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The influence of sensible heat on monsoon precipitation in central and eastern Tibet

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ABSTRACT: The sensible heat over the Tibetan Plateau influences the atmospheric circulation of East Asia and North America, and also the monsoon precipitation on the Plateau. Empirical Orthogonal Function (EOF) analysis of the patterns of the monsoon precipitation at 17 meteorological stations in central and eastern Tibet shows that the sensible heat during May over the central Tibetan Plateau relates closely to the first eigenvector weight time series (EOF1) of the monsoon precipitation for the eastern part of the Plateau from June to September. At the Amdo site the correlation coefficient exceeds 0.7, and the correlation between the EOF1 and the average of sensible heat at five sites (Amdo, Bange, Wudaoliang, Tuotuohe and Gaize) over the central Tibetan Plateau can exceed 0.80. This relationship suggests a mechanism of increased sensible heat flux in central Tibetan Plateau during May causing stronger cyclonic flow and low vortices in this area, resulting in more precipitation during the monsoon season on the eastern Plateau. From May to August, 1979, for example, this sensible heat effect can account for more than half of the precipitation. Based on this relationship, the sensible heat of central Tibet can be used as a 'predictor' of monsoon precipitation in central and eastern Tibet. Copyright © 2010 Royal Meteorological Society

KEY WORDS sensible heat; monsoon precipitation; Tibetan Plateau

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1. Introduction

Sensible heat flux over Qinghai and Tibet plays an important role in influencing atmospheric circulation in East Asia and North America. Wu *et al*. (2002) proposed the existence of an 'air pump' over the Qinghai–Tibet Plateau. The air over and around the Plateau sinks in winter and rises sharply in spring, acting like a giant pump effecting the air flows surrounding the Plateau, with impacts reaching as far as North America. According to the analysis of Liu *et al*. (2002), diabatic heating over the Tibetan Plateau provides the dominant driver of the air pump during the early transition season (before mid-May), causing the temporal variations of total diabatic heating to be in phase with sensible heating. The details of the variations of total diabatic heating and sensible heating show sensible heating to be important to the seasonal changes in Northern Hemispheric circulation (Luo and Yanai, 1983, 1984; Broccoli and Manabe, 1992).

Because boundary sensible heat flux drives the heating, many refer to this as the 'sensible heat pump'. The stronger the sensible heat, the more effective the pump, and *vice versa*. In spring, warm air over the Plateau rises up through the troposphere, sucking in the near-surface air from the surrounding region. This air movement affects the Plateau, its surroundings, and the large-scale circulation of the Asian monsoon region. Recent work (Wu and Zhang, 1998) shows the importance of sensible heating during the onset of the Asian monsoon, and the effects on circulation in the surrounding area. Zhang *et al*. (2002) indicate that longitudinal and latitudinal thermal contrasts caused by sensible heating on the mid-latitude Plateau trigger the onset of the Asian summer monsoon. Zhu (1987) showed that heating of the western Plateau might be responsible for variations of the East Asian circulation in early summer. Zhang *et al*. (1994) suggests that anomalous heating of the Plateau correlates with rainstorms in the Yangtze and Huaihe River basins during summer. A numerical sensitivity experiment by Li *et al*. (1997) demonstrated the circulation response and local climate changes caused by anomalous sensible heat flux on the Plateau. Zhong *et al*. (2004) suggest that sensible heat flux can significantly influence sand/dust storms of northern China. All these studies demonstrate the importance of understanding sensible heat flux in order to explain the intensity of the Asian monsoon and climate change in regions adjacent to the Plateau.

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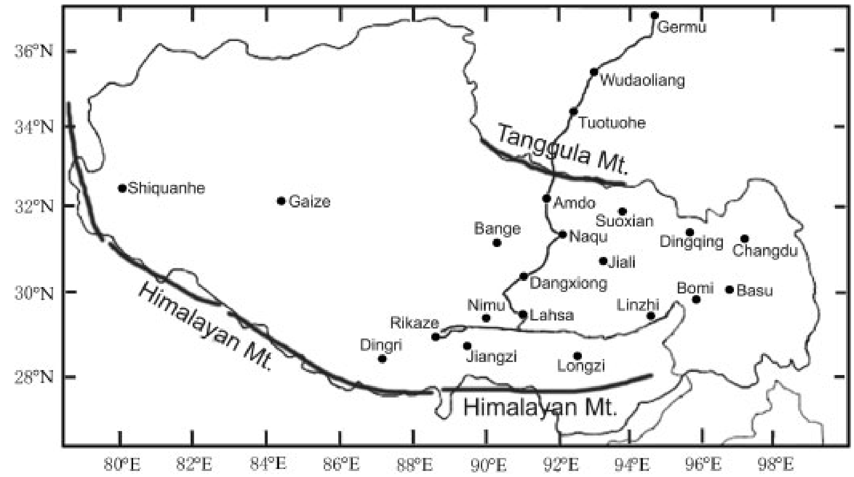

Figure 1. Locations of the observation sites, ● regular meteorological station.

Most water vapour on the Tibetan Plateau during summer and autumn comes from the Bay of Bengal, suggesting that the monsoon precipitation of this area may be an extension of the Indian Monsoon. However, monsoon precipitation on the Plateau does not correlate well with the well known Webster-Yang index (WYI), the correlation coefficient between them being only 0.27 over 40 years (Zhou and Jia, 2003). This means that the monsoon precipitation on the Tibetan Plateau has its own characteristics related to unique local topography (Kuo and Qian, 1981; Tang and Reiter, 1984).

Tang and Reiter (1984) define the Plateau Monsoon Index (PMI) as:

$$PMI = H_1 + H_2 + H_3 + H_4 - 4H_0 \quad (1)$$

where H_0, H_1, H_2, H_3 and H_4 are the anomalies of the 600 hPa geopotential height field at the centre (90 °E, 32.5 °N), east (100 °E, 32.5 °N), west (80 °E, 32.5 °N), south (90 °E, 25 °N), and north (90 °E, 40 °N) of the Plateau.

This index has been useful in forecasting the subsequent precipitation in West China, and also helpful in studying the Indian Monsoon's progress over the Plateau.

Few studies exist to date on the relationship between sensible heat and the monsoon precipitation on the Plateau. Wen *et al*. (2007) suggested that the meridional differences in sensible heat flux on the central Tibetan Plateau during early summer can influence monsoon precipitation on the eastern part of the Plateau. Based on this suggestion, the present study investigated mechanisms by which sensible heat flux on the central Plateau can influence the monsoon precipitation on the eastern part.

