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Key Points:
- Efficiency of NCEP-FNL and ERA-interim data sets in describing the Tibetan Plateau vortices are evaluated.
- Both NCEP-FNL and ERA-interim show good skills in presenting the characteristics of Tibetan Plateau vortices.
- Generally, NCEP-FNL performs better than ERA-interim, though with some caveats.

Evaluation of NCEP-FNL and ERA-Interim Data Sets in Detecting Tibetan Plateau Vortices in May–August of 2000–2015

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Abstract	Tibetan Plateau vortices (TPVs) are important rainfall triggers in southwestern and eastern China after they move off the plateau. Characteristics of the moving-off TPVs derived from two gridded data sets, the final operational global analysis data from the Global Forecasting System of National Centers for Environment Prediction (NCEP-FNL) and the ERA-interim data from the European Centre for Medium-Range Weather Forecasts, are evaluated against the Yearbooks of Tibetan Plateau Vortex and Shear Line (YB). Generally, NCEP-FNL captures more moving-off TPVs in YB than ERA-interim does. Both gridded data sets perform the best in capturing the TPVs in YB in May and the worst in July. Zonal propagation distances of TPVs are apparently better revealed in NCEP-FNL than in ERA-interim, and the performances of NCEP-FNL and ERA-interim in showing the meridional propagation distances and lifespans are similar. Positional deviations of TPVs in NCEP-FNL and ERA-interim reveal that both data sets show good skills in presenting the TPVs locations, and NCEP-FNL generally performs better than ERA-interim. In both gridded data sets, positional deviations of TPVs are larger before the TPVs move off the plateau than after moving off, and zonal deviations are always larger than meridional deviations. Before the TPVs move off, NCEP-FNL shows no specific preference for the directions of positional deviations, whereas ERA-interim tends to present further west TPVs locations relative to those in YB. After the TPVs move off, TPVs in both gridded data sets are always observed to the west and north of the TPVs in YB, which is more significant in ERA-interim.

1. Introduction

Tibetan Plateau vortices (TPVs) are primary rainfall producers over the Tibetan Plateau, leading to heavy rainfall over southwestern and eastern China when they move off the plateau (Ye & Gao, 1979). Most of the TPVs are generated over western and central Tibetan Plateau during June to August, and the occurrence frequency reaches the peak in June. Typical scales of TPVs are approximately 400–800 km horizontally and 2–3 km vertically (Feng et al., 2014; Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981; Luo, 1992; Luo et al., 1994; Ye & Gao, 1979). TPVs are shallow systems over the Tibetan Plateau, with the cyclonic circulation limited in the lower-middle troposphere. Positive vertical vorticity associated with the TPVs reaches a maximum at 500 hPa and disappears at 400 hPa (Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981; Ye & Gao, 1979). The TPVs always die out in situ or in the eastward movement, and some can move eastward and shift out of the Tibetan Plateau under certain conditions (Wang et al., 2009). The moving-off TPVs can impact not only the rainfall, but also the genesis and development of the weather systems located to the east of the Tibetan Plateau (Li, 2002; Li et al., 2017; Qiao & Zhang, 1994; Ye & Gao, 1979; Yu et al., 2015; Zhou et al., 2009).

