

Variations of snow cover in the source regions of the Yangtze and Yellow Rivers in China between 1960 and 1999

YANG Jianping, DING Yongjian, LIU Shiyin, LIU Jun Feng

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

E-mail: jianping@ns.lzb.ac.cn

ABSTRACT. Variations in annual maximum and accumulated snow depths, snow-cover duration, precipitation and air temperature have been analyzed using daily snow depth, monthly air temperature and monthly precipitation data from 1960 to 1999 from six meteorological stations in the source regions of the Yangtze and Yellow Rivers in China. Annual maximum snow depth, snow-cover duration and precipitation increased by ~ 0.23 , ~ 0.06 and $\sim 0.05\% \text{ a}^{-1}$, respectively, during the study period, while annual accumulated snow depth increased by $\sim 2.4\% \text{ a}^{-1}$. Annual mean air temperature increased by $\sim 0.6^\circ\text{C}$ over the study period. An unusually heavy snow cover in 1985 coincided with historically low air temperatures. Data from Tuotuohe and Qingshuihe meteorological stations are used to examine inter-station variability. The annual maximum and accumulated snow depths increased by ~ 0.35 and $\sim 10.6\% \text{ a}^{-1}$ at Tuotuohe, and by ~ 0.42 and $\sim 2.3\% \text{ a}^{-1}$ at Qingshuihe. However, from the late 1980s until 1999 the climate in the study region has become warmer and drier. The precipitation decrease in the 1990s (and not the rapid rise in measured temperature) is thought to be the primary cause of the decrease in snow depth in those years.

1. INTRODUCTION

Snow cover has a profound impact on the energy balance over the land surface and in the atmosphere due to its high albedo and low thermal conductivity. It is also important hydrologically when it melts (Barnett and others, 1989). Thus, the effects of snow cover on regional climate have attracted attention for many years (Blanford, 1884). The Tibetan Plateau is an important snow distribution region in the Eurasian continent. The thermal effect of snow cover can reach upwards to the middle of the troposphere (Wei and others, 2002). Numerous studies of the spatial distribution, variability and effects of snow cover on regional climate have been undertaken (e.g. Chen and Yan, 1981; Guo and Wang, 1986; Li, 1993, 1995, 1996; Xu and Li, 1994; Wei and Lu, 1995; Wei and others, 2002). As shown in Figure 1, compiled from the measured data at 71 meteorological stations, the snow cover on the Tibetan Plateau is unevenly

distributed. It is especially heavy in the northern foothills of the Himalaya and in the eastern parts of the Nyainqentangula Shan. Other areas of comparatively thick snow cover are the eastern parts of the Tanggula Shan, the A'nyemaqên Shan, the Bayan Har Shan and some areas lying along the eastern edge of the Tibetan Plateau. However, snow-cover variations in these latter areas mimic those on the rest of the Tibetan Plateau. Thus, when snowfall is abundant (or low) in these areas, snowfall on the whole Tibetan Plateau is also abundant (or low). These latter areas are noteworthy on the Eurasian continent for the variability of their snow cover (Vernekar and others, 1995). The Tanggula Shan, the A'nyemaqên Shan and the Bayan Har Shan form the boundaries of the source regions of the Yangtze and Yellow Rivers (Fig. 2). Thus, the hydrological regimes of these rivers are affected by this snow-cover variability.