2. Data and methods

2.1. Data

The study was carried out in the Tibetan Autonomous Region and the southern part of Qinghai Province (Figure 1). The sensible heat fluxes west of 91 °E, 31 °N were calculated and the Empirical Orthogonal Functions (EOF1) of the precipitation index for the region to the east was established. The Indian Monsoons provide the main control for precipitation during the rainy season in the study area: the southern water vapour from the Bay of Bengal coming into the study area between Linzhi and Bomi. The monsoon precipitation decreases from south to north, with distance from the water source. Table I shows the temperature and precipitation at the study locations.

The data used in this paper include:

1. Regular monthly observations and daily data since the 1950s from meteorological stations distributed over the Tibetan Plateau, published by the Chinese Meteorological Bureau (air temperature at 2 m height, ground surface temperature, and precipitation).
2. The National Centers for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) global atmospheric reanalysis data set (Kalnay *et al*., 1996), including monthly surface temperatures, monthly OLR (outgoing long wave radiation), monthly wind fields at the surface and 200 and 500 hPa, with a resolution of 2.5° × 2.5°.
3. The Indian Monsoon Precipitation index and the monsoon precipitation time series at different parts at different locations (http://www.cdc.noaa.gov/data/climateindices/List/).

2.2. Methods

By analyzing the monsoon precipitation over central and eastern Tibet during June, July, August and September, an anomaly time series of the monsoon precipitation was established. EOF analysis was then used to establish a precipitation index that can represent the precipitation conditions at the time of each large multidimensional data set. The EOF analysis provides a widely used statistical method for analyzing large multidimensional data sets. These can represent the spatial and temporal variability in such sets by using a number of empirical modes, which are required to be orthogonal relative to each other.

Table I. The location and climate condition at the observation sites.

Station	Latitude (N)	Longitude (E)	Elevation (m)	Air temperature (°C)			Precipitation	
				T_a	T_{min}	T_{max}	P_s	P_p
Amdo	32°21′	91°06′	4800	−3.0	−15.0	7.7	411.6	87.9
Bange	31°22′	90°01′	4700	−1.2	−11.3	8.3	189.6	93.0
Bomi	29°52′	95°46′	2736	8.6	−0.2	16.4	876.9	53.5
Changdu	31°09′	96°10′	3306	7.5	−2.6	16.1	477.4	78.5
Dangxiong	30°29′	91°06′	4200	1.3	−10.2	10.7	480.9	86.2
Dingri	28°38′	87°05′	4300	2.7	−7.4	11.8	318.9	96.7
Dingqing	31°25′	95°36′	3874	3.4	−7.1	12.3	487.1	75.1
Jiangzi	28°55′	89°36′	4041	4.7	−3.8	12.8	289.6	91.2
Jiali	30°40′	93°17′	4490	−0.9	−11.9	8.3	520.7	72.3
Lhasa	29°44′	91°08′	3648	7.5	−2.3	15.4	444.8	92.4
Longzi	28°25′	92°28′	3860	5.0	−4.7	13.0	279.4	90.0
Linzhi	29°34′	94°28′	3000	8.6	0.2	15.5	654.1	71.6
Naqu	31°09′	92°00′	4507	−1.9	−13.8	8.8	406.9	84.6
Nimu	29°26′	90°10′	3811	7.2	−2.9	15.1	308.2	88.5
Rikaze	29°15′	88°53′	3836	6.8	−3.8	14.5	431.5	95.8
Suoxian	31°53′	93°47′	4024	0.9	−8.7	10.2	455.1	78.3
Zedang	29°15′	91°46′	3553	6.4	−2.1	16.3	350.8	87.6

T_a, mean annual temperature.
T_{min}, mean monthly temperature of the coldest month.
T_{max}, mean monthly temperature of the hottest month.
P_s, mean annual precipitation (mm).
P_p, the percentage of precipitation during June, July, August, September.

EOF analysis can be used to decompose the observed variability into a set of orthogonal spatial patterns that are invariant in time (Singh, 2004). Calculating the temperature differences between the air at the 2 m level and ground level yields sensible heat flux time series during May for the Amdo, Bange, Tuotuohe, Wudaoliang and Gaize meteorological stations. The relationships between the indices and the sensible heat flux time series were then calculated. Lastly, the mechanisms by which the sensible heat on the central Plateau during early summer influences monsoon precipitation over the central and eastern parts of the Plateau were established by contrasting the composites.

3. The Indian monsoon precipitation over central and eastern Tibet

Most of the water vapour falling as monsoon precipitation on the central and eastern Plateau comes from the Bay of Bengal and Indian Ocean. According to Yang *et al.* (1987) and Gao *et al.* (1985), the water vapour passes the Brahmaputra-Yarlung Zangbo (Tsangbo) River and flows onto the Plateau. The monsoon start times and precipitation amounts show continuous variations along the river from northeastern India to the Plateau, suggesting that monsoon precipitation over the Plateau is a component of the Indian Monsoon. However, after the water vapour from the Bay of Bengal passes through the Great Yaluzangbu River Canyon (funneled by the canyon's deep incision in the high relief terrain), the precipitation varies greatly. According to Ueno (1998), the correlation coefficient of monsoon precipitation between two points over the Plateau varies with the distance between measuring points, the greater the distance, the lower the coefficient. In recent years, more and more reports emphasize the importance of local convection on monsoon precipitation over the Plateau (Yang *et al.*, 2004, 2006). Yang *et al.* (1990) reported strong and active cumulus activity in the area, very important for the maintenance of the large-scale circulation field on the Plateau. Based on the precipitation's $\delta^{18}O$ ratios, only 32% or less of total precipitation derives from transported ocean-air-vapour: and at least 48% of the precipitation derives from local evaporation vapour. The remaining 20∼22% may come from the transport of monsoon circulation with evaporation vapour in transit. Although monsoon precipitation fluctuates greatly over Tibet, the variation of the precipitation remains consistent within any given area. Lin and Wu (1990) suggest that the furthest distance that water vapour from the Bay of Bengal can reach would be 40 °N, 75 °E, which is beyond the current study area. The EOF analyses of Wei *et al.* (2003) and Zhou *et al.* (2000) indicate that the monsoon precipitation over the entire Tibet Autonomous Region south of the Tanggula Mountains shows a coherent variation because of similar EOF1 results. This indicates that monsoon precipitation within the study area shows simultaneous variations under both the influence of the Indian Monsoon and local convection.

