The Record-Breaking Extreme Drought in Yunnan Province, Southwest China during Spring–Early Summer of 2019 and Possible Causes

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ABSTRACT

In spring and early summer of 2019, Yunnan Province experienced the most severe seasonal drought on record, with days of extreme drought area exceeding $10^5$ km$^2$ far more than normal. Consistently, the precipitation in each month from February to June is over 30% less than normal, and about 50% less in the most severe drought period (April–June). The rainy season in Southwest China (SWC) started on the third pentad in June 2019, which is the second latest in history. The rainy season in Yunnan started on 24 June, which is the latest (29 days later than normal). On the contrary, the onset of the South China Sea summer monsoon (SCSSM) is abnormally early. The lag time between the start of the rainy season in SWC and the onset of the SCSSM in 2019 is 7 pentads, which is the largest since 1961, much longer than the climate mean (less than 1 pentad). The present study analyzes the possible reasons why the rainy season came extremely late and the drought disaster persisted and intensified after a much early SCSSM, at both seasonal and subseasonal timescales. The abnormally late onset of the rainy season and the second greatest potential evapotranspiration (PET) since 1981 are the direct reasons for the persistent drought. Statistical results show that the water vapor from southwest of Yunnan in April–June contributes more than that from the east at the seasonal scale. In April–June 2019, however, the southern branch trough (SBT) was abnormally weak, the large and strong anticyclonic wind anomaly prevailed over the Bay of the Bengal (BOB), and the meridional water vapor transport to Yunnan was weak. At the subseasonal scale, the weaker SBT lasted the longest, and the strong convection over the BOB came up late despite of an early onset of the SCSSM, which resulted in reduced low-level moisture convergence in Yunnan and development of drought prior to the SCSSM onset. From the onset of SCSSM to the start of rainy season in SWC, the SBT and meridional water vapor transport from the BOB were still weak, and the water vapor was mainly transported into the coastal area of South and Southeast China rather than Yunnan. After the start of the rainy season in SWC, the SBT was still weak. This led to less moisture transport in the westerlies to the west of Yunnan and the persistent extreme drought. Both the statistical results and case analysis indicate that the stronger Australian high in spring and early summer of 2019 was associated with the abnormally strong anticyclone over the BOB and the always weak SBT. In sum, the anomalous weakness of SBT played a critical role in the extreme drought occurrence and persistence in Yunnan of Southwest China in 2019.

Key words: Yunnan Province, extreme drought, South China Sea summer monsoon (SCSSM), rainy season in Southwest China (SWC), southern branch trough (SBT)

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1. Introduction

Drought is the most prominent meteorological disaster in China, which causes the most severe loss among all kinds of disasters. Statistical records show that the direct economic loss caused by drought exceeded 60 billion yuan per year from 2004 to 2015 (Zheng et al., 2019). Different from other disasters featured by specific seasonal and regional distributions, such as floods and typhoons, drought disasters in China may occur in any region and any season. In general cases, the frequency of drought in southern China is lower than that in northwestern and northern China (Ding et al., 2013). However, Southwest China (SWC), located on the south-
eastern side of the Tibetan Plateau and influenced by both the southwest monsoon and southeast monsoon during the prevailing summer monsoon period, shows obvious dry and rainy seasons in the annual cycle of precipitation. The dry season is from November to next April, with precipitation less than 15% of the total annual rainfall (Yan et al., 2013). Compared with the region south of the Yangtze River and South China at the same latitude, the rainy season in SWC starts relatively late, and the average start date is around the middle of May. If the rainy season in a certain year comes late, it often results in precipitation deficiency in the late spring and early summer, leading to spring drought or even consistent drought from winter to spring or from spring to summer in this region. This makes SWC the high incidence center of drought in southern China, with drought occurrence frequency obviously higher than that in eastern China at the same latitude. For example, in 1982, the start date of the rainy season in SWC was obviously later than usual, and therefore a severe spring drought occurred in Yunnan. The rainfall in Kunming in May was only 8 mm, which is the lowest during the preceding 80 years (Ding, 2008). In 1983, the start day of the rainy season was still later than normal, which resulted in a more severe drought in SWC, causing great economic losses to the local agriculture production.

Yunnan is in the low latitude, with mountains accounting for 84% of the total area of the province. It is vulnerable to drought and is the high-frequency center of drought in SWC (Cheng et al., 2009; Ding et al., 2013). The high frequency of drought in Yunnan is closely related to its geographical environment; especially, the topography has a great influence on the regional distribution of drought. Drought occurs with a high frequency over the whole year in the areas from Meili Snow Mountain in the northwest of Yunnan, alongside Mount Cangshan, to Mount Ailao in the east and northeast of Yunnan. Particularly, drought is prone to occur in the dry–hot valley areas such as the basins of Jinsha River, Lancang River, Nujiang River, Yuanjiang River, and Nanpan River (Cheng et al., 2009). Statistics show that 43% of the meteorological disasters in Yunnan are drought disasters, ranking first among all disasters, and spring droughts account for about 70% of all droughts in Yunnan (Song et al., 2003; Cheng et al., 2009). If the onset of the summer monsoon is late and the beginning of the rainy season is delayed, there will be continuous drought from spring to summer. Although the occurrence probability of spring–summer drought is far less than the winter–spring drought (Shen, 1982), spring–summer drought causes the most serious hazards. Cheng et al. (2009) suggested that 80% of the severe drought years in Yunnan were featured by spring–summer drought. From spring to the early summer of 2019, Yunnan Province was exposed to a very rare persistent meteorological drought. According to the Department of Emergency Management of Yunnan Province, the drought disaster from April to June in 2019 impacted on a total of 1.35 million hectares of crops including 79,000 hectares of total crop failure, causing 6.562 billion yuan of direct economic loss, which is more than the total direct economic loss of droughts in the previous five years.

