** supervision.

Availability of data and material The links that can be used to download the data used in this study are <http://apps.ecmwf.int/datasets/> for ERA-Interim, <http://worldmonsoons.org/global-monsoon-disturbance-track-dataset/> for HB2015 and https://zenodo.org/record/3890646#.YWd2-8g_FCI for VB2020.

Code availability Not applicable.

Ethics approval This research did not involve human subjects. Meteorological datasets used in this study can all be obtained from publicly accessible archives.

Consent to participate This research did not involve human subjects.

Consent for publication This research did not involve personal information for which consent was to be sought.

Conflict of interest The authors declare no competing interests.

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Figures

Figure 1

Spatial distributions of the genesis locations of the East Asian (a) monsoon lows, (b) monsoon depressions, and (c) deep depressions during May-October 1979-2018.

Figure 2

Month-by-month count of EAMDs formed in May-October.

Figure 3

Lifetimes of East Asian MLPSs (unit: day).

Figure 4

Movement paths of EAMDs.

Figure 5

Vertical structures of EAMDs in the meridional (upper) and latitudinal (lower) directions showing the relative vorticity (shaded area, unit: 10^{-5} s^{-1}) and specific humidity (contour lines, unit: g kg^{-1}) (left), potential vorticity (shaded area, unit: PVU, $1 \text{ PVU} = 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$), temperature (contour lines, unit: K) (middle), divergence (shaded area, unit: 10^{-5} s^{-1}), and vertical motion (vector) (right). The red line represents the central axis passing through the centers of the EAMDs.

Figure 6

Annual variation in the cumulative number of EAMDs in May-October identified by the HB2015 (orange, 1979-2012) and the VB2020 (blue, 1979-2018).

Figure 7

Genesis locations of the EAMDs identified by the HB2015 (blue) and the VB2020 (red) in May-October 1986.

Figure 8

Movement paths of the EAMDs identified by the HB2015 (blue) and the VB2020 (red) in May-October 1986.

Figure 9

Movement paths of EAMD #1 identified by the HB2015 (blue line) and the VB2020 (green line) showing the 850 hPa relative vorticity (shaded areas, only showing regions with a relative vorticity of >0.5 , unit: 10^{-5} s^{-1}) and stream function (contour lines, spacing: 20, unit: $10^5 \text{ m}^2 \text{ s}^{-1}$) at typical time points (left column) and the 850 hPa wind field within 15° latitude and longitude of the depression's center (dot) (right column, unit: m s^{-1}). (a, b) At the time of depression formation identified by the HB2015; (c, e) at

the time of depression formation identified by the VB2020; (e, f) at the time of depression extinction identified by the VB2020; and (f, h) one time step after the depression extinction identified by the VB2020.

Figure 10

Movement paths of EAMD #5 identified by the HB2015 (blue line) and the VB2020 (green line) showing the 850 hPa relative vorticity (shaded areas, only showing regions with a relative vorticity of >0.5 , unit: 10^{-5} s^{-1}):

10–5 s^{–1}) and stream function (contour lines, spacing: 20, unit: 10⁵ m² s^{–1}) at typical time points (left column) and the 850 hPa wind field within 15° latitude and longitude of the depression's center (dot) (right column, unit: m s^{–1}). (a, b) At the time of depression formation identified by the HB2015; (c, e) at the time of depression formation identified by the VB2020; (e, f) at the time of depression extinction identified by the VB2020; and (f, h) one time step after the depression extinction identified by the VB2020.

Figure 11

Movement paths of EAMD #7 identified by the HB2015 (blue line) and the VB2020 (green line) showing the 850 hPa relative vorticity (shaded areas, only showing regions with a relative vorticity of >0.5 , unit: 10^{-5} s^{-1}) and stream function (contour lines, spacing: 20, unit: $10^5 \text{ m}^2 \text{ s}^{-1}$) at typical time points (left column) and the 850 hPa wind field within 15° latitude and longitude of the depression's center (dot) (right column, unit: m s^{-1}). (a, b) At the time of depression formation identified by the VB2020; (c, e) at the time of depression formation identified by the HB2015; (e, f) at the time of depression extinction identified by the VB2020; (f, h) one time step after the depression extinction identified by the VB2020.

Figure 12

Mean sea level pressure anomaly near the MLPS's center calculated by (a) the HB2015 and (b) the VB2020 at 12:00 on June 29, 1986 (unit: hPa).