This study provides an EOF analysis of the precipitation anomaly time series for 17 sites on the central and eastern Plateau during 1974–2004. Table II shows that the first eigenvalue can explain nearly half, and

Table II. The eigenvalues and their explained variance in the EOF analysis on the monsoon precipitation in the central and east plateau.

	Eigenvalue	Accumulative variance (%)
The first	1.9373	49.5
The second	0.6115	65.1
The third	0.4109	75.6

the first three eigenvalues more than three quarters, of the variance, indicating the potential value of the EOF analysis.

Figure 2 describes the eigenvector field of the EOF analysis. Note that all of the study area shows a positive feature indicating that the main variations of the monsoon precipitation show simultaneous variations. Consequently, the first eigenvector weight time series (EOF1) can represent the monsoon precipitation in the central and eastern part of the Plateau, due to the high first eigenvalue.

In order to extend the EOF1 time series, another EOF analysis was performed on the precipitation by interpolating where data were missing. When the span of the time series was extended back from 1974 to 1966, the output of the new EOF shows almost the same results as previously.

A correlation analysis between the longer EOF1 and the monsoon precipitation anomaly time series of observations from the 17 stations show that 16 locations pass the 0.01 level test (the exception being Dingri, where the significance test levels do not pass the 0.05 criterion) (Figure 3). Consequently, this study concludes that the index can represent the monsoon precipitation of the study area.

Analysis of the index time series of EOF1 (Figure 4), demonstrated a slowly increasing trend. The correlation coefficient between the linear trend and the corresponding time is 0.302, however the analysis does not pass the 0.05 significance test ($p = 0.058$), a conclusion similar to that found by Du and Ma (2004). This may result from the increase in precipitation caused by an acceleration of water vapour circulation (IPCC, 1995; Li, 1999). This indicates that EOF1 can reflect real conditions of the monsoon precipitation over the central and eastern Tibetan Plateau.

4. The relationship between the EOF1 of the monsoon precipitation in central and eastern Tibet and the sensible heat flux over central Tibet

Because the sensible heat from April to June dominates the diabatic heating over the Tibetan Plateau, the current hypothesis was tested by using the sensible heat during May to represent late spring and early summer.

Because the temperature difference between the air and ground controls the sensible heat flux, these differences were used to replace the sensible heat flux for simplifying the calculations (Jiang and Wang, 2000; Zhang *et al.*, 2006; Wen *et al.*, 2007). High correlation coefficients were found when comparing the anomaly of the sensible heat flux time series (temperature difference between 2 m air and ground) during May from 1966 to 2003 with that of April and June (Table III). The coefficient for the average of April, May and June reached 0.90. This indicates the feasibility of replacing the sensible heat during April, May and June by that of the single month of May.

According to Wen (2007), the differences of heat flux during May between Amdo and the several southern

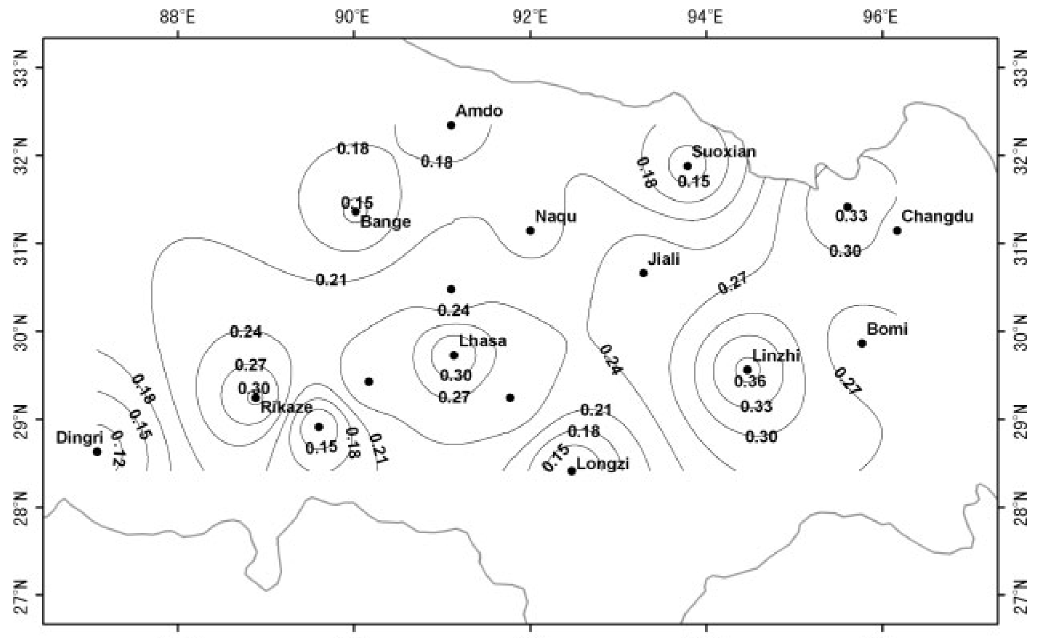

Figure 2. The first eigenvector field of the EOF analysis on the monsoon precipitation in the central and eastern parts of the Plateau.