Under the background of global warming, the drought in Yunnan shows a significant increasing trend. Especially, since 2000, precipitation in Yunnan has decreased, the accompanying drought events have increased, the area of drought has increased, and the occurrence cycle of drought has been shortened from 2–3 to 1–2 yr (Cheng et al., 2009). Jin et al. (2018) also revealed that the occurrence frequency, cumulative intensity, and number of cumulative impact stations of regional drought in Yunnan are increasing. Moreover, climate projections show that the risk of drought in SWC will be further enhanced in the future (Qin et al., 2015).

Many studies have analyzed the main causes of drought in Yunnan in recent years. Due to the interseasonal differences of circulations related to precipitation anomalies, the formation mechanisms of winter and spring droughts are different. For example, diagnosis and analysis of severe winter drought in Yunnan Province from 2009 to 2010 showed that the main cause of drought was the anomalous circulation systems in the westerly belt. In the mid–high latitudes, the negative and positive geopotential height anomalies were over Lake Baikal and coast of East Asia, respectively. The mid–high latitudes westerlies were relatively flat from the west of Lake Baikal to East Asia. Under this situation, the cold air in winter was weak and difficult to affect SWC. In the low latitudes, the southern branch trough (SBT; also called the India–Burma trough) over the Bay of Bengal (BOB) weakened, and Yunnan Province was controlled by a northwesterly anomaly (Yang et al., 2012). Meanwhile, the North Atlantic Oscillation (NAO) was also closely related to winter drought in Yunnan (Song et al., 2011). But the above circulation anomalies were not identified for spring drought. For the spring drought in Yunnan, the onset time of the summer monsoon as well as the position and intensity anomalies of the tropical circulation are considered to have a more direct effect. For example, Liu et al. (2007) pointed out that the lagged seasonal conversion of the mid–upper tropospheric circulation, the late onset of the South China Sea summer monsoon (SCSSM), the weaker-than-normal
tropical convection, and the more southward, more westward, and stronger-than-normal western Pacific subtropical high (WPSH), were the most direct reasons for the severe drought in Yunnan from the late spring to early summer in 2005. Meanwhile, Yan et al. (2007) revealed the important roles of the sustained easterly anomaly at 850 hPa in the North Indian Ocean and the continuous enhancement and westward extension of WPSH. Zheng et al. (2014) further compared the circulations in May in four extremely dry and flood years with normal conditions, and found that the circulation differences in the low latitudes in dry years were obvious: (1) the WPSH at the lower levels was stronger and more westward than normal; (2) the equatorial westerly was blocked when moving eastward and northward; (3) the summer monsoon in the BOB and Indochina Peninsula was weaker and broke out later than normal; and (4) the water vapor transport in Yunnan was mainly from the westerly belt, rather than from the tropical area.

Nonetheless, drought monitoring results in recent years show that the location and intensity of the WPSH are not the direct cause of the drought in Yunnan; when the tropical Indian Ocean was warm and the El Niño appeared in eastern Pacific, the WPSH tended to be strong and westward, but there was no lack of spring rainfall in a vast area in Yunnan. For example, affected by the super El Niño event, the WPSH in spring 2016 showed this distribution feature, but drought did not occur in SWC (including Yunnan) from March to June. On the contrary, the precipitation in western SWC even increased by more than 50%. On the other hand, the WPSH has a very significant trend of decadal enhancement and westward extension in the 21st century (Gao et al., 2014), but the precipitation in Yunnan is still dominated by interannual variability, and it is not rare for precipitation to occur over wide areas in Yunnan in the recent two decades. Besides, the SCSSM in 2019 broke out in the second pentad of May, which is abnormally early (Ding and Gao, 2020), when Yunnan suffered an extremely severe drought in 2019. This is inconsistent with previous studies, which indicated that spring drought in Yunnan was prone to occur when the summer monsoon broke out late.

To further explore the causes of drought in SWC, this paper tries to analyze the seasonal evolution and extreme characteristics of the record-breaking drought during spring–summer 2019 in Yunnan Province. From both the seasonal and intraseasonal perspectives, contributions of the various circulation anomalies, such as the SCSSM, WPSH, SBT and so on, to the occurrence and development of this extreme drought are revealed, through comparing the anomalous location and intensity of the tropic-

2. Data and methods

The daily precipitation data from 1981 to 2019 used in this study are obtained from the “Dataset of Daily Surface Observation from Chinese Surface Stations (V3.0),” which is provided by the National Meteorological Information Center of China Meteorological Administration (CMA; Ren et al., 2012). This dataset was produced with improved quality from the baseline meteorological data and with the inconsistency between the national- and provincial-level archived datasets removed. The data quality and spatial resolution (number of stations) are improved significantly compared with the previously observed precipitation data. The dataset has been widely used in operational and research works. 126 surface stations in Yunnan Province with complete data records are selected in this study. Besides, the yearly onset date of SCSSM and the observed sequence of the start date of the rainy season in SWC during the same period derived by the National Climate Center (NCC) of CMA is also used. The atmospheric circulation data including geopotential height at 500 hPa and horizontal wind at 850 hPa are from the NCEP/NCAR reanalysis daily dataset on a horizontal resolution of 2.5° × 2.5° (Kalnay et al., 1996; Kistler et al., 2001).