Sounding observations over the Tibetan Plateau for detecting TPVs are mostly in 12-hr interval, except a few stations operating an intensive observation in 6-hr interval but within a very short duration. Additionally, the sounding stations are sparse, which are mainly located over the eastern Tibetan Plateau. Thus, the small number of stations and large temporal interval of sounding observations over the Tibetan Plateau make it hard to fully understand the TPVs (e.g., evolution mechanism, structure, interaction between TPVs and the other systems, etc.) by merely using sounding observations. Therefore, gridded data are unavoidable used in the research on TPVs, whose reliability is needed to be assessed. Gridded data from different
sources are evaluated over the Tibetan Plateau in previous work, especially on the surface and near-surface variables (Gao et al., 2014; Ma et al., 2008; Wang & Zeng, 2012; You et al., 2013; Zhu et al., 2012). Bao and Zhang (2013) assessed the reliability of four elements (temperature, dew point depression, wind direction, and wind speed) from four widely used gridded data sets against 11 sounding observations over the Tibetan Plateau. Nevertheless, the efficiency of gridded data in presenting the characteristics of TPVs is not involved in previous studies. Considering that the moving off TPVs have important effect on the rainfall and weather systems to the east of the Tibetan Plateau, the TPVs moving off the Tibetan Plateau are focused on in this work. The Yearbooks of Tibetan Plateau Vortex and Shear Line (YB) from the Institute of Plateau Meteorology, China Meteorological Administration (CMA) based on the observational data are taken as the standard observations of TPVs. In recent 5 years, the National Centers for Environment Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis (NCEP-NCAR), NCEP Climate Forecast System reanalysis (NCEP-CFSR), the final operational global analysis data from NCEP (NCEP-FNL), and ERA-interim from the European Centre for Medium-Range Weather Forecasts (ECWMF) are the four most frequently used gridded data sets in detecting TPVs (Chen & Gao, 2015; Curio et al., 2018; Feng et al., 2017; Guan & Li, 2019; Li et al., 2018; Lin, 2015; Liu et al., 2018; Liu & Li, 2016; Tian et al., 2015; Zhao et al., 2016), among which NCEP-FNL and ERA-interim with medium spatial resolutions are selected to be evaluated against YB in presenting moving-off TPVs in this work. However, the other two gridded data sets (NCEP-NCAR and NCEP-CFSR) are also very important in research on TPVs, and the evaluation of them is very necessary and useful, which needs further investigation in the further work. YB is so far the only published statistics data set of TPVs based on observational data; thus, understanding the difference between YB and the gridded data in describing TPVs is important and

Figure 1. Interannual (a) and monthly variations (b) of the numbers of moving-off TPVs during May–August of 2000–2015 detected by YB (black lines), NCEP-FNL (red lines), and ERA-interim (blue lines).
necessary. Besides, comparison between NCEP-FNL and ERA-interim in presenting the moving-off TPVs is beneficial for understanding the relative reliability and efficiency of these two gridded data in depicting different aspects of TPVs.

Data and method is provided in section 2. Interannual and monthly variations of the moving-off TPVs shown in YB, NCEP-FNL, and ERA-interim are explored in section 3. In section 4, the cases in YB that are captured by NCEP-FNL (ERA-interim) are selected, and the characteristics of these cases shown in NCEP-FNL (ERA-interim) are compared with those in YB. Furthermore, the moving-off TPVs commonly presented in YB, NCEP-FNL, and ERA-interim are selected, and the efficiency of NCEP-FNL and ERA-interim are further assessed against YB in section 5. Conclusion and discussion are given in section 6.

2. Data and Method

NCEP-FNL is the final operational global analysis data from the Global Forecasting System of the National Centers for Environment Prediction, and ERA-interim is reanalysis data from the ECWMF. Both NCEP-FNL and ERA-interim are collected at 6-hr intervals with global coverage, and the horizontal resolution is 1° × 1° in the former (http://rda.ucar.edu/datasets/ds083.2, ds083.2|DOI: 10.5065/D6M043C6) and approximate 0.7° × 0.7° in the latter (Dee et al., 2011). YB from the Institute of Plateau Meteorology, CMA is based on the sounding observations with 12-hr intervals, which are referred as the standard observations of TPVs. Since YB starts from 1998 and NCEP-FNL from July 1999, and the TPVs mainly occur in May–August, the research period of this work is limited in May–August of 2000–2015.

A TPV is defined as a low which forms over the Tibetan Plateau with closed contour lines or cyclonic winds at three observation stations at 500 hPa (Lhasa Workgroup for Tibetan Plateau Meteorology Research, 1981).

Figure 2. Percentages of moving-off TPVs in YB that are captured by NCEP-FNL (gray) and ERA-interim (white): (a) interannual variation, (b) monthly variation.
In this work, because there are always more than one TPV at the same time, the TPVs are identified manually despite of the heavy workload, which is more exact than automatic tracking methods in identifying and positioning a specific case. Referring to the definition given by Lhasa Workgroup for Tibetan Plateau Meteorology Research (1981), a TPV in the gridded data is defined as a low over the Tibetan Plateau with cyclonic circulation in 500 hPa winds field. A moving-off TPV is defined as a TPV that shifts out of the plateau region, where the elevation exceeds 3,000 m.