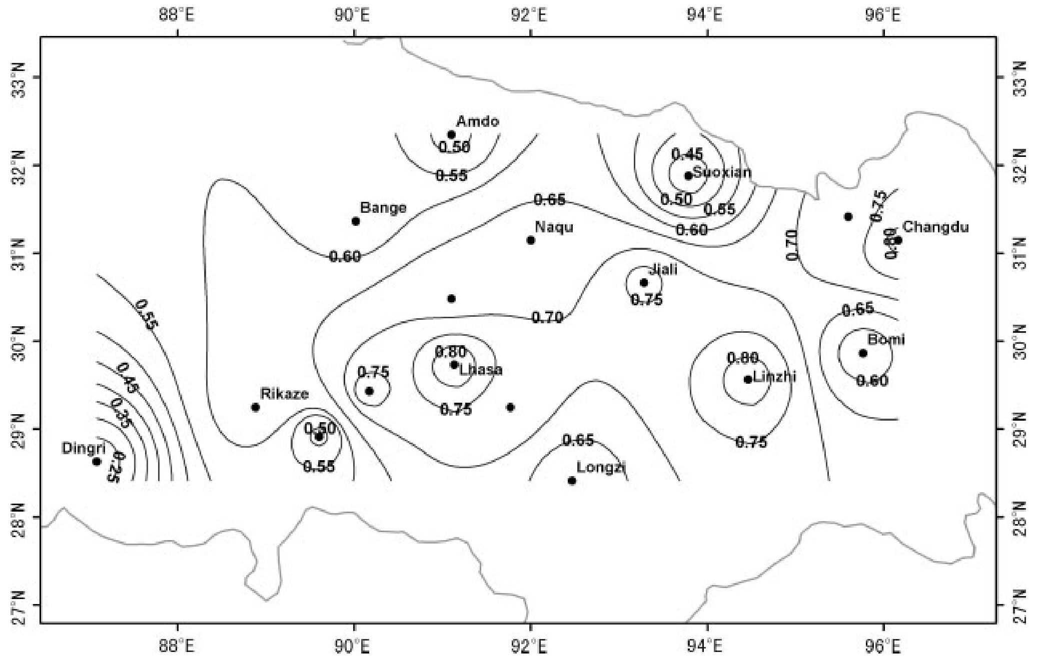

Figure 3. The correlation coefficient between the EOF1 of the monsoon precipitation on the Plateau and the time series of sensible heat flux during May at 16 meteorological stations.

Table III. The relation coefficient between sensible heat flux during May and that of the other year, as well as that of the average of April, May, June.

	April	May	June	Average of AMJ
May	0.559[a]	1	0.604[a]	0.902[a]

[a] Indicate significant at 99% level.
The average of AMJ is the anomaly time series of the mathematic average of the sensible heat flux of April, May and June.

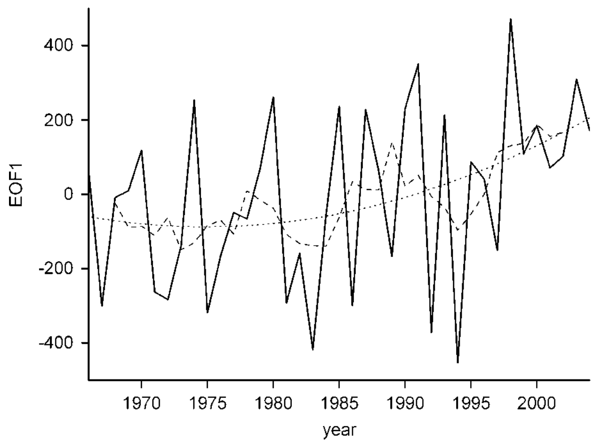

Figure 4. The first eigenvector field of the EOF analysis on the monsoon precipitation in the central and eastern part of the Plateau. Bold line is EOF1, dash line the 5 year smoothing of EOF1, and dot line the trend.

meteorological stations correlate with the subsequent monsoon precipitation on the central and eastern parts of the Tibetan Plateau; and the sensible heat flux at the centre of the Plateau plays a key role in influencing the monsoon precipitation. A latitudinal shear line of horizontal wind flows across the Plateau near 32 °N (Figure 5) and divides the Plateau into parts along distinct geographical features. Air flowing from the south converges along this line with air flowing from the north, forming a synoptic system. The influence of sensible heat on the precipitation can change the convection of the shallow boundary layer: the higher the sensible heat flux, the stronger the convection. Because of the location of Amdo, the high sensible heat flux can result in low air pressure near the surface layer over the central portion of the Plateau. Water vapour from the south can push further northward, and result in more precipitation over the eastern parts of the Plateau. Because of its persistence observed by Duan *et al*. (2003), the sensible heat flux can influence the subsequent monsoon precipitation. Based on this pattern, the relationship between the sensible heat flux over the central Plateau and the monsoon precipitation of the eastern Plateau were analyzed by correlating their time series. Before the analysis, the two time series must be random with respect to any systematic trends. The linear trend of the sensible heat at Amdo is not significant, with $r = 0.293$, $p = 0.075$, and (as discussed previously) the apparent linear trend of the sensible heat at Amdo is also not significant, with $r = 0.293$, $p = 0.075$. Consequently, this study concludes that the cross correlation analysis is valid. The 1974–2004 time series result shows a good correlation between the sensible heat flux over the central Plateau and the monsoon precipitation on the eastern Plateau: the correlation coefficient reaches 0.730 (Figure 6), and passes the 0.01 significant level test. For the longer period (1966–2004), the relationship does not match the relationship of the shorter period, however, the correlation coefficient still exceeds 0.587.

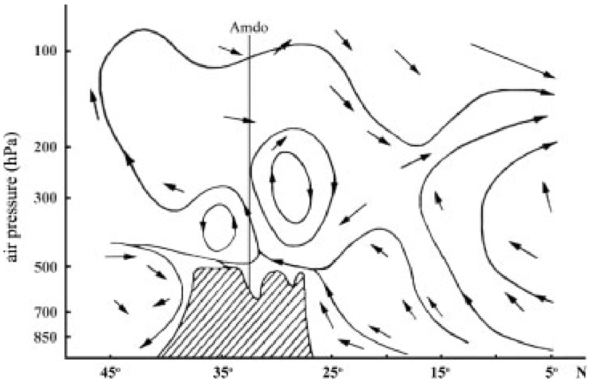

Figure 5. The average circulation during July along 90 °E (vertical velocity scaled up 200-fold).