The monitoring data of daily areas of meteorological drought with different intensity grades are from the NCC of CMA. The drought index used in this study is the Meteorological Drought Composite Index (MCI; Liao and Zhang, 2017; Zhang et al., 2017) based on the latest national standard for meteorological drought grading (GBT-20481-2017). The formula is $MCI = Ka \times (a \times SPI_{60} + b \times MI_{30} + c \times SPI_{90} + d \times SPI_{150})$, where $SPI_{60}$ is the standardized weighted precipitation index in the recent 60 days, $MI_{30}$ is the relative humidity index in the recent 30 days, and $SPI_{90}$ ($SPI_{150}$) is the standardized precipitation index in the recent 90 (150) days. According to the national meteorological drought standard (GB/T 20481-2017), $a$, $b$, $c$, and $d$ in the above formula are the weight coefficients of the corresponding items, which are 0.5, 0.6, 0.2, and 0.1, respectively. The season adjustment index, $Ka$, is 1.1, 1.2, and 1.0 for March, April, and May, respectively, and $Ka$ is 1.2 for the three months of summer. This index is officially employed by the NCC as a real-time operational drought monitoring index, and has been widely used in various climate departments in China.
3. Overview of the 2019 spring–summer Yunnan drought

An extremely severe and persistent meteorological drought occurred in Yunnan from spring to early summer of 2019. The NCC daily drought area monitoring results for medium, severe, and very severe drought events show that since the mid-April 2019, the areas of stronger-than-medium drought in Yunnan had expanded rapidly and reached the largest in the first 10 days of May. On 19 May, it reached 340,000 km$^2$, accounting for 86% of the total area of Yunnan (Fig. 1). From mid-May to mid-June, the area of stronger-than-medium drought maintained around 300,000 km$^2$. From the beginning of May, the drought intensity changed from medium to severe and reached the maximum in early and mid-June. Due to continuously less precipitation, very severe drought regions increased sharply in early June and maintained from early June to mid-June. Heavy rainfall significantly decreased the range of drought in late June, but more than half of the area still suffered from severe and very severe droughts (Liu and He, 2019). With the increase of precipitation in July in Yunnan Province, the severe and very severe droughts almost disappeared since late July. Furthermore, in spring and summer of 1981–2019, there were 49 days/cases when the area of the daily very severe drought covered over 10$^5$ km$^2$, of which 35 days/cases occurred in 2019, and the strongest 27 drought events also occurred in 2019. The area of very severe drought was over 230,000 km$^2$ on 23 June 2019, which was the largest in history, further indicating the long duration and extreme strength of the drought in 2019.

Figure 1 also reveals that the seasonal evolution characteristics of spring and summer droughts in 2019 were significantly different from the climatology. Climatologically, winter and early spring are dry season in SWC, during which precipitation is less, and the number of drought days and the range of drought areas are larger than in other periods. With the enhancement of the Somalian cross-equatorial flow (CEF) and establishment of the BOB CEF in May, the water vapor intruding into SWC has increased and the Southwest China rainy season (SWRS) begins. The drought area in Yunnan decreases, especially the area that suffers from severe and very severe droughts reduces significantly (see the three curves in Fig. 1). However, the drought in 2019 showed an opposite (increasing rather than decreasing) seasonal evolution trend, compared with the climatology.

![Fig. 1. Variations of the daily area of the moderate (light yellow), severe (yellow), and extreme (reddish brown) droughts (bar; 10$^5$ km$^2$) in Yunnan from 1 March to 31 August 2019 based on the monitoring data of the National Climate Center (NCC) of China. The three curves from top to bottom show the the climate mean areas of the moderate, severe, and extreme droughts, respectively. The upper left panel shows all the 49 cases with the daily drought area exceeding 10$^5$ km$^2$ in March–August during 1981–2019, and the corresponding case years in different colors.](image-url)
4. Precipitation anomaly during the 2019 Yunnan drought

The occurrence and development of drought depends on the change in budget of evaporation and precipitation. Although meteorological drought is affected by many factors and the weight of each factor in different drought indices is different (Zhang et al., 2017), precipitation is undoubtedly the most important factor. Before analysis of the precipitation anomaly, the Thornthwaite method (Thornthwaite, 1948) is used to calculate the normalized value of potential evapotranspiration (PET). In 2019, this value is 1.36, i.e., the positive PET anomaly exceeded one standard deviation in 2019, which is next to 2015 for all the 39 yr of the study period (2015 is also a spring drought year). The large evapotranspiration in 2019 is conducive to the development of drought. Then, the precipitation anomaly during the extreme continuous drought during spring–summer of 1961–2019 in Yunnan Province is analyzed next. The table on the left side of Fig. 2 shows the percentage of the monthly precipitation anomaly from March to August since 1961. Light blue, blue, and dark blue represent different levels of anomaly percentage, namely, from −50% to −30%, from −80% to −50%, and less than −80%, respectively. Because the precipitation in Yunnan is almost concentrated in summer, the probability of the monthly precipitation anomaly percentage being less than −30% for each month in summer is significantly lower than that in spring. However, in 2019, the percentage of the precipitation anomaly is continuously lower than −30% from February to June, which never happens in the preceding 60 years. Particularly, in May, Yunnan is usually affected by the beginning of the rainy season with rapidly increasing precipitation; but in 2019, the precipitation of May is only 38% of the climatology. The situation in 1992 is the most similar to 2019. The precipitation from March to June of this year is about 80% of the climatology, and a continuous drought occurred also from spring to summer, but with smaller drought area and less intensity than those in 2019. From April to June 2019, when the drought occurred and developed, the average precipitation is 43% less than normal (histogram) and the standardized anomaly is −2.15. It is the lowest absolute value since 1961. Therefore, from the perspective of precipitation, the continuously lower-than-normal rainfall from March to June is the direct cause of the record-breaking extreme drought in 2019.