Snow cover is a product of climate, and snow-cover variations are necessarily influenced by climate change. Ke

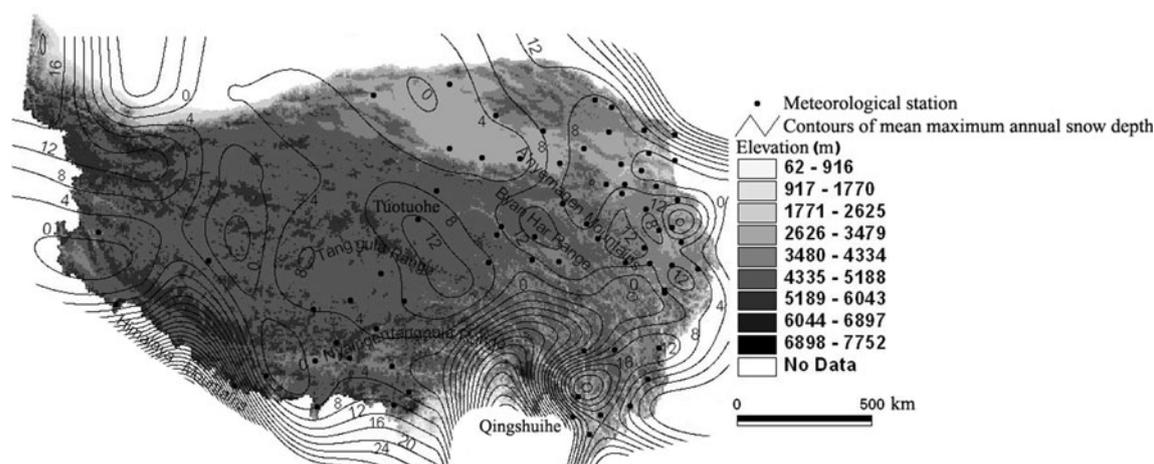


Fig. 1. Sketch map showing the spatial distribution of average maximum snow depth on the Tibetan Plateau. (Contour interval 40 mm.)



Fig. 2. Geographical location of the study region in China and meteorological stations near to and in the source areas of the rivers. Arrows show direction of flow of rivers.

and others (1997) analyzed variation of snow cover using daily snow-depth data from 1957 to 1990 at 60 meteorological stations across the Tibetan Plateau. Their study showed that annual snow depth increased by ~1.7% between 1957 and 1990, and that this snow-cover increase resulted from an increase in precipitation during the cold season (October to May).

We examine whether snow cover continued to increase into the 1990s, and how it has changed with progressive climatic warming. We analyze the variability and trends in maximum snow depth, accumulated snow depth, snow-cover duration, air temperature and precipitation in the source regions of the Yangtze and Yellow Rivers from 1960 to 1999.

2. DATA SOURCE AND OBSERVATION PROGRAM

2.1. Description of the study region

The source region of the Yangtze River is between 32°30' and 35°40' N and between 90°30' and 96°00' E. The watershed

area is $12.24 \times 10^4 \text{ km}^2$. The source region of the Yellow River is between 33°00' and 35°35' N and between 96°00' and 99°40' E. Its watershed covers $4.49 \times 10^4 \text{ km}^2$ (Ding and others, 2002). Both areas are on the Tibetan Plateau (Fig. 2). The mean height above sea level is >4000 m. The source regions are the entire drainage basins of these rivers in Figure 2.

2.2. Snow cover, meteorological data and the observation program

Locations of six meteorological stations in the study region are shown in Figure 2, and further data are given in Table 1. Because snow-cover and meteorological data from the Qumalai and Zhongxinzhan stations are discontinuous, they are not included in the regionally averaged time series. The remaining six stations are part of the permanent meteorological station network of China, and were not relocated during the period 1960–99 (CMA, 2003). Furthermore, as these stations are all located at lower elevations, the resulting records all contain a low-elevation bias. There

Table 1. Main physical characteristics at the six meteorological stations

Station	Latitude (N)	Longitude (E)	Altitude m.a.s.l.	Long-term mean annual air temperature °C	Long-term annual precipitation mm
Wudaoliang	35°13'12"	93°04'48"	4614.2	-5.5	271.7
Tuotuohe	34°13'12"	92°25'48"	4534.3	-4.2	276.6
Zado	32°54'	95°18'	4068.5	0.3	524.5
Maduo	34°55'12"	98°13'12"	4273.3	-4.0	313.0
Dari	33°45'	99°39'	3968.5	-1.1	544.2
Qingshuihe	33°48'	97°07'48"	4417.5	-4.9	511.6