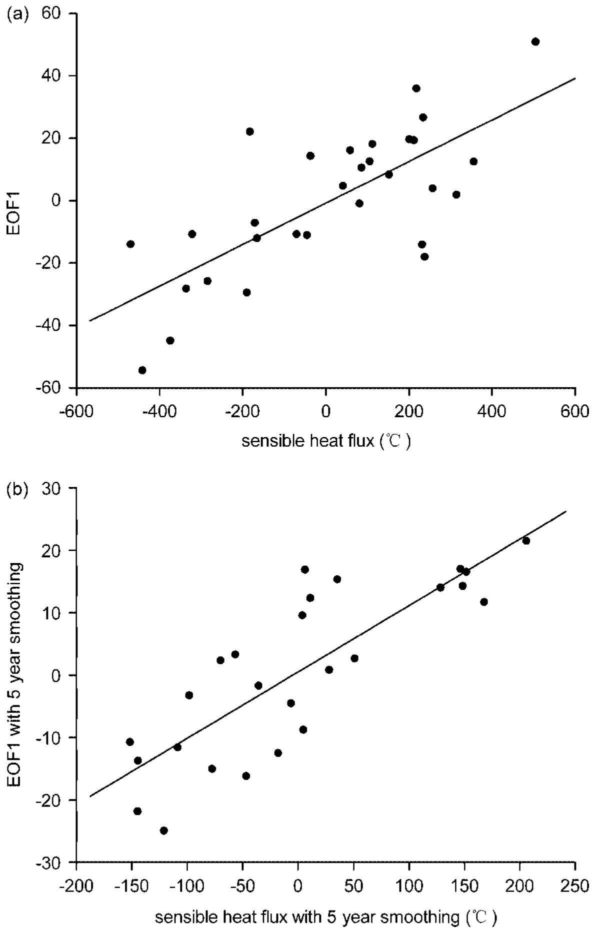

Figure 6. The relationship between the sensible heat flux at Amdo site during May and the EOF1: (a) the raw data, $y = 0.814 \times +10.587$, $r = 0.730$ and (b) the data by 5 year smoothing, $y = 6.367 \times -3.229$, $r = 0.823$.

In order to prove the hypothesis outlined above, the correlation coefficients for other sites were calculated (Table IV). The results show that similar relationships also exist at Tuotuohe, Gaize, Bange and Wudaoliang, (the three sites other than Gaize that pass the 0.05 significant level test). Averaging the standardized anomaly time series of sensible heat fluxes at Amdo, Tuotuohe, Gaize, Bange and Wudaoliang, provides a new time series

Table IV. The relation coefficient between sensible heat flux during May and EOF1 of the monsoon precipitation.

Site	Amdo	Bange	Gaize	Tuotuohe	Wudaoliang	Average
n	31	25	30	30	25	25
A	0.730[b]	0.500[a]	0.338	0.365[a]	0.415[a]	0.806[b]

[a] Indicate significant at 95% level.
[b] Indicate significant at 99% level.
n, the number of the sample.
A, the relationship coefficient between sensible heat flux and EOF1.

to represent the sensible heat conditions on the central Tibetan Plateau. Because the meteorological observations at Bange and Wudaoliang do not begin until 1979, the time series are relatively short. However, the correlation coefficient between the new time series and EOF1 of monsoon precipitation on the eastern Tibetan Plateau reaches 0.806, and passes the 0.01 significance test. These calculations demonstrate a relationship between the sensible heat flux and precipitation.

Studies using the 2–3 year period of the monsoon precipitation over the eastern Tibetan Plateau (Wei *et al.*, 1999; Liu *et al.*, 2003) reveal the trends of both the precipitation and sensible heat flux' and indicate a very high correlation between the sensible heat flux and the precipitation EOF1 after 5a smoothing. The correlation coefficient at the Amdo site reaches 0.823. The sensible heat flux and precipitation index show very similar trends, so the sensible heat flux on the central Plateau during May can potentially be used as a 'predictor' of monsoon precipitation in the eastern Plateau. Because no meteorological observations exist over the broad area between Gaize and Bange, other approaches are necessary to prove this relationship.

5. A mechanism by which the sensible heat flux can influence the monsoon precipitation over the eastern Tibetan Plateau

Figure 7 indicates atmospheric circulation, which was explored as a mechanism affecting the influence of sensible heat flux on the monsoon precipitation. The year of 1998, with the highest sensible heat, was chosen for analysis, and 1983, with the lowest, for contrast. Figure 7(a) and (b) suggest a shear line along 33 °N in the surface wind field, where winds south of 33 °N and north of 33 °N converge. Amdo lies near this line. The stronger circulation of 1998 is more likely to form cyclones than the lesser winds of 1983.

In the 500 hPa wind field (Figure 7(c) and (d)), the Westerlies prevail over the entire Tibetan Plateau, with the intensity of winds in 1998 weaker than those of 1983.

A large anticyclone exists at 200 hPa. The intensity of the anticyclone in 1998 exceeded that of 1983.

In order to define years with higher and lower sensible heat years, the average sensible heat flux from June to September was standardized by subtracting the mean and dividing by the standard deviation (SD). A year with a value >1.0 SD was defined as a year with high sensible heat. Conversely, a value <−1 SD was defined as lower sensible heat. Based on this division, there were 4 years with high sensible heat (1998, 1987, 1985, 1968) and 7 years with low sensible heat (1983, 1992, 1982, 1975, 1981, 1970, 1971). The standard of selecting the representative year is usually 1 SD (Pan *et al*., 2005; Wang and Qian, 2009; Yan *et al*., 2009) and the fraction of selected years to the total number is one third to one-fourth. When the number of the selected years is few, the standard can extend to 0.8 SD (Liu *et al*., 2006). Composite analyses of the 500 hPa and surface wind fields, outgoing long radiation (OLR), and ground surface temperatures were used to study the impact of sensible heat on monsoon precipitation (Figure 8).

- 500 hPa and surface wind fields: The surface air pressure at Amdo, Naqu, and other adjacent sites varies around 570 hPa. Consequently, the surface and 500 hPa winds were used to represent the boundary layer water vapour transport direction. From both Figure 5(a) and (b), one can identify relative large scale convection circulation located near 30 °N, 90 °E. The centre of this convection lies very close to Amdo, which can lead to more precipitation over the central and eastern parts of Tibet.
- OLR: As an indicator of cloud cover, OLR can reflect the local convection and precipitation conditions over the Plateau (Wang and Zhong, 1992; Liu and Li, 2007).