Furthermore, Fig. 3 shows the cumulative precipitation and percentage of the cumulative precipitation anomaly from 1 March to 31 August in 2019 (spring and summer). The cumulative precipitation of the climatology is also shown in Fig. 3 and the slopes of the curves in different periods show the increasing rate of precipitation in this period. The climatology (blue dotted line) shows that the slope of the cumulative precipitation curve has increased significantly from mid- to late May. This is mainly because the average start time of SWRS is mid-May (Yan et al., 2013; Bai and Gao, 2017). But for 2019, the slope of the cumulative precipitation curve before the 5th pentad of May is very small. Although it has an increase from the end of May to June, the growth rate is still lower than the climate value, resulting in significantly less precipitation from mid-May to the end of June and the cumulative anomaly percentage lower than −50%. That is to say, the cumulative precipitation from March is less than half of the normal amount, the soil entropy deficiency must have been serious, and the drought gets developed. The results derived from Fig. 3 are consistent with those from Fig. 1.

The NCC monitoring shows that the SCSSM in 2019 broke out in the second pentad of May. It is the fourth earliest year since 1961, after the first pentad of May in 1965, 1994, and 2008. One of the basic characteristics of the SCSSM onset is the enhancement and eastward propagation of the Somalian CEF and establishment of the BOB CEF (He et al., 2001; Gao et al., 2014). With the establishment and strengthening of the above-mentioned CEFs, the westerly over the equatorial Indian Ocean also enhances, and more warm and moist airflows intrude into SWC. For the climatology, the average start time of the SWRS is pentad 29.2, which lags less than 1 pentad behind the average SCSSM onset time (Pentad 28.6). However, as shown in Fig. 4, the SWRS in 2019 started at the third pentad in June, which is the second latest year in history, after 1977, resulting in the SWRS lagging behind the SCSSM by 7 pentads. This difference is the largest since 1961. However, in 2019, the rainy season of Yunnan Province arrived on 24 June, which is 29 days later than normal, setting the latest record in history. In 2019, the rainy season is postponed, and there is no obvious rainfall process in Yunnan and its surrounding areas. Consequently, drought has developed rapidly from May to June.

5. Atmospheric circulation anomalies during the 2019 Yunnan drought

5.1 Characteristics of seasonal circulation anomalies

The spring drought in SWC is closely related to the arrival date of the rainy season, which is affected by the
low-level airflow over the tropical Indian Ocean and
BOB. Yan et al. (2003, 2013) found that when the BOB
monsoon broke out late, the rainfall in Yunnan was less
in May; but when the BOB monsoon broke out early or
normally, the amount of rainfall was mainly related to
the activity of cold air in the mid–low latitudes. Bai and
Gao (2017) found that, of several CEFs at the lower level
of the Eastern Hemisphere, only the strength of the
Somalian CEF and BOB CEF can affect the start date of
the rainy season and rainfall. They also found that strong
(weak) jet is accompanied by early (late) rainy season.

Influenced by the upstream CEFs, the westerlies in the
equatorial Indian Ocean and the southwestlies over the
BOB will also be enhanced before the rainy season,
providing abundant water vapor for SWC.

Wang and Wang (2018) conducted a comparative analysis
of the typical spring drought and flood in SWC
from 1951 to 2011. They found that the main reason for
spring drought in SWC was that the air over 500 hPa was
controlled by the ridge of high pressure, the divergent
airflow was strong, and the transport of water vapor and
the convergence of cold and warm air were not obvious.