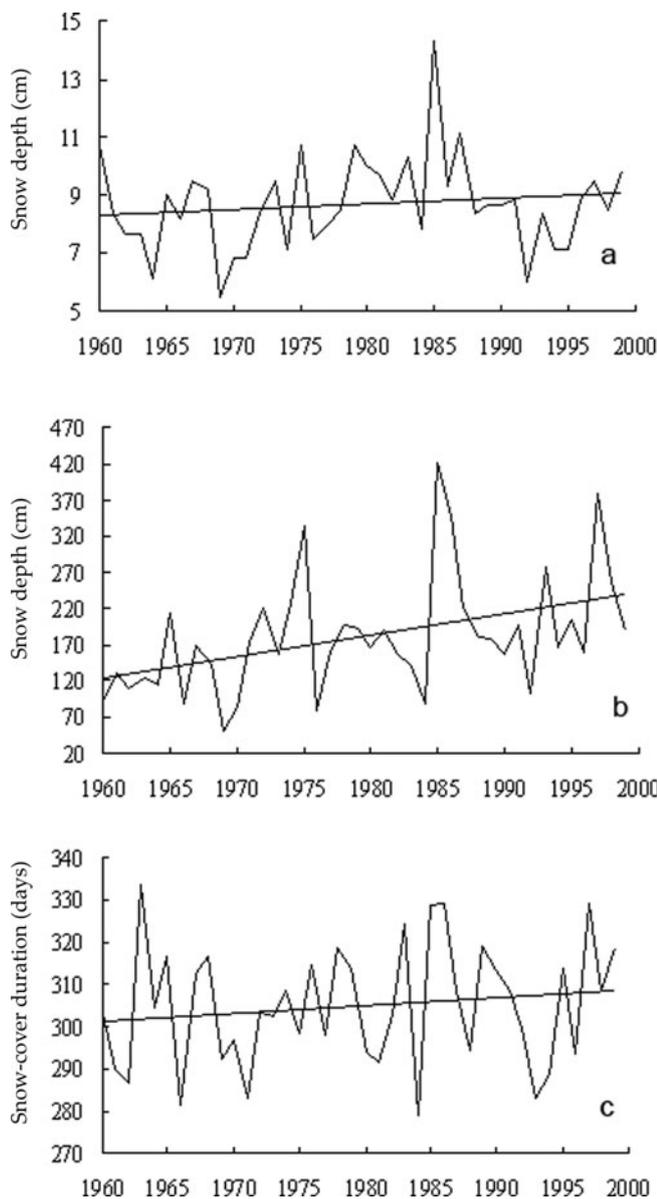


Fig. 3. Time series of regionally averaged (a) annual maximum snow depth, (b) annual accumulated snow depth and (c) annual snow-cover duration in the source regions of the Yangtze and Yellow Rivers during 1960–99. Straight lines indicate linear trends.

are no meteorological stations in higher mountain areas of the Plateau. Despite this bias, these stations provide the best data available. The snow-cover and meteorological data from these six stations are complete; there are no missing values during the period 1960–99.

The data used in this study are daily snow depth, monthly mean air temperature and monthly precipitation between 1960 and 1999. According to the instructions for taking surface meteorological observations (CMA, 2003) in the visual field from the point where the station is located, if more than 50% of the ground is snow-covered, snow depth should be measured, and a day of snow cover is counted. New snow depth, excluding accumulated old snow, is measured to the nearest 0.01 m in a flat and open area near the meteorological observation field. Daily snow depth is an average of three measurements in this area. Air temperature is observed with temperature sensors placed in a ventilated shutter. Both solid (snow) and liquid (rain) precipitation is

measured with gauges (CMA, 2003) which, however, are not equipped with wind shields. Thus, we assume precipitation is underestimated. Observing instruments for snow depth, air temperature and precipitation have not changed during the study period. Thus, these data series have good homogeneity. Annual snow-cover duration is the total number of days with snow cover each year.