It should be noted that all the results are based on the statistics of moving-off TPVs in May–August of 2000–2015.

3. Interannual and Monthly Variations of the Moving-Off TPVs

The 104 moving-off TPVs during May–August of 2000–2015 are presented in YB, and 70 are detected in both NCEP-FNL and ERA-interim. Thus, YB shows more cases than the gridded data sets, and NCEP-FNL and ERA-interim exhibit a similar ability in revealing the number of moving-off TPVs.

Interannual variations of the number of moving-off TPVs in YB, NCEP-FNL, and ERA-interim are shown in Figure 1a. In YB, the number of moving-off TPVs in each year before 2004 is around six, and reaches a peak in 2005, with the number being nine. Only three TPVs occur in 2006, and the number increases and reaches another peak in 2008. The number of moving-off TPVs is the minimum in 2009 and remains at a high level around nine during 2010–2013, and then reduces sharply after 2013. Generally, less moving-off TPVs are detected by the two gridded data sets compared with YB except 2000, 2007, and 2008. Correlation coefficient for the numbers of moving-off TPVs between NCEP-FNL and YB is 0.46 and that between ERA-interim and YB is 0.56, which exceed the 90% and 95% confidence level, respectively. Thus, both gridded data sets can basically reflect the interannual variation of the number of moving-off TPVs, and ERA-interim coincides...
better with YB than NCEP-FNL does. Additionally, the correlation coefficient between the numbers of moving-off TPVs in NCEP-FNL and those in ERA-interim exceeds 99% confidence level, with the value of 0.81, implying that the two gridded data sets are highly consistent with each other in presenting the interannual variation of the number of moving-off TPVs.

Monthly variations of the number of moving-off TPVs in YB, NCEP-FNL, and ERA-interim are shown in Figure 1b. In YB, the number of moving-off TPVs reaches the maximum in June and the minimum in August, with the numbers being 36 and 17, respectively; more moving-off TPVs are found in July than in May. Generally, less moving-off TPVs are observed in both gridded data sets in each month compared with that in YB. However, in both NCEP-FNL and ERA-interim, the peaks of the number of moving-off TPVs are found in June and the valleys in August, coinciding well with that in YB. Specifically, the number of moving-off TPVs detected by NCEP-FNL in July is a bit larger than that in May, which is consistent with YB; on the contrast, more moving-off TPVs are found in May than in July in ERA-interim. Therefore, NCEP-FNL performs better than ERA-interim in presenting the monthly variation of the number of moving-off TPVs.

All in all, both NCEP-FNL and ERA-interim can basically reveal the interannual and monthly variations of the number of moving-off TPVs. ERA-interim performs better in reflecting the interannual variation, whereas NCEP-FNL performs better in monthly variation.

4. Moving-Off TPVs in YB Captured by Gridded Data

Percentages of the moving-off TPVs in YB that are captured by gridded data in each year are shown in Figure 2a, and those in each month during May–August are presented in Figure 2b. In 2000, 2003, 2005,
2007, 2009, 2011, and 2014, the percentages for NCEP-FNL and ERA-interim are comparable. In 2006 and 2008, more cases in YB are captured by ERA-interim than by NCEP-FNL. In the rest 7 years, percentages of the cases in YB that are captured by NCEP-FNL are obviously larger than those by ERA-interim, implying that NCEP-FNL is more efficient than ERA-interim in presenting the TPVs in YB in these 7 years. Thus, NCEP-FNL and ERA-interim show different performance in detecting the moving-off TPVs in YB, and generally, the former performs better than the latter. In Figure 2b, for both NCEP-FNL and ERA-interim, the maximums of the percentages appear in May and minimums in July, implying that the two gridded data sets both perform the best in capturing the moving-off TPVs in YB in May and the worst in July. Moreover, the percentages for NCEP-FNL are larger than ERA-interim in each month, and the differences between the percentages for NCEP-FNL and those for ERA-interim are remarkably larger in July and August than those in May and June, indicating that NCEP-FNL is more efficient than ERA-interim in capturing the TPVs in YB, especially in July and August.