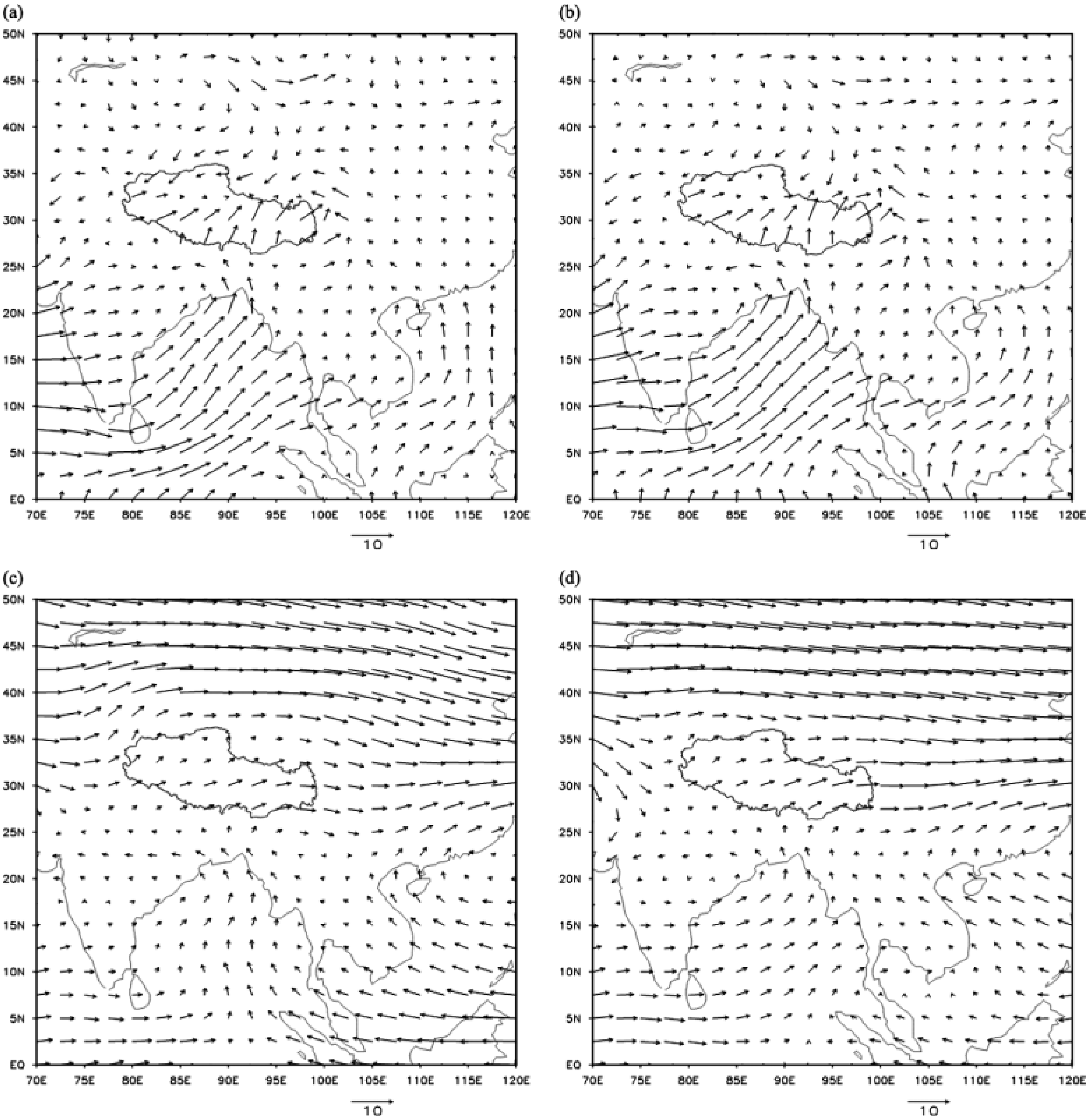

Figure 7. The wind field at surface: (a) 1998; (b) 1983; 500 hPa, (c) 1998; (d) 1983; 200 hPa, (e) 1998; and (f) 1983.

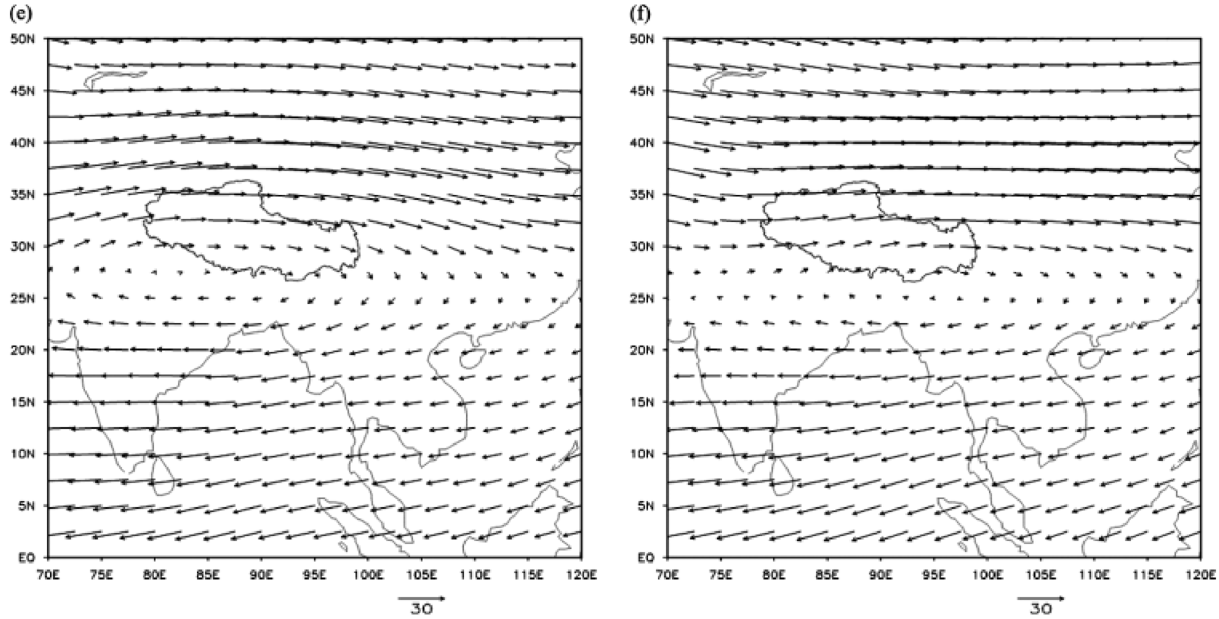

Figure 7. (*Continued*).

Figure 5(c) indicates that the convection is stronger during the four higher sensible heat years than in the lower 7 years, and that the strongest area lies over the eastern Plateau, with a boundary about 80–105 °E, 20–32 °N.

- Ground surface temperatures: Higher ground surface temperatures indicate stronger convection and lower air pressure near the ground surface. However, the temperature difference between the continental and ocean areas determines the intensity of Indian monsoon, so a higher ground surface temperature may result in a stronger Indian Monsoon. From Figure 5(d), one can expect higher ground surface temperatures in the higher sensible heat flux years than in the years with lower sensible heat.