3. VARIABILITY OF SNOW COVER IN THE STUDY REGION

3.1. Variability of the regionally averaged time series

The regionally averaged annual maximum snow depth decreased gradually from 1960 to 1964 (Fig. 3a). After 1964, it fluctuated, but generally increased until 1987. The 1985 snow cover was exceptional, the highest for the 40 year period. The maximum snow depth for a single snowfall, 39 cm, was recorded at Tuotuohe station on 18 October 1985. Thereafter, the daily average snowfall exceeded 200 mm until 28 February 1986. This unusual snow accumulation accompanied the lowest mean annual air temperature for the 40 year period. From 1987 to 1992 the annual maximum snow depth decreased. After 1992, it increased. Linear regression calculations indicate that it increased $\sim 0.23\% \text{ a}^{-1}$ ($P > 0.25$) during 1960–99.

The annual accumulated snow depth, i.e. the accumulation of daily snow depth throughout the year, increased gradually until 1999 (Fig. 3b). In 1985 it was 422.7 cm, the highest for the 40 year period. It increased $\sim 2.4\% \text{ a}^{-1}$ ($P < 0.01$) between 1960 and 1999.

The annual snow-cover duration exceeded 270 days in the study region (Fig. 3c), but it was highly variable from 1962 to 1967 and from 1983 to 1985. The long-term trend is an increase of $\sim 0.06\% \text{ a}^{-1}$ ($P > 0.25$) over the 40 year period.

Summarizing, the variability of annual snow-cover duration was small. The regionally averaged annual maximum and accumulated snow depths increased from 1960 to 1999. However, the annual maximum snow depth was reduced between 1988 and 1999. That is, heavy snow cover decreased in the source regions of the Yangtze and Yellow Rivers over the Tibetan Plateau after 1987.

3.2. Variability of the station time series

Time series for the annual maximum and accumulated snow depth from the six meteorological stations are given in Tables 2 and 3, respectively. Tuotuohe station, in the source region of the Yangtze River, and Qingshuihe station, near the source region of the Yellow River, are located in central regions of relatively thick snow cover (Fig. 1). These stations were therefore selected for detailed study in order to show inter-station variability (Fig. 4). As shown in Figure 4a and b, annual maximum snow depth had the same trend as annual accumulated snow depth over the 40 year period. However, the specific variations at Tuotuohe were different from those at Qingshuihe. At Tuotuohe, they fluctuated, but generally increased to 1985, decreased from 1985 to 1994, and increased again after 1994 (Fig. 4a). At Qingshuihe (Fig. 4b), they both declined irregularly from 1960 to 1969. Then the annual maximum snow depth increased from 1970 to 1985 and from 1986 to 1999, while the annual accumulated snow depth was highly variable from 1970 to 1976 and from 1996 to 1999.

Table 2. The annual maximum snow depth (cm) at each station for each year of the study