Furthermore, differences between the characteristics of moving-off TPVs shown by YB and those by the gridded data are investigated. For a TPV in YB, in its moving-off process, if a TPV in NCEP-FNL (ERA-interim) is observed shifting out of the Tibetan Plateau, it is considered that this moving-off case is both presented in YB and NCEP-FNL (ERA-interim). Accordingly, during May–August of 2000–2015, 59 cases are found both presented in YB and NCEP-FNL, and 48 in YB and ERA-interim, which are categorized as group 1 and 2, respectively. Characteristics of the cases in group 1 (group 2) shown in NCEP-FNL (ERA-interim) are compared with those in YB in subsection 4.1 (subsection 4.2).

4.1. NCEP-FNL

Figure 3 provides the trajectories of cases in group 1 derived from NCEP-FNL and YB. The red dots represent the average locations of the TPVs that appear at the same longitude, which are calculated as follows.

TPVs with the longitude between $\text{lon} - 0.5^\circ$ and $\text{lon} + 0.5^\circ$ are considered appearing at $\text{lon}$, and the average latitude ($\text{lat}$) of the TPVs appearing at $\text{lon}$ is calculated as
where \( \text{lat}_i \) indicates the latitude of a TPV whose longitude is between \( \text{lon} - 0.5^\circ \) and \( \text{lon} + 0.5^\circ \), and \( n \) is the number of TPVs with the longitude between \( \text{lon} - 0.5^\circ \) and \( \text{lon} + 0.5^\circ \). The value of \( \text{lon} \) starts from 80°E, increases by 1°, and ends at 135°E. Thus, the average location of the TPVs at \( \text{lon} \) is considered as \( \text{lon}, \text{lat} \). Noted that for a specific \( \text{lon} \), if \( n = 0 \), then there will be no mark for average location in the figure.

Before the TPVs move off the Tibetan Plateau, in NCEP-FNL, the TPVs are mainly located between 32°N and 36°N, and move roughly eastward with the average latitude at around 34°N. In YB, the TPVs scatter from northern edge to southern edge over the central and eastern Tibetan Plateau, and the average locations at each longitude distribute slightly northeastward along with the increase of longitude. After the TPVs move off the Tibetan Plateau, in both NCEP-FNL and YB, most of the TPVs die out to the west of 112°E, and some northeastward traveling TPVs move further east. The average locations of the TPVs to the east of 112°E in NCEP-FNL are observed further north than those in YB.

Genesis locations of TPVs observed in NCEP-FNL mainly distribute in two areas, one is 83–91°E, 32–36°N and the other is 94–100°E, 32–38°N, and only the latter region is found in YB (Figure 4), which may be because the sparse sounding observations over the western plateau used in YB. Furthermore, genesis locations of the TPVs in NCEP-FNL scatter evenly in the two areas mentioned above, whereas those in YB are centered at 96°E, 34°N. In both NCEP-FNL and YB, the TPVs primarily disappear in the region of 103–112°E, 30–40°N, and the northeastern China.

### 4.2. ERA-Interim

Trajectories of the cases in group 2 derived from ERA-interim and YB are shown in Figure 5. Before the TPVs move off the Tibetan Plateau, in ERA-interim, the TPVs are concentrated between 33°N and 36°N, and shift...
northward slightly in their eastward movement. In YB, the trajectories of TPVs are more disperse, and the TPVs scatter in a larger meridional range. After the TPVs move off the Tibetan Plateau, in both ERA-interim and YB, most of the TPVs disappear to the west of 112°E, and some can travel further eastward, which is similar to the ones in group 1. The number of TPVs moving to the east of 112°E is larger in YB than in ERA-interim, and more TPVs are found to the south of 35°N in the region to the east of 112°E in YB, causing the average location of TPVs to the east of 112°E to be further south in YB than those in ERA-interim.