6. Discussion

Since the 1980s, Tang has used ground temperatures from the previous winter and spring to predict the subsequent monsoon precipitation. Tang found that (1) the 0.8 m depth ground temperatures during the winter on the eastern Tibetan Plateau play an important role on the subsequent spring precipitation in eastern China (Tang *et al*., 1984, 1987a), (2) that the 1.6 m depth ground temperatures in the eastern Tibetan Plateau can used to forecast whether the precipitation during the following monsoon season will be above or below normal (Tang *et al*., 1987b), and (3) temperatures at a depth of 3.2 m in China can be used to forecast the future monsoon conditions for the country (Tang and Zhang, 1994), and this idea was also validated in the U.S.A (Tang and Reiter, 1986). However, the mechanism of the ground temperature on monsoon precipitation is not so clear. Tang reports a belief that monsoon precipitation relates to ground temperatures during the preceding winter. These studies suggest similarly that the sensible heat during May (represented by the temperature difference between the ground and air) relates to the monsoon. Hence, the influence of ground temperatures on monsoon precipitation can easily be explained by the sensible heat.

According to the study by Yang *et al*. (2004), two factors contribute to the monsoon precipitation in central and eastern Tibet: the Indian monsoon and the precipitation resulting from local convection. Sensible heat flux may contribute to both of these components.

Three branches of ocean water vapour flow can influence the monsoon precipitation over the eastern Tibetan Plateau: one from the Arabian Sea to the west of the Plateau (near 86 °E and across the Himalaya Mountains), one from water vapour ascending the Himalayan Mountains, and, most importantly, the water vapour from the Bay of Bengal. The strong thermal divergence caused by the low pressure cell over the Tibetan Plateau and high pressure over the surrounding oceans controls the general moisture transport during the Indian summer monsoon, and produces north- to northwestward, counterclockwise humid eddies originating in the Bay of Bengal. The Indian Monsoon Trough and monsoon low pressure are important weather systems for both the Tibetan Plateau and northeast India during the monsoon season. The calculated EOF1 does not appear to be correlated with the All Indian Monsoon Precipitation Other scientists also found this relationship. For example, Xu and Gao (1962) found that a monsoon over the Tibetan Plateau differs from either the East Asian Monsoon and the Indian Monsoon; and Tang and Reiter (1984) report that this special Plateau monsoon exists on both the western American plateau and the Tibetan Plateau; and the study of Wei *et al*. (1999) shows there are no relationships among the East Asian Monsoon, the Indian Monsoon, and the Plateau Monsoon. However, the calculated EOF1

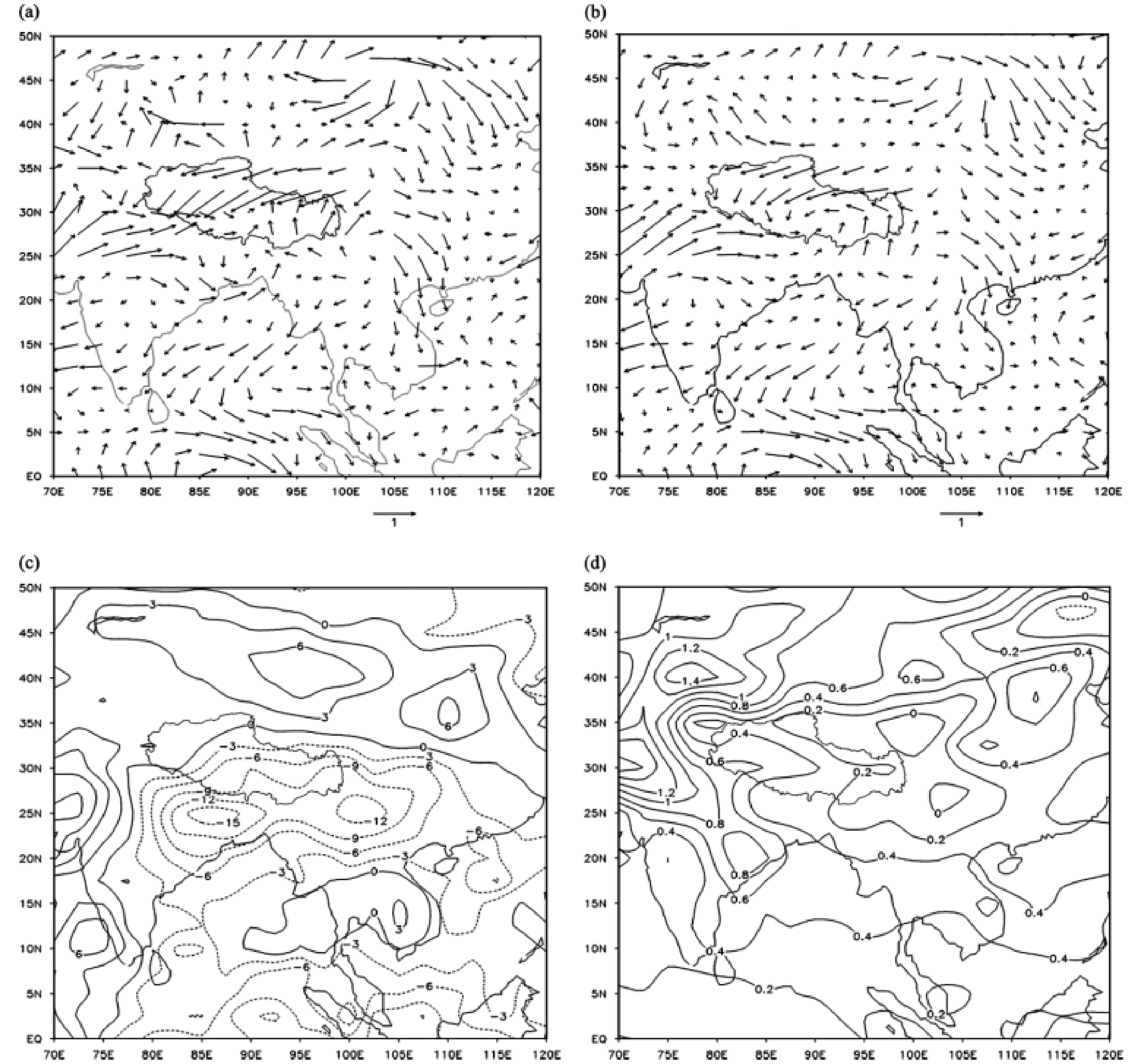

Figure 8. The differences in meteorological factors between the higher and lower heat flux years (high-low): (a) surface wind field; (b) 500 hPa wind field; (c) outgoing longwave radiation (OLR); (d) ground surface temperature. Wind vector is measured in meters per second, OLR in watts per square meter and temperature in degrees centigrade.

correlates significantly with the precipitation over northeast India because of their adjacent locations (with a correlation coefficient of 0.42 and passing 0.01 level tests). When the boundary layer on the central Tibetan Plateau shows a lower air pressure caused by higher sensible heat flux, it favours further penetration of the southerly water vapour onto the Plateau.