| Vol. | MAR | APR | MAY | JUN | JUL | AUG |
|------|-----|-----|-----|-----|-----|-----|
| 1961 | -40 | -7  | -3  | 5   | 3   | 39  |
| 1963 | -9  | -20 | 64  | 17  | 5   | 8   |
| 1965 | -36 | -23 | -6  | 20  | -2  | 11  |
| 1967 | -35 | -21 | -6  | 20  | -32 | 9   |
| 1969 | 10  | -20 | -39 | -22 | 2   | -3  |
| 1971 | -42 | -46 | -21 | -2  | 4   | 21  |
| 1973 | 10  | -18 | -7  | 0   | 31  | -8  |
| 1975 | -45 | -14 | -6  | 20  | 6   | 54  |
| 1977 | -36 | -19 | -15 | 6   | 6   | -16 |
| 1979 | 48  | 10  | 8   | 12  | 15  |     |
| 1981 | 41  | 42  | 23  | 4   | 7   | 28  |
| 1983 | 20  | -10 | 29  | 11  | -9  | -14 |
| 1985 | -44 | 34  | -37 | -27 | 10  | -9  |
| 1987 | -53 | -40 | 50  | 46  | -18 | 3   |
| 1989 | -22 | -40 | -53 | 8   | 8   | 25  |
| 1991 | -43 | 0   | -63 | -10 | -24 | -2  |
| 1993 | 26  | 42  | 3   | -18 | -10 | -26 |
| 1995 | 86  | 8   | 79  | 28  | 5   | 45  |
| 1997 | -17 | 16  | -23 | 17  | 1   | 4   |
| 1999 | -46 | 11  | 0   | -31 | -21 | 29  |
| 2001 | 94  | 15  | 21  | 25  | 2   | 2   |
| 2003 | -33 | 6   | 26  | -7  | 3   | 11  |
| 2005 | -57 | 12  | -24 | 31  | -16 | 48  |
| 2007 | 33  | 6   | 26  | -7  | 3   | 11  |
| 2009 | 17  | 23  | -24 | 31  | -16 | 48  |
| 2011 | -12 | -47 | 14  | -25 | 20  |     |
| 2013 | -12 | -47 | 14  | -25 | 20  |     |
| 2015 | 177 | -25 | 25  | 40  | -10 | 11  |
| 2017 | -62 | 7   | 22  | -16 | 3   | -27 |
| 2019 | -62 | 7   | 22  | -16 | 3   | -27 |

Fig. 2. The percentage of precipitation anomaly from March to August (left chart; %) and standardized precipitation (right bar) in April–June
over Yunnan during 1961–2019. The light blue, blue, and dark blue in the left chart denote the percentage from −50% to −30%, from −80% to
−50%, and less than −80%. The thin and thick dashed lines in the right chart show the standardized values of ±1 and ±2, and the red bar shows
the year 2019.
Fig. 3. The accumulated precipitation in Yunnan from 1 March to 31 August in 2019 (blue solid line; mm), climate mean (blue dashed line; mm), and percentage of the accumulated precipitation since 1 March 2019 (red line; %).

Fig. 4. The onset dates of the rainy season of Southwest China (SWC; solid bar; yellow shows 2019, grey shows the other years, and the grey dashed line means the climatology) and South China Sea summer monsoon (SCSSM; hollow bar; red shows 2019, black shows the other years, and the black dashed line means the climatology) during 1961–2019. The numbers (24, 25, ...) on the vertical axis denote the 6th pentad of April, the 1st pentad of May, and so on.
Hereby, the correlation between the average precipitation and circulation fields in Yunnan from April to June is analyzed (Fig. 5). To avoid the influence of the extreme event in 2019 on the statistical results, the correlation analysis period is from 1981 to 2018. The shaded area in Fig. 5 shows the correlation between precipitation and geopotential height at 500 hPa. The tropical areas from the Arabian Sea to the west of South China are all negative correlation that has passed the confidence test at the 95% level. The most significant negative correlation center is located in the BOB region, which is consistent with the results of Wang and Wang (2018). The correlation of precipitation and low-level wind shows that the influence of southwesterly water vapor transport from the west of Yunnan Province on precipitation is obvious from April to June, which is most significant in the BOB area. The correlation vector is northwesterly in the west of 85°E and southwesterly within 85°–100°E, indicating the important role of SBT in the BOB area. The correlation vector is northeasterly in South China, which is located to the east of Yunnan. The precipitation from April to June in Yunnan Province is affected by the southwesterly water vapor transport in the west and easterly water vapor transport in the east, but the contribution from the west is more significant. Meanwhile, a significant enhancement trend of the geopotential height field is seen. In order to reveal the role of SBT, Fig. 5 also plots the correlation between the precipitation in Yunnan and the vorticity at 850 hPa in this period. The thick and thin lines in Fig. 5 represent the 99% and 95% confidence levels, respectively. The distribution of the correlation between the precipitation and vorticity is in good agreement with the correlation between precipitation and wind. The largest positive correlation centers are located in the north of the BOB and the east of Sri Lanka, respectively. Compared with the climate average position of SBT from April to June, it is found that when the trough is stronger and deeper, the southwesterly water vapor transport in front of the SBT is favorable for more water vapor and therefore more precipitation in Yunnan. On the contrary, if the height field over the BOB is higher and the SBT is weaker, this condition will be against precipitation and in favor of drought occurrence and development.

Figure 6 shows the average atmospheric circulation and anomaly field from April to June in 2019. The solid line represents the geopotential height at 500 hPa and the yellow area indicates the positive anomaly over 15 gpm. There is positive geopotential height anomaly from the Arabian Sea to Yunnan. The anomaly value is higher than 15 gpm. Compared with the climatology, the 5860-gpm geopotential height contour is located to the north of 20°N and the south boundary of the 5880-gpm contour enclosed area is to the south of the equator. This indic-
ates that the geopotential height field in the BOB is obviously higher. Combined with the results above (Wang and Wang, 2018), such a circulation situation is conducive to the occurrence and development of drought in SWC in spring. For the wind anomaly at 850 hPa, there is an extremely strong anticyclonic circulation in the BOB. The southern boundary of the anticyclonic circulation is extending across the equator and reaches the Southern Hemisphere. Its northern boundary is located in the south of the Tibetan Plateau. Based on the relevant results in Fig. 5, it is easy for this anticyclone circulation center to weaken the southwesterly water vapor transport over Yunnan, and this is the most direct reason for drought occurrence in Yunnan from April to June.

