Climatic and Hydrologic Changes in the Tien Shan, Central Asia

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ABSTRACT

The authors analyze climatic and hydrologic data from 110 sites collected from the middle of the twentieth century to the present in the Tien Shan, one of the largest mountain systems of central Asia. In spite of a few confounding interregional variations in the temporal changes of surface air temperature, precipitation, runoff, glacier mass, and snow thickness in the Tien Shan, it has been possible to establish statistically significant long-term trends in these key hydroclimatic variables. The average rise in air temperature was 0.01°C yr^{-1} over the range, with slightly lower values below 2000-m elevation. The precipitation in the Tien Shan increased 1.2 mm yr^{-1} over the past half-century. The precipitation increase is larger at low altitudes in the northern and western regions than at altitudes above 2000 m. A decrease in snow resources occurred almost everywhere in the Tien Shan; the maximum snow thickness and snow duration have decreased on average 10 cm and 9 days, respectively. The annual runoff has dropped or did not change significantly in Tien Shan rivers. The main factor determining the change in river runoff is the type of precipitation (liquid or solid). Over the last few decades, periods of glacier decline have coincided with declining river runoff.

1. Introduction

Remarkably little is known about decadal changes of hydrometeorological characteristics in river basins of continental high-mountain regions (Nash and Gleik 1991; Beniston et al. 1994; Barry 1994). Some evidence has indicated central Asian glaciers, and other continental glaciers, may be receding. For example, during the period from 1957 to 1980 ice volume in the Pamiro-Alai glaciers decreased 66 km^3 (13% of their total volume), which is about equivalent to mean annual runoff of the Amu Darya River, one of the largest central Asian rivers nourishing the Aral Sea (Konovalov and Shchetinnicov 1994). However, currently, about 1580 km^3 of freshwater is still stored in the central Asian glaciers, including those in the Tien Shan and Pamiro-Alai (Krenke 1980).

In spite of the previous attention devoted to large-scale water balances and continental-scale hydrologic regimes (Budyko 1977; Karl et al. 1991, 1993; Groisman et al. 1994), little effort has been dedicated to analysis of regional, long-term changes in hydrologic regimes and runoff formation in high-mountain systems.

Since the middle of the nineteenth century, an extensive hydrometeorological network has been in place in the Tien Shan mountains. The Tien Shan has been well explored and carefully described by Russian scientists, but these mountains are largely unknown in the west. The first regular hydrologic and meteorological observations were begun in the middle of the last century by the Russian Main Geophysical Observatory, and, in 1991, about 2000 meteorological stations and hydrologic sites were operational at locations between 700 and 3500 m. Here, we analyze 52 yr of data to evaluate twentieth century, hydroclimatic changes in the region.

2. Study region, observations, and methods of analysis

a. Regional hydrology

The Tien Shan is one of the largest mountain systems in central Asia and covers 800 000 km^2 between 69°

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and 95°E and 39° and 46°N. Its major peaks stand about 4000–6000 m, the highest point is at 7439 m, and the deepest intermountain depression is 150 m below sea level. About half of the Tien Shan region is above 3000 m. The main mountain ranges are oriented from east to west, except the Borohoro, Meridionalniy, and Fergana ranges (Fig. 1). Its latitudinal extent is about 1980 km across central Asia. The Tien Shan, as the first montane barrier to northern air masses moving to central Asia, plays an important role in determining the climatic processes in northern central Asia, similar to that of the Himalayas to the south.

The Tien Shan is in a region of internal drainage, which is subdivided into separate closed basins that include the Aralo-Caspian, Balkhash, Issik Kul, and Tarim hydrographic regions (Fig. 2). According to Kuznezova (1984), the horizontal moisture transport over the Tien Shan is about 50 kg m^{-1} s^{-1}. The annual runoff of the major Tien Shan rivers is on average 67 km^3 yr^{-1}, which includes net glacial melt of about 7 km^3 yr^{-1}, and runoff formed by annual precipitation onto the glacier surfaces and transformed to overland runoff of about 6.5 km^3 yr^{-1} (Dikih 1993). On average, glacial runoff is about 10% of total runoff at the mouth of mountain valleys (Akbarov 1984). During droughts, the proportion of glacial runoff increases to 20% of the total as a result of decrease of cloudiness and precipitation, and increase of solar radiation, air temperature, and glacier melt. In some basins, such as that of the Tarim River, the proportion of glacial runoff can be as high as 40% of total runoff (Kuznezov 1968).

