Climatic features of atmospheric heat source/sink over the Qinghai-Xizang Plateau in 35 years and its relation to rainfall in China

ZHAO Ping (赵　平) & CHEN Longxun (陈隆勋)

Chinese Academy of Meteorological Sciences, Beijing 100081, China

Correspondence should be addressed to Zhao Ping (email: pinzhao@163bj.com)

Received September 10, 2000

Abstract Using the 1961—1995 monthly averaged meteorological data from 148 surface stations in the Qinghai-Xizang Plateau (QXP) and its surrounding areas, calculation of the 35-year atmospheric heat source/sink ($\langle Q_1 \rangle$) and an analysis on its climatic features and relation to rainfall in China have been made. It is found that on the average, the atmospheric heat source over the QXP is the strongest in June (78 W / m^2) and cold source is the strongest in December (–72 W/m^2). The sensible heat of the surface increases remarkably over the southwest of the QXP, causing the obvious increase of $\langle Q_1 \rangle$ there in February and March, which makes a center of the atmospheric heat source appear over the north slope of the Himalayas. Afterwards, this center continues to intensify and experiences noticeable migration westwards twice, separately occurring in April and June. The time when the atmosphere over the east of the QXP becomes heat source and reaches strongest is one month later than that over the southwest of the QXP. In summer, the latent heat of condensation becomes a heating factor as important as the sensible heat and is also a main factor that makes the atmospheric heat source over the east of the QXP continue growing. On the interdecadal time scale, $\langle Q_1 \rangle$ of the QXP shows an abrupt change in 1977 and a remarkable increase after 1977. The atmospheric heat source of the spring over the QXP is a good indicator for the subsequent summer rainfall over the valleys of the Changjiang and Huaihe rivers and South China and North China. There is remarkable positive correlation between the QXP heat source of summer and the summer rainfall in the valleys of the Changjiang River.

Keywords: Qinghai-Xizang Plateau, atmospheric heat source/sink, climatic characteristic, rainfall in China.

The study of the atmospheric heat source/sink over the QXP has been one of the major subjects in the QXP meteorology and received a great deal of attention. Yeh et al.[1] and Ji et al.[2] investigated the atmospheric heat source/sink over the QXP and obtained many important results. Chen et al.[3] calculated the daily $\langle Q_1 \rangle$ values over the QXP in 1979 from such physical quantities as radiation, sensible heat, and latent heat of condensation. They reported a mean $\langle Q_1 \rangle$ value of 76 W/m^2 over the QXP for 1979 summer. Yanai et al.[4] analyzed the $\langle Q_1 \rangle$ values over the QXP. Their value for 1979 summer is in good agreement with that of Chen et al.[3]. Using 1993—1996 observations with an interval of 20 minutes at the automatic weather stations which were built in Lhasa (29.7°N, 91.1°E), Xigaze (29.2°N, 88.9°E), Nagqu (31.5°N, 92°E) and Nyingchi (29.6°N, 94.5°E) and 1961—1995 monthly averaged meteorological data at surface stations, Zhao et al.[5, 6] calculated the monthly atmospheric and surface long-wave and short-wave radiation, surface sensible heat flux and surface latent heat flux from evaporation over the QXP and revealed their climatic characteristics.

So far, the long time series of the heat regime over the QXP has not been obtained. This paper calculates the 35-year $\langle Q_1 \rangle$ values over the QXP and analyzes its climatic features and relation to rainfall in China.

1 Computational methods

The heat source/sink for a given air column is defined as

$$\langle Q_1 \rangle = SH + R_{net} + LP, \quad (1)$$

where SH is the sensible heating flux at the surface; R_{net} the net radiation in the atmosphere and LP the condensation-released latent heat; R_{net} has the forms as follows:

$$R_{net} = S_0 \downarrow (1 - A_P) - S \downarrow (1 - A) + R_e - R_\infty,$$

where $S_0 \downarrow$ denotes the solar radiation arriving at top of the atmosphere; the methods of calculating SH, LP, the total radiation at the surface ($S \downarrow$), the planetary albedo (A_p), the surface albedo (A), the outgoing longwave radiation at top of the atmosphere (R_∞) and the effective radiation at the surface (R_e) are given by Yeh et al.[1] and Zhao et al.[5, 6]. The atmosphere is called a heat (or cold) source when $\langle Q_1 \rangle$ is >0 (or <0). Using the 1961—1995 monthly data at 148 stations of China in the QXP and its vicinity (not shown in figure) and eq. (1), we calculated the monthly $\langle Q_1 \rangle$ values for 1961—1995. The Qinghai-Xizang Plateau under study is the area with the topographic height of 3000 m or more except for that west of 90°E and north of 33°N.