Year	Wudaoliang	Tuotuohe	Zaduo	Maduo	Dari	Qingshuihe
1960	5	6	9	7	22	15
1961	4	6	4	6	8	22
1962	7	12	5	4	11	7
1963	9	2	11	4	12	8
1964	5	5	9	4	7	7
1965	10	3	4	9	14	14
1966	4	4	13	7	10	11
1967	14	9	7	6	14	7
1968	4	18	5	7	11	10
1969	8	2	4	7	6	6
1970	9	6	7	6	6	7
1971	4	4	5	4	11	13
1972	5	6	6	6	10	17
1973	4	9	16	3	13	12
1974	4	6	6	9	5	13
1975	4	6	10	16	10	18
1976	7	6	5	6	11	10
1977	5	5	10	7	10	11
1978	4	2	14	8	9	14
1979	7	10	20	7	10	10
1980	4	6	15	9	12	14
1981	7	16	6	4	13	12
1982	6	9	7	7	9	15
1983	4	5	14	10	11	18
1984	7	2	7	8	7	16
1985	13	39	6	10	9	9
1986	7	25	4	5	7	8
1987	4	13	13	14	10	13
1988	9	5	8	4	13	11
1989	9	4	6	7	15	11
1990	4	5	12	11	8	12
1991	4	4	14	11	6	14
1992	6	6	4	4	8	8
1993	6	4	11	4	12	13
1994	9	3	6	4	11	10
1995	7	4	7	4	9	12
1996	6	5	12	12	10	8
1997	6	8	12	8	12	11
1998	5	3	12	5	12	14
1999	8	9	5	7	5	25
Trend	+0.07	+0.35	+0.76	+0.56	-0.48	+0.42
(% a ⁻¹)	(P > 0.25)	(P > 0.25)	(P > 0.25)	(P > 0.25)	(P < 0.25)	(P > 0.25)

Note: Trend is linear trend over the period 1960–99. + sign indicates increase, – sign decrease.

Using linear regression, at Tuotuohe the annual maximum and accumulated snow depths increased $\sim 0.35\% \text{ a}^{-1}$ ($P > 0.25$) and $\sim 10.6\% \text{ a}^{-1}$ ($P > 0.25$), respectively, during 1960–99 (Tables 2 and 3). In contrast, at Qingshuihe the annual maximum and accumulated snow depths increased $\sim 0.42\% \text{ a}^{-1}$ ($P > 0.25$) and $\sim 2.3\% \text{ a}^{-1}$ ($P < 0.05$), respectively (Tables 2 and 3).

Annual snow-cover duration was highly variable between 1973 and 1990 at Tuotuohe station (Fig. 4c). It increased $\sim 0.08\% \text{ a}^{-1}$ ($P > 0.25$) over the 40 year period. In contrast, at Qingshuihe, except in 1966, 1982, 1993 and 1996 when snow-cover duration was exceptionally low, it fluctuated regularly (Fig. 4d). Over the 40 year time-span, it decreased $0.12\% \text{ a}^{-1}$ ($P < 0.25$).

At the station scale, the variability of annual snow-cover duration is small. The significance level is low, generally

Table 3. The time series for the annual accumulated snow depth (cm) at each station for each year of the study

Year	Wudaoliang	Tuotuohe	Zaduo	Maduo	Dari	Qingshuihe
1960	60	21	38	34	157	228
1961	52	17	103	83	145	381
1962	69	61	121	29	132	254
1963	251	23	82	47	87	254
1964	74	35	182	55	111	244
1965	101	24	53	369	427	317
1966	46	29	69	70	157	162
1967	217	167	71	207	163	184
1968	118	117	78	85	113	345
1969	44	10	28	61	56	100
1970	71	36	55	70	116	146
1971	34	26	89	93	442	364
1972	38	117	91	88	178	799
1973	50	81	309	35	146	320
1974	45	39	117	442	74	646
1975	34	26	87	828	175	856
1976	61	51	37	46	112	174
1977	43	47	100	295	211	268
1978	44	29	314	361	156	276
1979	58	26	464	69	200	340
1980	21	42	478	52	203	204
1981	77	60	89	40	226	644
1982	102	86	74	148	192	332
1983	84	56	120	173	145	272
1984	32	11	150	51	83	202
1985	190	1660	94	170	119	303
1986	91	1420	54	151	130	242
1987	80	203	200	209	170	457
1988	61	96	237	42	283	375
1989	110	61	159	101	222	427
1990	41	32	102	204	181	373
1991	23	10	398	45	221	484
1992	43	48	106	91	204	132
1993	66	54	349	125	567	510
1994	63	15	116	87	440	280
1995	120	64	276	65	286	410
1996	77	67	248	146	185	226
1997	148	158	385	261	474	849
1998	82	29	231	104	217	867
1999	76	291	64	37	100	564
Trend	-0.28	+10.6	+5.4	-0.17	+2.6	+2.3
(% a ⁻¹)	(P > 0.25)	(P > 0.25)	(P < 0.05)	(P > 0.25)	(P < 0.05)	(P < 0.05)

Note: Trend is linear trend over the period, 1960–99. + sign indicates increase, – sign decrease.