The extreme characteristics of the SBT or cyclonic circulation intensity in the lower layer from April to June 2019 are further analyzed. The normalized values of the geopotential height and vorticity of each layer centered in the BOB (80°–100°E average) are given here. In the geopotential height field, the whole troposphere to the south of 20°N exceeds one standard deviation (Fig. 7a). The two strongest centers are located in the middle troposphere of the near-equatorial region and north of the BOB, with center values exceeding 2.5. For a three-month average, this value indicates that the geopotential height is abnormally strong. The vorticity values of each layer are also given (Fig. 7b). It can be seen that its distribution is obviously different with that of the geopotential height. The negative center below −1 is mainly located in the BOB area at a level lower than 500 hPa, which is consistent with the geopotential height field in Fig. 7a. Other than the obvious anomaly of the geopotential height in the near-equatorial region shown in Fig. 7a, the negative vorticity intensity in this region is not strong. It can be seen from Fig. 7 that the strongest vorticity center is located in the central area of the BOB, ranging from 15°N to 20°N. This position is consistent with locations of the strongest correlation center in Fig. 5 and the anticyclone circulation center in Fig. 6. As shown in Fig. 7, the intensity of the SBT is abnormally weak from April to June 2019, whether it is characterized by the geopotential height or vorticity.

5.2 Characteristics of intraseasonal circulation anomalies

The three-month average atmospheric circulation anomaly on seasonal timescale is analyzed above. Since May is the period of seasonal transition, coincident with the start of the summer monsoon and initiation of rainy season in 2019, we focus on May and divide the related

Fig. 6. The geopotential height (solid contour; gpm) and its anomaly at 500 hPa (shading; gpm; only values greater than 15 gpm are shown) as well as the horizontal wind anomaly at 850 hPa (arrow; m s$^\text{-1}$) in April–June 2019. The dashed contour denotes the 5860 and 5880 gpm at 500 hPa for the climate mean. The character “A” means the anticyclonic wind anomalies. The grey shading indicates the altitudes over 1500 m.
period into three subseasonal stages: before the onset of SCSSM (1 April–10 May), after the onset of SCSSM to the onset of SWRS (11 May–10 June), and after the onset of SWRS (11 June–30 June). Thereafter, the circulation and especially the SBT characteristics during the three subseasonal periods/stages are analyzed.

Before the onset of the monsoon, the southerly flow is established in Somalia, but located to the west of its climatological position (Fig. 8a). The BOB CEF and westerly flow over the north side of the tropical Indian Ocean have not been established. There is an anticyclonic circulation anomaly at 850 hPa over the BOB, but the 500-hPa geopotential height anomaly is not strong, being around 10–20 gpm. Induced by the anticyclonic anomaly, the westerly water vapor transport over Yunnan during this period mainly comes from the extratropical area to the north of 20°N, while the traditional main water vapor source and southwesterly wind component on the east side of the BOB, are weak. This anticyclone anomaly circulation also caused the center of the positive westerly anomaly in the Indian Ocean to be located from Myanmar to the south of SWC. At the same time, the original wind field shows that the southwesterly water vapor transport from the north of Yunnan reaches Sichuan Province and the south of Northwest China, leading to obviously increased precipitation in these areas, while the water vapor in Yunnan is insufficient with less rain (figures omitted).

During the period from the onset of SCSSM to the beginning of SWRS (Fig. 8b), the middle layer of the troposphere in the BOB is still controlled by a positive geopotential height anomaly 20–30 gpm higher than usual, resulting in a stronger-than-normal anticyclonic wind anomaly in this area. Although the Somali CEF further enhances and the CEFs in the BOB and South China Sea have been established, this anticyclonic anomaly circulation can force the meridional component of the southwesterly water vapor flux in the BOB to weaken continuously. The location of the water vapor transport is more inclined to South China and southeast coast of China. Therefore, during this period, there is more precipitation in South China and southeast coast of China, but less precipitation in Yunnan (figures omitted). After the beginning of SWRS (Fig. 8c), the west side of the BOB and the middle troposphere in the northeast of India are still controlled by the positive geopotential height anomaly. The anticyclonic circulation anomaly in the lower layer induces easterly anomaly between 10°N and 20°N, and the easterly anomaly component also appears on the west side of Yunnan, which indicates that the water vapor intruding into Yunnan in this period is still weak. Compared with Fig. 5, Fig. 8 shows that the water vapor transport anomalies on the east side of Yunnan are different during different periods, among which the anomalous westerly component appears in the first two periods before the onset of SCSSM, being consistent with the relevant results in Fig. 5. However, in the period from mid–late May to June (Fig. 8c) with the most severe drought, the easterly anomaly in the east part of Yunnan Province indicates a non-typical circulation condition for spring–summer drought. In summary, the anticyclonic anomaly in the BOB maintaining for the above-mentioned three stages causes the continuous weakness of the water vapor intruding into the west of Yunnan. This is the main reason for the development and maintenance of the drought in Yunnan from April to June 2019.