In order to verify the rationality of our $\langle Q_1 \rangle$ values, we make a comparison with other authors[3, 4] over the QXP for 1979 summer (not shown in figures). It is seen that the distribution and regional averages of our $\langle Q_1 \rangle$ values are very close to those of Yanai et al.[4], especially in the east part of the QXP, and the regional averages are also in good agreement with those of Chen et al.[3]. Therefore, our $\langle Q_1 \rangle$ values can been used in climatic research.

2 Climatic features of atmospheric heat source/sink

2.1 30-year climatic feature

From the monthly distribution of the QXP $\langle Q_1 \rangle$ values averaged over 1961—1990, it is seen that all the $\langle Q_1 \rangle$ values over the plateau are negative in January, namely the cold source, with its high center being located around 35°N, 93°E, 34°N, 98°E and 29°N, 101°E (fig. 1(a)). In February $\langle Q_1 \rangle$ values over the QXP begin to increase so that some parts of the southern QXP become the atmospheric heat source. In March one high-value center is around Cona (28°N, 92°E) and another is in the Gongshan county (27.7°N, 98.6°E). In April (fig. 1(b)), the heating center at Cona shifts noticeably westward to Lhaze (29.1°N, 87.6°E) with its value increasing to 81 W/m^2 and the heating center in the Gongshan county still remains there with the value of 126 W/m^2 that is its annual maximum. In May the atmosphere over the QXP becomes the heat source. The strongest heating center in the southwestern QXP still appears around Lhaze. In the eastern QXP, however, the previous heating center around the Gongshan county greatly reduces in May. In June, the maximal heating center over the QXP appears at Jiulong county (29°N, 101.3°E) with the value of 160 W/m^2. In the meantime, the heating center in the southwest part has moved from Lhaze to Burang (30.5°N, 81.4°E) with its central value increasing to 130 W/m^2 that is the annual maximum in the southwest part of the QXP. This is the second obvious movement of the heating center in the southwestern QXP toward west. In July (fig. 1(c)), the heat source of the southwest part starts to weaken. Its heating center withdraws eastward to 85°E and then remains there till October, with the central value diminishing gradually. On the contrary, the heat source over the eastern QXP continues to get enhanced in July, especially in some areas where the values are over 120 W/m^2. Since August the atmospheric heat sources over the whole QXP begin to weaken and to October (fig. 1(d)) the atmosphere acts as a cold source over the majority of the QXP.