A latitudinal shear line exists over the central Plateau (Figure 7(a) and (b)). Winds from the northeast dominate north of the shear line, while winds from the southwest dominate south of the line. When higher sensible heat flux occurs with lower air pressures near ground surface over the central Plateau, the convection strengthens and the southward compensatory circulation exceeds that of the northward flow, strengthening the Indian Monsoon coming onto the Plateau (Figure 5).

For local convection, a very important sub-synoptic scale precipitation system exists over the central and western parts of the Plateau, called the 'Plateau low vortex', which extends below 400 hPa and is active at the 400 hPa isobar surface during spring and summer. Since its average spatial scale is 400–500 km, the vortex is just a low pressure, rather than a circulation. The location of a low vortex near Naqu, is also called the 'Naqu low vortex'. According to the studies of Li *et al*. (2002, 2006), the formation of the vortex relates to the sensible heat transport over this area; the higher the sensible heat flux, the stronger the low vortex. Unique atmospheric conditions on the western and central Plateau cause the birth, growth and development of low vortices, because the air maintains superadiabatic conditions during spring and early summer. For example, at the Shiquanhe station, Qiao and Zhang (1994) observed a 1.39 °C $(100\ \mathrm{m})^{-1}$ adiabatic rate. When an air parcel goes upward, its temperature remains higher than that of ambient air. According to the CISK (Conditional Instability of the

Second Kind) mechanism of conditionally unstable air, when air with an elevated temperature moves upward, it will warm the air column above it, and divergence of the upper layer and convergence at the lower layer will strengthen, thus creating a positive reaction.

The Plateau's low vortex creates the main synoptic precipitation system because its formation and development is accompanied by air ascension and convection. Furthermore, when moving beyond the Plateau, this usually fosters a series of adverse synoptic systems of board spatial scale, such as rainstorms and thunderstorms in Sichuan and Chongqing to the east of the Plateau (Yang *et al.*, 2001). According to statistics of the low vortices between May and September 1969–1976 (Qiao and Zhang, 1994), when a low vortex moves from west to east over the Plateau, the precipitation averaged 6 mm per event over the central and eastern part of the Plateau. Low vortices develop relatively well during June and July, their life spans average more than 36 h, and they coincide with high precipitation. However, during May and August, low vortices are underdeveloped. When a Plateau low vortex moves beyond the Plateau, precipitation generally reaches 30 mm.

Low vortices on the Plateau play an important role in the monsoon precipitation over the central and the eastern Plateau. For instance, Qiao and Zhang (1994) investigated a low vortex that occurred in 1979 in detail. Using the average 6 mm as the precipitation caused by the low vortex (Qiao and Zhang, 1994), the contributions of low vortices to the monsoon precipitation were determined and are shown in Table V.

Table V indicates that a low vortex in May has the highest contribution to the precipitation, and a low vortex occurring during May through August also may be responsible for more than half of the precipitation. Based on the above analysis, the importance of the low vortices to the monsoon precipitation over the central and eastern Plateau was determined.

From the above analysis, there appears a good relationship between sensible heat and subsequent monsoon precipitation, so the sensible heat flux of central Tibetan Plateau during May can be used to predict the monsoon precipitation on the eastern Tibetan Plateau. The prediction procedure follows.

The linear relationship between the sensible heat and EOF1 of the monsoon precipitation is established using the earlier data. Due to the spatial progression of the sensible heat flux, the arithmetical average of the normalized anomaly of the temperature difference between ground and air was used to represent the sensible heat at Amdo, Bange, Gaize, Tuotuohe and Wudaoliang during May as independent variables to calculate the EOF1 value of future monsoon precipitation (the temperatures of ground and air are available from regular meteorological stations). At the beginning of each June, the deficit or excess of monsoon precipitation on the eastern Tibetan Plateau can then be obtained easily.

Table V. The percentage of the precipitation caused by Plateau low vortex to that of monsoon precipitation in 1979.

	May	June	July	August	May to August
n	3	9	10	5	27
A (mm)	18	54	60	30	162
B (mm)	24.5	84.4	145.8	106.1	360.8
C (%)	73.5	64.0	41.2	28.3	51.75

n, the number of Plateau low vortex with life span >36 h.
A, the precipitation of low vortex.
B, average monsoon precipitation (June to August) of 16 points.
C = (A/B) × 100.

7. Conclusions

The monsoon precipitation over the central and eastern Tibetan Plateau is influenced by Plateau Monsoon: the water vapour comes mainly from the Bay of Bengal. Although a large spatial fluctuations of the monsoon precipitation exist within the study area due to the local topography, the EOF analysis indicates that the monsoon precipitation shows simultaneous variations, and the precipitation EOF1 provides a good indicator of the monsoon precipitation during May to September between 1974 and 2004 at 17 sites.

The monsoon precipitation on the central and eastern Plateau correlates with the sensible heat flux during May at the Amdo site, the relationship also exists at its surrounding sites of Tuotuohe, Gaize, Bange and Wudaoliang and over the central part of the Plateau.

Two mechanisms can account for the correlation. First, NCEP/NCAR data indicate that in higher sensible heat years, convection forms more easily over the central Plateau: the stronger the convection, the stronger low pressure over the central Plateau, which strength the meridional (south–north) convergence and brings more water vapour from the Bay of Bengal to the Plateau. Second, in a high sensible heat year, the air temperature's superadiabatic lapse rate over the area favours the deepening of the surface shallow low pressure and promotes the formation and development of low vortices, which bring more local convection precipitation during the monsoon season.

The sensible heat flux during May over the Central Tibetan Plateau can be used as a 'predictor' of monsoon precipitation over the eastern Plateau.

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