Furthermore, the vorticity anomalies in the BOB from April to June and from the monsoon onset to the end of June are compared with each other. Combined with Fig. 5, the area of 0°–25°N, 80°–100°E is selected to calcu-
Fig. 8. The wind field (stream line; m s$^{-1}$) and its anomaly (arrow; m s$^{-1}$) at 850 hPa as well as the geopotential height anomaly at 500 hPa (shading; gpm; only values greater than 20 gpm are given) during (a) 1 April–10 May (before the onset of SCSSM), (b) 11 May–10 June (from the onset of SCSSM to that of rainy season in SWC), and (c) 11–30 June (after the onset of rainy season in SWC). The character “A” means the anticyclonic wind anomalies. The grey shading indicates the altitudes over 1500 m.
late the regional mean. According to the three-month average results, the vorticity has a significant weakening trend after the 2007 (Fig. 9), which is consistent with the interdecadal decrease of precipitation in Yunnan from April to June since 2007 (figures omitted). On the interannual scale, 2019 is the second lowest since 1981, second only to 2010. The results of Fig. 1 also show that a severe meteorological drought occurred in Yunnan in spring 2010. The number of days with an extreme drought area of more than $10^5$ km$^2$ is 7, second only to 2019. If only the period after the onset of SCSSM is considered, the vorticity value at 850 hPa over the BOB is the lowest since 1981. Therefore, the SBT in the BOB is abnormally shallow from the middle–late spring to the early summer. The statistical results also show that 2019 is also the year with the largest negative vorticity anomaly after the summer monsoon. The results of Fig. 9 show that from April to June 2019, the strength of SBT is not only weak but also features a long duration, resulting in the continuous weakening of the southwesterly water vapor transport in front of the trough and continuous deficient precipitation in Yunnan, thus causing the occurrence and rapid development of the 2019 Yunnan extreme drought.

The abnormal enhancement of the anticyclone in the BOB or weakness of the SBT leads to the obvious weakening of water vapor convergence in the lower troposphere over Yunnan Province. The water vapor budget at 700 hPa over Yunnan (22.5°–27.5°N, 97.5°–105°E) is examined. By comparison of the daily water vapor flux divergence and the corresponding climatology in Yunnan Province from April to June of 2019, it can be seen that the water vapor budgets in the lower layer are quite different in different periods (figures omitted). In April, the divergence value of the water vapor flux is close to the climate value, because the water vapor intruding into Yunnan before the onset of summer monsoon over the BOB and the South China Sea is related to the circulation over the BOB, but also affected by the midlatitude westerly system. In May, when the monthly increase of precipitation in Yunnan is the most obvious, the divergence value in Yunnan is almost higher than the climate value for the whole month, indicating that the convergence of water vapor in the lower layer is weak and the circulation condition is not conducive to precipitation. Compared with May, the net income of water vapor in June is better, but it is still lower than the climate value in most periods. Therefore, the shortage of water vapor income at the lower level from May to June is the direct reason for drought.

The precipitation in the beginning of the rainy season in Yunnan is closely related to the onset of the southwest summer monsoon in the BOB. By case analysis, Zheng and Duan (2005) pointed out that the early and strong onset of BOB monsoon is the direct reason for the early start of rainy season and excessive rainfall in Yunnan in 2001. Liu et al. (2007) found that the frequency of low pressure in the BOB in early summer has a significant negative correlation with the start of the rainy season in Yunnan Province, and the low-pressure system is condu-

![Fig. 9. The standardized vorticity at 850 hPa averaged over 0–25°N, 80°–100°E during April–June (hollow bar) and 11 May–30 June (solid bar). Yellow and red highlight the year 2019.](image)
cive to more precipitation in early summer. The daily real-time monitoring of OLR in the BOB area by the NCC (figures omitted) shows that the OLR in this area usually drops below 225 W m\(^{-2}\) in the second pentad of May. But for 2019, the OLR in the BOB region briefly dropped to 225 W m\(^{-2}\) at the end of April and beginning of May, and then rapidly rose to more than 225 W m\(^{-2}\) again at the end of the first 10 days of May, afterward steadily dropped to below 225 W m\(^{-2}\) until 26 May. It is almost 20 days later than the climatology. The lagging onset of the deep convection in the BOB in 2019 results in the late outbreak of the BOB summer monsoon. It is also directly related to the continuous enhancement of the abnormal anticyclone in the BOB mentioned above, which is also the main reason for the sustained drought in Yunnan in May, and is consistent with the research results of Zheng and Duan (2005) and Liu et al. (2007).

5.3 Influences of the Australian high

From Fig. 8, it can be seen that the weaker-than-normal SBT mainly appears after the onset of the summer monsoon from mid-May to June. Therefore, the correlations between the vorticity and sea level pressure (SLP) and wind field at 850 hPa over the BOB during 11 May–30 June of 1981–2018 are calculated (Fig. 10). It is shown that the SLP signals that affect the intensity of the anticyclone in the BOB in this period mainly come from the Southern Hemisphere, in which the southwest Indian Ocean is a significant negative correlation region, and the main body of Australia and its south side is a significant positive correlation region. This indicates that the Mascarene high and Australian high have a significant impact statistically. Similar to SLP, the signal of the wind field at 850 hPa manifests the cyclonic correlation vectors in the southwestern Indian Ocean, especially the east side of South Africa and Mascarene Islands (marked with “C” in the figure), while the main body and south of Australia are anticyclonic correlation vectors (marked with “A” in the figure). This shows that when the Australian high is strong, it is easy to stimulate the southeast wind anomaly component in its northeast side, leading to the strengthening of the east wind anomaly in the equatorial Indian Ocean, especially in the BOB in Northwest Australia. At the same time, if the Mascarene high to the west of it is weak, the northwest side of the Mascarene high is prone to stimulate an anomalous northwesterly, further enhancing the easterly anomaly over the BOB. The easterly anomaly over the equatorial region of the BOB favors the maintenance of the anticyclone over it.