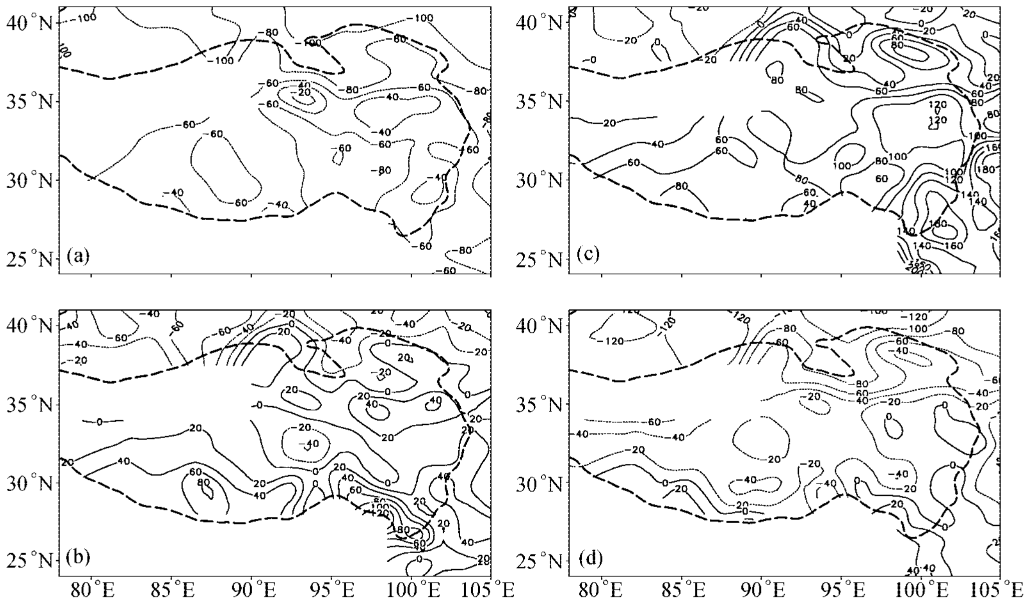

Fig. 1. QXP 〈Q_1〉 values (W/m^2) averaged over 1961—1990 (thick dashed line is the 3000-m contour of topography). (a) January; (b) April; (c) July; (d) October.

Table 1 shows the 〈Q_1〉 and its components averaged over 1961—1990 for the southwest (SWQXP) and east (EQXP) of the QXP and the whole QXP. EQXP denotes area with a topographic height of ⩾3000 m east of 90°E. SWQXP denotes the area west of 90°E and south of 33°N, with a topographic height of ⩾300 m, and the whole QXP is the sum of EQXP and SWQXP. From table 1 it can be seen that the whole QXP atmosphere acts as a heat source from

April to September with its peaks at 78 and 75 W/m^2 separately in June and July and as a cold source in the other months with its peak at –72 W/m^2 in December. All $\langle Q_1 \rangle$ values in the southwest part of the QXP are much greater than those in the east from February to May, especially in March when the value is 30 W/m^2 greater. $\langle Q_1 \rangle$ values of the east part exceed those of the southwest part from June to September, with a value of July in the east being 40% greater. The atmosphere over southwest of the QXP acts as a heat source from March to September, with the maximum of 75 W/m^2 in June, and as a cold source in the rest, with the minimum of –75 W/m^2 in December. The atmospheric heat source over the east part starts in April, one month later than in the southwest part, and also ends in September and has the maximum of 81 W/m^2 in July (also one month later than in the southwest). Thus the cold source in the east part lasts one month longer than it does in the southwest part. The cold source of the east part is also the strongest in December with a $\langle Q_1 \rangle$ value of –71 W/m^2. In seasonal transition, the $\langle Q_1 \rangle$ value increases most remarkably in February and March over southwest of the QXP, and from April to June over the east.

Table 1 The monthly SH, R_{net}, LP and $\langle Q_1 \rangle$ values averaged over 1961—1990 for the southwest and east parts of the QXP and the whole QXP with their annual means (unit: W/m^2)

Month		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean
SWQXP	SH	6	31	62	88	100	99	73	61	54	36	15	1	52
	R_{net}	–68	–58	–59	–58	–54	–53	–79	–83	–74	–63	–71	–79	–67
	LP	3	5	6	5	12	29	64	67	31	9	3	3	20
	$\langle Q_1 \rangle$	–59	–22	10	36	57	75	58	45	11	–18	–54	–75	5
EQXP	SH	9	22	39	55	64	58	50	44	33	24	14	6	32
	R_{net}	–73	–67	–68	–63	–56	–56	–60	–68	–78	–77	–77	–80	–69
	LP	3	5	11	20	39	76	91	77	63	23	5	3	35
	$\langle Q_1 \rangle$	–60	–40	–19	12	47	79	81	53	19	–30	–58	–71	1
QXP	SH	9	24	45	63	73	69	56	48	38	27	14	5	39
	R_{net}	–72	–64	–66	–62	–55	–55	–65	–72	–77	–74	–75	–80	–69
	LP	3	5	9	17	32	64	84	75	55	20	4	3	31
	$\langle Q_1 \rangle$	–60	–34	–12	18	50	78	75	51	17	–27	–57	–72	2

Table 1 shows that both surface sensible heat and latent heat of condensation have the atmosphere heated, but the atmospheric net radiation makes the atmosphere cold. In winter, the sensible heat and latent heat are too weak to compensate for the heat loss due to the radiation, thereby generating an atmospheric cold source. In spring, the increase of the sensible and latent heat turns the atmospheric cold source of winter into a heat source in the QXP and makes the heat source to strengthen gradually. In the southwest part, the change is mainly due to the remarkable increase of the sensible heat of spring because the latent heat is weaker in this season. In July and August, although latent heat grows rapidly, the atmospheric net radiation and sensible heat are obviously reduced, which makes the sensible and latent heat and net radiation comparable in magnitude. The balance among them is responsible for the great decrease of the heat source in the southwest QXP in this period. Different from this case, the sensible heat over the eastern QXP is weaker and grows slowly, so that the heat source there emerges one month later than the southwest counterpart does. Nevertheless, the sensible heat is still a main factor responsible for the 〈Q_1〉 increase in the east part from late winter to spring. In summer the latent heat intensifies noticeably over east of the QXP while the sensible heat decreases there. Thus latent heat acts as a main factor that makes the heat source in the east part continue increasing during summer.