In Figure 6, genesis locations of the TPVs in ERA-interim are observed from the western to eastern Tibetan Plateau to the north of 32°N, with a high frequency center being in 82–89°E, 32–36°N. In contrast, TPVs shown in YB are mainly generated over central and eastern Tibetan Plateau, and some at the eastern edge of the

Table 1
Average Positional Deviations (Absolute Values) (Unit: Degree) in TPV's Lifecycles, Before and After Moving-Off the Tibetan Plateau

| Stage             | Data set   | Zonal deviation | Meridional deviation |
|-------------------|------------|-----------------|----------------------|
| Lifecycle         | NCEP-FNL   | 1.58            | 0.98                 |
|                   | ERA-interim| 1.89            | 1.03                 |
| Before moving off | NCEP-FNL   | 1.76            | 1.07                 |
|                   | ERA-interim| 2.18            | 1.11                 |
| After moving off  | NCEP-FNL   | 1.49            | 0.93                 |
|                   | ERA-interim| 1.70            | 0.97                 |

Figure 7. Zonal (a) and meridional (b) propagation distances (unit: degree), as well as lifespans (unit: hour) (c) of the cases in group 3 shown in YB (black lines), NCEP-FNL (red lines), and ERA-interim (green lines).
plateau. TPVs in ERA-interim mainly die out in the region of 33–39°N to the west of 112°E, and only a few die out to the east of 120°E. Similarly, most of the TPVs in YB disappear to the west of 112°E, but the disappearing locations of TPVs in YB are more disperse compared with those in the ERA-interim data, and more TPVs sustain and die out to the east of 120°E.

Therefore, moving-off TPVs in YB captured by NCEP-FNL are more than by ERA-interim. Both gridded data sets perform the best in revealing the number of moving-off TPVs in May, and the worst in July. In both NCEP-FNL and ERA-interim, the genesis locations of moving-off TPVs are further west and the trajectories are more concentrated compared with those in YB. Genesis locations of the TPVs in NCEP-FNL scatter over the Tibetan Plateau, whereas those in ERA-interim are concentrated in 82–89°E, 32–36°N.

It should be noted that some of the differences between the detecting results of TPVs derived from YB and those from gridded data may be attributed to the different temporal and spatial resolutions of the data sets, but not merely the quality of the gridded data.

5. Moving-Off TPVs Commonly Presented in all of the Three Data Sets

The 46 moving-off TPVs commonly presented in YB, NCEP-FNL, and ERA-interim in May–August of 2000–2015 are classified as group 3, to further assess NCEP-FNL and ERA-interim in depicting the same cases.

Figure 7 shows the zonal and meridional propagation distances, as well as the lifespans of the cases in group 3 presented in YB, NCEP-FNL, and ERA-interim. Correlation coefficient for zonal propagation distances between NCEP-FNL and YB is 0.71, and that between ERA-interim and YB is 0.40, both of which exceed the 99% confidence level (Figure 7a). Thus, NCEP-FNL is more efficient than ERA-interim in reflecting
the zonal propagation distances of TPVs. Regarding the meridional propagation distances (Figure 7b), the correlation coefficients between NCEP-FNL and YB, and between ERA-interim and YB, both exceed the 99% confidence level, with the values being 0.87 and 0.89, respectively, indicating that both NCEP-FNL and ERA-interim perform well and similarly in presenting the meridional propagation distances of TPVs. Correlation coefficient for TPVs lifespans between NCEP-FNL and YB is 0.66, and that between ERA-interim and YB is 0.62, implying that NCEP-FNL and ERA-interim show no obvious difference in revealing the lifespans of TPVs (Figure 7c). All in all, zonal propagation distances of TPVs are better revealed in NCEP-FNL than in ERA-interim, and the performance of the two gridded data sets in showing the meridional propagation distances and lifespans are similar. Additionally, it is inferred that both gridded data sets are better at presenting the meridional propagation distances of TPVs than at zonal propagation distances and lifespans, because of the larger correlation coefficients for meridional propagation distances between the gridded data sets and YB. Zonal propagation distances are better displayed than lifespans in NCEP-FNL, and the situation in ERA-interim is opposite. Furthermore, correlation coefficients for zonal propagation distances, meridional propagation distances, and lifespans between NCEP-FNL and ERA-interim are 0.54, 0.90, and 0.78, respectively, and all of them exceed the 99% confidence level, demonstrating that NCEP-FNL and ERA-interim are well consistent with each other in presenting these three aspects of TPVs.