$P > 0.25$. Except at Dari where the annual maximum snow depth decreased, and at Wudaoliang and Maduo where the annual accumulated snow depths decreased, all annual maximum and accumulated snow depths increased over the 40 year study period. The variation trends in the annual maximum and accumulated snow depths at Tuotuohe and Qingshuihe are consistent with those of the regionally averaged maximum and accumulated snow depths during 1960–99. Values of annual maximum and accumulated snow depths at Qingshuihe show an opposite direction to the regionally averaged values during 1985–99. Although not discussed here, the variations in these parameters at the other four meteorological stations were also analyzed (Tables 2 and 3). We find that among the six stations the situation at Tuotuohe played a dominant role in the regionally averaged snow depth decrease between 1985 and 1999.

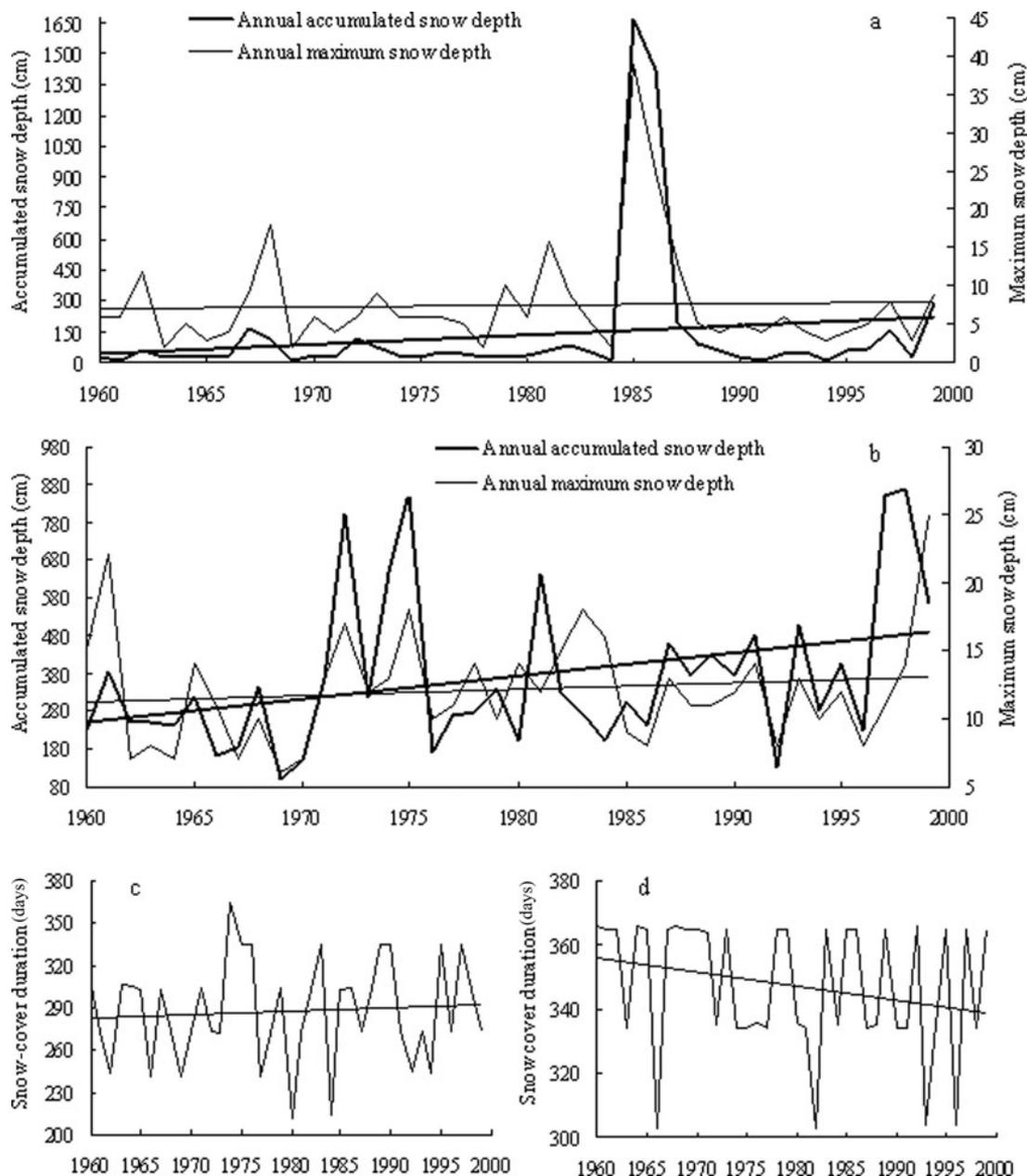


Fig. 4. (a, b) Time series of annual maximum snow depth and annual accumulated snow depth at Tuotuohe (a) and Qingshuihe (b). (c, d) Annual snow-cover duration at Tuotuohe (c) and Qingshuihe (d). Straight lines indicate linear trends.

4. CLIMATE BACKGROUND OF SNOW-COVER VARIATION

Mean annual air temperature decreased from 1960 to 1963 and increased from 1963 to 1970. It changed little during the 1970s, increasing over that decade by $\sim 0.1^{\circ}\text{C}$. Temperature was highly variable from 1982 to 1985, and increased sharply after 1985 (Fig. 5a). The average increase during the 1980s was again $\sim 0.1^{\circ}\text{C}$. During the 1990s however, air temperature increased by $\sim 0.3^{\circ}\text{C}$. Thus, the air-temperature increase occurred primarily during the 1990s. On average over the 40 year study period, air temperature increased $\sim 0.6^{\circ}\text{C}$, or $0.015^{\circ}\text{C a}^{-1}$ ($P < 0.05$). Anomalous years were 1965, 1983, 1985 and 1997.