2.2 35-year temporal variation

The analysis on the temporal variation of seasonal and annual mean 〈Q_1〉 values of the whole QXP during 1961—1995 shows that the 〈Q_1〉 value of winter ranges from – 65 to – 40 W/m^2. It exhibits a greatly decreasing trend in the 1960s and the early 1970s with the minimum of –66 W/m^2 in 1977 and a noticeable rise from 1978 to 1983 with the sub-maximum of –48 W/m^{-2} in 1983. In spring, the 〈Q_1〉 values are positive, which means a heat source, and show a decreasing trend in the 1960s, with the minimum of 3 W/m^2 in 1969. A significantly rising trend is observed from the 1970s to the middle 1990s, peaking at 27 W/m^2 in 1989. In summer, the 〈Q_1〉 value is 50—80 W/m^2 and displays a decreasing trend from 1961 to 1977 with the minimum of 53 W/m^2 in 1977 and an oscillations in later years. We notice that the〈Q_1〉values in summers of 1962, 1974, 1980, 1984, 1987 and 1993 exceed 70 W/m^2 with the maximum in 1962, corresponding to the relatively strong heat source over the QXP, and in the summers of 1967, 1972, 1975, 1977 and 1978 are below 60 W/m^2 with the minimum in 1977, corresponding to the relatively weak heat source. In autumn, the 〈Q_1〉 value varies between –15 and –35 W/m^2. It shows a conspicuous decreasing trend from 1971 to 1976 and then an increasing trend till the end of the 1980s and again a decreasing trend in the 1990s. Additionally, the 〈Q_1〉 values experience more remarkable interdecadal variation in winter and spring and autumn. All values of these four seasons have the minimums or sub-minimums around 1976—1977. This feature is also seen from the temporal curve of the annual mean 〈Q_1〉 values over the QXP. From fig. 2 it can be seen that the annual mean 〈Q_1〉 value exhibits a decreasing trend in the 1960s and an increasing trend in the later 1970s and early 1980s. The obvious interdecadal change occurs around 1977. We calculated the 10-year 〈Q_1〉 means separately for 1967—1976 and 1978—1987. They are respectively –3.6 and 1.6 W/m^2 (fig. 2). The analysis on the moving t-technique[7] for these two means shows that the difference between them is remarkable (at a significance of 99.9%) and maximizes in this case.

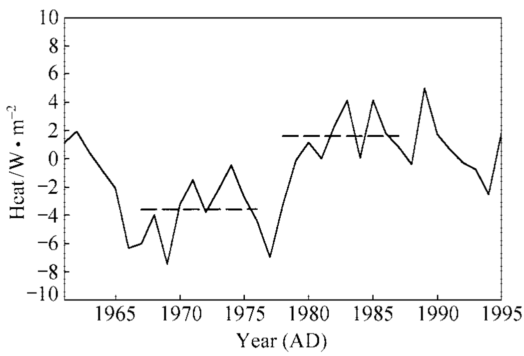

Fig. 2. The temporal variation of annual mean 〈Q_1〉 value (solid line) over the QXP during 1961—1995 and the 10-year〈Q_1〉means (dashed line) separately for 1967—1976 and 1978—1987.