To assess the accuracy of NCEP-FNL and ERA-interim in presenting the TPVs locations, the TPVs positional deviations in the two gridded data sets are investigated. Zonal (meridional) deviation is calculated as the absolute value of distance between the TPV zonal (meridional) location in gridded data sets and that in YB. Thus, the positional deviations in Table 1 and Figures 8 and 9 are absolute values. Noted that, for a
specific case, only the times when the TPV is simultaneously captured by the gridded data and the YB are involved in the calculation.

Table 1 provides average positional deviations in TPVs lifecycles, before and after moving off the Tibetan Plateau. Average zonal deviations in TPVs lifecycles in NCEP-FNL and ERA-interim are 1.58° and 1.89°, respectively, indicating that NCEP-FNL is more precise than ERA-interim in presenting the zonal locations of TPVs. Meanwhile, the average meridional deviations in TPVs lifecycles in NCEP-FNL and ERA-interim are very close, with the values being 0.98° and 1.03°, respectively, implying similar performance of these two gridded data sets in reflecting the meridional locations of TPVs. Specifically, before the TPVs move off the Tibetan Plateau, average zonal deviations of the TPVs in NCEP-FNL and ERA-interim are 1.76° and 2.18°, respectively, and those after the TPVs move off are 1.49° and 1.70°, indicating that both NCEP-FNL and ERA-interim perform better in the stage after the TPVs move off the plateau than before moving off, and NCEP-FNL is better than ERA-interim in presenting the zonal locations of TPVs in both stages. The average meridional deviations in both NCEP-FNL and ERA-interim after the TPVs move off the Tibetan Plateau are slightly smaller than before moving off, and the values of the meridional deviations in the two gridded data sets in both stages are similar. Thus, NCEP-FNL and ERA-interim perform similarly in displaying the meridional locations of TPVs.

Average zonal and meridional deviations of each case derived from NCEP-FNL and ERA-interim are shown in Figure 8. Coefficient correlation between the zonal (meridional) deviations in NCEP-FNL and those in ERA-interim is 0.31 (0.53), which exceed the 95% (99%) confidence levels. Thus, the positional deviations of a specific TPV in NCEP-FNL and ERA-interim are always simultaneously large or small,
demonstrating a generally synchronous performance of NCEP-FNL and ERA-interim in presenting the TPVs locations, especially in meridional locations.

Figure 9 presents distributions of TPVs positional deviations (absolute values) in percentages. For the two gridded data sets, in both stages before and after the TPVs move off the Tibetan Plateau, the percentages of zonal and meridional deviations between 0° and 1° are the largest, followed by those in the range of 1° to 2°. Actually, more than 85% of the zonal (meridional) deviations are smaller than 3° (2°), indicating that the two gridded data sets are both reliable in reflecting the TPVs locations, especially in meridional locations. Before the TPVs move off the Tibetan Plateau, percentages of the zonal deviations between 0° and 1°, 1° and 2°, and 2° and 3° are larger in NCEP-FNL than in ERA-interim, implying that NCEP-FNL performs better than ERA-interim in presenting the zonal locations of TPVs (Figure 9a). Regarding the meridional deviations (Figure 9b), more than 60% of the deviations are smaller than 1° in both NCEP-FNL and ERA-interim, and the percentages of meridional deviations between 1° and 2° are the secondary. The total percentages of meridional deviations ranging from 0° to 2° in NCEP-FNL and ERA-interim are comparable, coinciding with the similar average meridional deviations of the TPVs locations in NCEP-FNL and ERA-interim shown in Table 1. After the TPVs move off the Tibetan Plateau (Figures 9c and 9d), percentages of the zonal and meridional deviations between 0° and 1° both increase apparently in both gridded data sets compared with those before the TPVs move off, corresponding to smaller average positional deviations of TPVs after moving off (Table 1). Thus, NCEP-FNL and ERA-interim are more accurate in presenting the TPVs locations out of the Tibetan Plateau. Specifically, percentages of zonal deviations between 0° and 1° in NCEP-FNL and ERA-interim are comparable, and the total between 1° and 3° is larger in NCEP-FNL than in ERA-interim, indicating a better performance of the former (Figure 9c). Percentage of the meridional deviations between 0° and 1° in NCEP-FNL is much higher than that in ERA-interim, whereas that between 1° and 2° is much
lower in NCEP-FNL (Figure 9d), leading to small difference in the average meridional deviations between NCEP-FNL and ERA-interim after the TPVs move off the plateau (Table 1).