The precipitation increase occurred largely in the 1980s (Fig. 5b). The average precipitation during the 1980s was 24.3 mm above the long-term mean. It was below the long-

term mean in the 1960s and 1970s. The four occurrences (1980, 1983, 1985 and 1987) of ≥ 100 mm maximum snow depth were attributed to the heavy precipitation in the 1980s. During the 1990s, though annual precipitation increased, it was still 8.4 mm below the long-term mean. Precipitation increased 7.5 mm, or $\sim 0.05^{\circ}\text{C a}^{-1}$ ($P > 0.25$), over the 40 year study period.

The regionally averaged annual maximum snow depth, accumulated snow depth, snow-cover duration, air temperature and precipitation all exhibited increasing trends during the 40 year study period. The air-temperature increase was notable. The number of sunshine hours increased ~ 5.3 hours a^{-1} during 1960–99 (Yang and others, 2004), contributing to the increase in air temperature. Prior to the late 1980s, air temperature increased slightly, precipitation increased and snow depth and snow-cover duration increased. From the late 1980s to 1999, especially

from 1990 to 1999, while air temperature progressively increased, precipitation was 32.7 mm lower than the average for 1980–89, and snow depth and snow-cover duration also decreased. It seems snow depth variability is primarily determined by precipitation. The precipitation decrease is believed to be the major cause of the decrease in snow depth in the 1990s. With global warming, precipitation in the study region has exhibited an increasing trend. This has been documented by some studies (Liu and others, 1998; Yang and others, 2004). Though the precipitation increase is small, the climate has become gradually warmer and drier during the 40 year study period.