Figure 11 shows the SLP and 850-hPa wind anomaly field at 11 May to 30 June of 2019. Compared with Fig. 10, the case in 2019 shows similar characteristics with the correlation analysis. The most significant circulation anomaly in the SLP anomaly field appears in the Southern Hemisphere, especially in Australia, where the high pressure is significantly stronger, and anomalous values in the south is more than 3 hPa. The northern part of the Mascarene high pressure, however, is a negative anomaly area. Corresponding to the relevant results, in this period of 2019, the component of southeast wind anomaly is to the northeast side of Australia, and then converges along the north side of Australia and flows into the equatorial region. The easterly anomaly along the equator is the most significant over the BOB, which is conducive to stimulating and maintaining the anticyclo-

![Fig. 10. Distribution of the correlation between the 850-hPa vorticity over the Bay of Bengal (BOB) and SLP (blue and yellow shadings, and contours; the shadings are at the 95% and 99% confidence levels, respectively), and the wind field (arrow) during 11 May–30 June of 1981–2018. The grey shading indicates the altitudes over 1500 m.](image-url)
nic circulation anomaly over the BOB. In contrast, the negative anomaly on the north side of the Mascarene high is not significant enough in 2019. Therefore, the entirety of the overall circulation pattern is similar to the related results, but the anomalous value is relatively small, especially to the west of 80°E, the equatorial region is covered by the westerly anomaly component, which is inconsistent with the correlation analysis. Thus, it can be concluded that the strong Australian high in spring and early summer of 2019 has led to the strong anticyclone anomaly over the BOB and the weak SBT.

6. Conclusions and discussion

From April to June in 2019, record-breaking drought occurred in Yunnan Province, which lasted for a long time and is extremely severe. The number of days with drought areas of over $10^5 \text{ km}^2$, i.e., suffering from very severe drought, in 2019 is far more than that in other years. The drought is directly accompanied by continuous deficiency of precipitation in Yunnan. The rainfall amount is 30% less than normal during five consecutive months, from February to June. During the most concentrated period of drought occurrence and development, from April to June, the precipitation is 43% less than normal, which is the lowest year since 1961. Although the onset of the South China Sea Summer Monsoon (SCSSM) is in the second pentad of May, which is two weeks earlier than usual (the 5th pentad of May), the Southwest China rainy season (SWRS) in 2019 began in the third pentad of June, which is the second later in history. The start day of rainy season in Yunnan is 24 June, 29 days later than usual, which is the latest in history. Concentrated dry and rainy seasons are characteristics of precipitation in Yunnan. The unusually late rainy season and large PET further induced drought in the late spring and early summer of 2019.

For the climatological mean, the start of SWRS lags behind the onset of SCSSM for less than one pentad. It is found that the early onset of SCSSM is conducive to more precipitation in the subsequent rainy season in SWC. However, why did the onset of Yunnan rainy season delay more than one month after the onset of SCSSM in 2019? The statistical results show that the geopotential height field from the Arabian Sea to west of South China has a significant negative correlation with precipitation in Yunnan from April to June, with the most significant negative correlation center located over the BOB. In the low-level wind field, the precipitation in Yunnan from April to June is affected by the water vapor transport from the BOB in the west and east, but the contribution from the west is more significant. From April to June in 2019, a positive geopotential height anomaly occurs over an area from the Arabian Sea to Yunnan, and the anomaly in the northern part of the BOB exceeds 2.5 standard deviations. There is an extremely strong anticyclonic circulation in the BOB with the negative vorticity below 500 hPa in this area less than one standard deviation than normal, weakening the meridional water vapor transport over Yunnan. From the atmospheric circulation perspective, these are the most direct reasons for the lack of rainfall in spring and summer in Yunnan.

By focusing on three stages of the drought development, that is, before the onset of SCSSM, from the onset of SCSSM to the onset of SWRS, and after the onset of SWRS, it is found that the SBT is continuously weak during the above-mentioned three periods, because of the
Development of drought in Yunnan. Drought monitoring through oceanic and atmospheric processes. SST anomalies and teleconnections are key factors. Oceanic northern equatorial Pacific SST are all conducive to the occurrence and development of El Niño, decaying La Niña, and warming Indian Ocean. Ren, 2016). Tao et al. (2014) pointed out that the development of drought in Yunnan in 2019. However, the mechanism reflected in winter on the interdecadal timescale (Lu and Liu, 2019). The present study mainly investigated the influence of the continuous weakening of SBT on the spring–summer drought in Yunnan in 2019. However, the mechanism responsible for the continuous weakening of SBT has not been analyzed yet, which might be related to the effect from the tropical sea surface temperature (SST). Previous studies indicate that the tropical Indian Ocean has a direct impact on SBT, but this relationship is often reflected in winter on the interdecadal timescale (Lu and Ren, 2016). Tao et al. (2014) pointed out that the developing El Niño, decaying La Niña, and warming Indian Ocean SST are all conducive to the occurrence and development of drought in Yunnan. Drought monitoring shows that there was an El Niño developing in the central–eastern equatorial Pacific Ocean since September 2018, which peaked in November 2018. At the same time, the Indian Ocean basin wide mode (IOBW) index was positive since November 2018 (Ding and Gao, 2020), but both the El Niño and IOBW indices were not strong. Therefore, it is perhaps necessary to analyze how the early tropical SST anomalies induce a continuous weakening SBT.

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