In addition to the absolute positional deviations of TPVs investigated above, the directions of positional deviations are further explored. Accordingly, positive and negative deviations are marked by brown and green colors, respectively, in Figures 10 and 11, and the dots represent the locations of group 3 TPVs in YB. TPVs located to the west of 102°E are considered in the stage before moving off the Tibetan Plateau, and the ones to the east of 102°E are after moving off. Positive (negative) zonal deviations mean that the TPVs locations in gridded data sets are to the east (west) of those in YB; positive (negative) meridional deviations indicate that the TPVs locations in gridded data sets are to the east (west) of those in YB.

In NCEP-FNL (Figure 10), before the TPVs move off the Tibetan Plateau, 44.1% (45.2%) of zonal (meridional) positional deviations are positive and 49.5% (46.2%) are negative, indicating that the ratio of easterly (northerly) deviations is similar to that of westerly (southerly) deviations. After the TPVs move off the Tibetan Plateau, more TPVs (58.5%) are located to the west of the TPVs shown in YB, compared with those located to the east (36.3%); the ratio of northerly deviations (50.3%) is larger than that of southerly deviations (39.8%). Thus, NCEP-FNL shows no specific preference in the directions of positional deviations when the TPVs are located over the Tibetan Plateau, and tends to present further west and north TPVs locations relative to those in YB after the TPVs move off the plateau.

In ERA-interim (Figure 11), before the TPVs move off the Tibetan Plateau, the ratio of westerly deviations (67.4%) is apparently higher than that of easterly deviations (30.5%) (Figure 11a), implying that ERA-interim always shows a further west location of a TPV relative to the TPV position in YB. Meanwhile, the ratios of northerly and southerly deviations are similar, with the values being 45.3% and 47.4%, respectively (Figure 11b). After the TPVs move off the Tibetan Plateau, more TPVs (65.5%) are found to the west of the TPVs in YB, whereas 29.7% are found to the east (Figure 11a). Simultaneously, the ratio of northerly deviations is 51.7%, which is larger than that of southerly deviations (37.9%). Therefore, before the TPVs move off the plateau, ERA-interim shows no preference for the direction of meridional deviations, but is more likely to cause westerly positional deviations of TPVs; after the TPVs move off the Tibetan Plateau, the TPVs in ERA-interim are usually observed to the west and north of those in YB. Specifically, although both NCEP-FNL and ERA-interim tend to present further west and north locations of the TPVs after moving off, this tendency is more significant in the latter because of the larger differences between the percentages of positive deviations and those of negative deviations.

According to the statistics above, NCEP-FNL and ERA-interim can capture a portion of moving-off TPVs in YB. Thus, common features of the moving-off TPVs in YB that are observed in neither of the two gridded data sets are further discussed. The 43 TPVs detected in neither NCEP-FNL nor ERA-interim are explored, and two major characteristics of these TPVs are summarized in Figure 12. Generally, more than 60% of these TPVs have at least one of the two characteristics as follows: originate at the edge of the Tibetan Plateau, and the lifespans are shorter than 24 hr. Additionally, most of the 43 TPVs in Figure 12a disappear to the west of 112°E, implying that NCEP-FNL and ERA-interim often miss the TPVs with short propagation distances. According to the previous work (Li et al., 2019), the maintenance of TPVs depends on their own intensity.
greatly, thus, the TPVs with short lifespans and short propagation distances may be relatively weak. Therefore, it is inferred that the gridded data may perform badly in presenting the winds field near the edge of the Tibetan Plateau and in detecting weak cyclonic circulations.