5. CONCLUSIONS AND DISCUSSION

The source region of the Yangtze and Yellow Rivers encompassed by the Tanggula Shan, the Kunlun Shan, the Bayan Har Shan and the A'nyêmaqên Shan is an area of abundant snow cover on the Tibetan Plateau. The snow-cover variability in this region is unusual on the Eurasian continent. The regionally averaged annual maximum snow depth increased $\sim 0.23\% a^{-1}$ over the 40 year study period. The long-term trend in the regionally averaged annual accumulated snow depth was an increase of $2.4\% a^{-1}$ during 1960–99. There was an exceptional snow year in 1985, when unusually heavy snow cover was accompanied by an all-time low air temperature. Snow-cover duration exceeded 270 days in the source region. However, its variability was small. It only increased $\sim 0.06\% a^{-1}$ during 1960–99.

The annual maximum and accumulated snow depths at Tuotuohe meteorological station increased ~ 0.35 and $\sim 10.6\% a^{-1}$, respectively, over the 40 year study period. The changes at Tuotuohe are consistent with those of the regionally averaged maximum and accumulated snow depths.

At Qingshuihe, annual maximum and accumulated snow depths increased ~ 0.42 and $\sim 2.3\% a^{-1}$, respectively, over the 40 year study period. Between 1985 and 1999, changes in annual maximum and accumulated snow depths at Qingshuihe exhibited the opposite sign to changes in regionally averaged maximum and accumulated snow depths. Of all stations, the situation at Tuotuohe played a dominant role in the regionally averaged snow depth decrease between 1985 and 1999.

Though annual precipitation increased slightly ($0.05\% a^{-1}$) during the 40 year study period, in the 1980s it was 24.3 mm above average. As a consequence of the heavy precipitation in the 1980s, the regionally averaged maximum snow depth exceeded 100 mm four times during that decade.

Mean annual air temperature increased by $\sim 0.6^\circ C$ over the 40 year study period. Precipitation in the 1990s was 32.7 mm lower than the average precipitation of the 1980s. Precipitation decrease was the major cause of the decrease in maximum snow depth in the 1990s. Air temperature, precipitation, maximum snow depth, accumulated snow depth and snow-cover duration increased over the total study period. However, the air-temperature increase was notable and precipitation increase was small. So, while precipitation increased over the total 40 year study period, in later years the climate tended to become warmer and drier.

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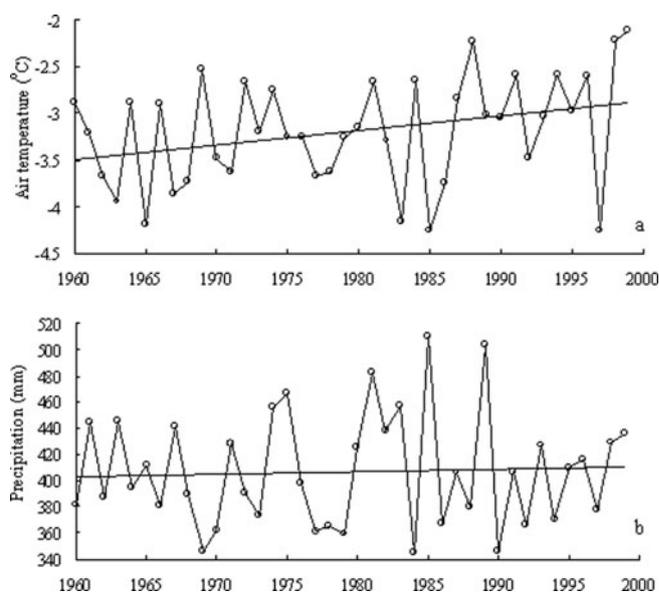


Fig. 5. Time series of regionally averaged (a) mean annual air temperature and (b) annual precipitation. Straight lines indicate linear trends.

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