3 Relation of $\langle Q_1 \rangle$ to summer rainfall in China

Correlation analysis is conducted between the $\langle Q_1 \rangle$ over the QXP and the rainfall amount at 160 stations of China during 1961—1995. The results show that the atmospheric heat source intensity of spring and summer separately has good correlation with the summer rainfall in some parts of China. Fig. 3 shows the correlation of the summer rainfall separately to the atmospheric heat source of April and summer. It is seen that a belt of remarkable positive correlation between the summer rainfall and the heat source of April emerges in the valleys of the Changjiang and Huaihe rivers. Especially in some areas of the Changjiang River valleys the correlation passes the test at the 95% significance (fig. 3(a)), with their central values passing the test at 99% significance. Meanwhile, remarkable negative correlation appears in South and North China and passes the test at the 95% significance in Guangdong Province, Guangxi Zhuang Autonomous Region, middle part of the Inner Mongolia Autonomous Region and east of North China, with their central values passing test at 99% significance. From the correlation between the summer rainfall and the summer heat source (fig. 3(b)) we see a belt of remarkable positive correlation from Lhasa (29.7°N, 91.1°E) to East China, with the correlation passing the test at the 95% significance in Lhasa, eastern QXP, some areas of the Changjiang River valleys and their maximal values passing the test at the 99% significance.

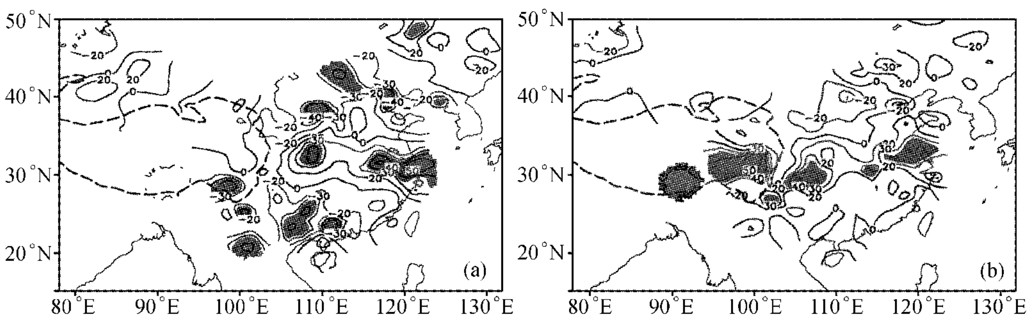

Fig. 3. Correlation coefficients (×100) of the QXP $\langle Q_1 \rangle$ to summer rainfall at 160 stations of China during 1961—1995. Shaded areas pass the test at the 95% significance; thick dashed line is 3000-m contour of topography. (a) Between $\langle Q_1 \rangle$ of April and rainfall; (b) between $\langle Q_1 \rangle$ of summer and rainfall.

Therefore, the QXP heat regime of April may act as an indicator of subsequent summer precipitation over the valleys of the Changjiang and Huaihe rivers and South and North China. Because the intensity of the QXP heat source in summer has a close relation to the 500-hPa low-pressure systems produced over the QXP[1]. Eastward moving of these systems frequently can cause the rainfall in the valleys of the Changjiang River, which leads to the remarkable positive correlation between the QXP heat source and the rainfall in the valleys in summer.

4 Conclusions

Through the analysis on the climatic characteristics of the atmospheric heat source/sink over the QXP and its relation to the rainfall in China, it is found that the QXP atmosphere acts as a heat source only from April to September with the maxima of 78 and 75 W/m^2 respectively in June and July, and as a cold source in the other months with the minimum of –72 W/m^2 in December. All $\langle Q_1 \rangle$ values are much bigger in the southwest part of the QXP than in its east part from February to May, but bigger in the east than in the west for June, August and September. In the southwest part, the remarkable increase of the surface sensible heat causes the noticeable $\langle Q_1 \rangle$ growth in February and March, leading to a center of the atmospheric heat source on the north slope of the Himalayas. Afterwards this center moves noticeably westward twice, respectively occurring in April and June, and its value increases gradually. The atmospheric heat source and its maximum in east part of the QXP emerge one month later than in the southwest part. In summer, the latent heat of condensation largely increases and becomes a heating factor as important as the sensible heat flux. The increase of the latent heat of summer over the eastern QXP causes the heat source to continue growing while the western counterpart does not strengthen the heat source. The $\langle Q_1 \rangle$ value over the QXP shows a remarkable interdecadal variation and an abrupt change in 1977. After 1977 the $\langle Q_1 \rangle$ value obviously grows. The heat source of April may act as an indicator of the subsequent summer precipitation over the valleys of the Changjiang and Huaihe rivers and South and North China. However, the reason for this needs further investigation. The QXP heat source of summer has remarkable positive correlation to the summer precipitation in the valleys of the Changjiang River, which is probably related to the frequent movement eastward of the 500-hPa low-value systems produced over the QXP in summer.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 40075018).

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