6. Conclusion and Discussion

TPVs, generated over the Tibetan Plateau at 500 hPa, always trigger heavy rainfall over southwestern and eastern China when they move off the Tibetan Plateau. Thus, the moving-off TPVs are focused on in this work. Because of the low temporal and spatial resolutions of the sounding observations over the Tibetan Plateau, especially over the western plateau, the gridded data are necessary in the research on TPVs. Thus, YB based on the sounding data are referred as the observational data sets, and the efficiency of NCEP-FNL and ERA-interim in revealing the characteristics of the moving-off TPVs is assessed against YB. The results are summarized as follows.

Less moving-off TPVs are presented in NCEP-FNL and ERA-interim than those in YB, and the two gridded data sets detect the same quantity of moving-off TPVs. Generally, both NCEP-FNL and ERA-interim can basically reflect the interannual and monthly variations of the number of moving-off TPVs; specifically, ERA-interim is better at revealing the interannual variation, whereas NCEP-FNL is better at revealing the monthly variation.

Percentages of the TPVs in YB captured by NCEP-FNL and ERA-interim are comparable in 2000, 2003, 2005, 2007, 2009, 2011, and 2014, larger in ERA-interim than in NCEP-FNL in 2006 and 2008, and much higher in NCEP-FNL in the rest 7 years. Both gridded data sets perform the best in capturing the TPVs in YB in May, and the worst in July. NCEP-FNL is more efficient than ERA-interim in capturing the TPVs in YB, especially in July and August.

Trajectories of the TPVs shown in NCEP-FNL (ERA-interim) are much concentrated than those in YB before the TPVs move off the plateau. Genesis locations of TPVs in YB are found over the central and eastern Tibetan Plateau, and those in NCEP-FNL scatter from western to eastern Tibetan Plateau, whereas those in ERA-interim are centered in 82°–89°E, 32°–36°N.

Both NCEP-FNL and ERA-interim show good skills in describing the zonal and meridional propagation distances, as well as lifespans of TPVs, among which the meridional propagation distances are best presented in both gridded data sets. NCEP-FNL performs better in describing the zonal propagation distances than in lifespans, and ERA-interim performs inversely. Zonal propagation distances of TPVs are better revealed in NCEP-FNL than in ERA-interim, and the performances of two gridded data sets in showing the meridional propagation distances and lifespans are similar.

Positional deviations of TPVs in NCEP-FNL and ERA-interim are explored. The two gridded data sets always perform synchronously well or badly in displaying the location of a specific case. In both NCEP-FNL and ERA-interim, more than 85% of the zonal (meridional) deviations are smaller than 3° (2°), and the percentages of zonal and meridional deviations between 0° and 1° are the largest, indicating that NCEP-FNL and ERA-interim are both reliable in reflecting the TPVs locations, especially in meridional locations. Generally, average zonal deviation is larger than average meridional deviation in both gridded data sets; the average zonal deviation in NCEP-FNL is smaller than that in ERA-interim, whereas the average meridional deviations in the two gridded data sets are similar. Additionally, both zonal and meridional deviations are larger before the TPVs move off the Tibetan Plateau than after moving off in both NCEP-FNL and ERA-interim, implying that the gridded data sets perform better after the TPVs move off.

Regarding the directions of TPVs positional deviations, before the TPVs move off the Tibetan Plateau, NCEP-FNL shows no specific preference for the directions of positional deviations, whereas ERA-interim tends to present further west TPVs locations relative to those in YB. After the TPVs move off, the TPVs in both gridded data sets are always observed to the west and north of the TPVs in YB, which is more significant in ERA-interim.

It should be noted that the results in this work are based on the TPVs in May–August of 2000–2015, which may be not representative for the moving-off TPVs beyond this period. Additionally, although both of the definitions of TPVs in YB and in gridded data are based on winds field, there may be some difference
because the former is derived from observational sounding stations and the latter from gridded data. Besides, because of the 12-hr interval of the sounding data used in YB, it is difficult to be sure that a TPV observed at one time step is the same TPV as observed 12 hr ago. However, the YB provides objective TPVs locations observed by the sounding observations, which is a very important reference for identifying the TPVs. This work merely reveals the differences among the three data sets in detecting TPVs based on statistics results of TPVs, and the essential reasons inducing the differences should be deeply explored in the future work.

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