b. Regional climatic conditions

On the basis of circulation processes prevailing in different parts of the mountains, precipitation regime and orographic features, we identified the following regions: western, northern, central, and eastern Tien Shan (Fig. 3a) (Aizen et al. 1995). The main factor determining the climatic regimes is the interaction between the southwestern branch of the Siberian anticyclonic circulation and cyclonic activity from the west. The western region is under weak influence of the Siberian anticyclonic circulation and moderate influence of the southwestern cyclonic circulation that brings warm, moist air masses into the region. As a result, up to 50 mm $month^{-1}$ of precipitation falls during autumn and winter, from November to February, and maximum precipitation (up to 80 mm $month^{-1}$) occurs in spring, from March to June (Fig. 3b). The northern region is situated under strong influence of the Siberian anticyclonic circulation, which deceases the quantity of winter precipitation; maximum precipitation (up to 120 mm $month^{-1}$) is observed in spring and summer (Fig. 3b). The high ranges surrounding the central and eastern Tien Shan prevent the entrance of moisture and result in low winter precipitation (about 10 mm $month^{-1}$); convection results in summer maxima (up to 130 mm $month^{-1}$) (Fig. 3b). The synoptic- and mesoscale patterns of atmospheric circulation, coupled with strong orographic effects, govern the pattern of river runoff in the Tien Shan. The most conspicuous feature is the coincidence of maximum, warm season precipitation with the melting of glaciers and snow. The climatic and orographic regional differentiation of the Tien Shan provides the key for the understanding of varying patterns of hydroclimatic variability and twentieth century climatic change throughout the region.

c. Methods of analysis

Our analysis considers only mountainous terrain of the Tien Shan and is based on spatial averaging within three regions (western, central, and northern Tien Shan, illustrated in Fig. 3) and within altitudinal belts. To minimize the inherent spatial and temporal noise of high-resolution time series, we analyzed seasonal and annual periods over large regions. We did not spatially average data for the eastern region because of the sparse data there. The eastern Tien Shan comprises mainly territory of the People's Republic of China. Two altitudinal belts are considered: one comprising foothill terrain below 2000 m and the other comprising high mountain terrain above 2000 m. We used Thiessen's method (Diskyn 1970; Ward 1975) for spatial averaging:

$$f_s = \sum_{i=1}^{n} a_i f_i, \tag{1}$$

where f_s is area mean, f_i is value at point i, and a_i is weight determined by the area of the Thiessen polygon for station i. The standard relative errors of averaging, *se* (Gandin and Kagan 1976) were less than 10%:

$$se^2 = \frac{\sum_{i=1}^{n} (f_s - a_i f_i)^2}{\sum_{i=1}^{n} (\bar{f} - f_i)^2}, \tag{2}$$

where $\bar{f}$ is the mean of the point samples.

We examined mean summer (June–August) and annual air temperature, warm season and annual precipitation, annual maximum snow thickness and snow duration, and warm season (March–October) and annual runoff. To calculate an annual mass-balance index (B, g cm^{-2}), Eq. (3) was used:

$$B = [P_{Z_0} + \gamma(P)\,(Z_{e.l.} - Z_0)] - [A_{Z_0} - \gamma(A)\,(Z_{e.l.} - Z_0)], \tag{3}$$

where P_{Z_0} (mm) is the annual precipitation (October–September) at the Z_0 (m) altitude of nearest meteorological station; $Z_{e.l.}$, is long-term average altitude of equilibrium line position calculated by Kurowski's (1891) method; $\gamma(P)$, $\gamma(A)$ (mm m^{-1}) are the altitudinal gradients of precipitation and ablation determined through the results of field studies and long-term data

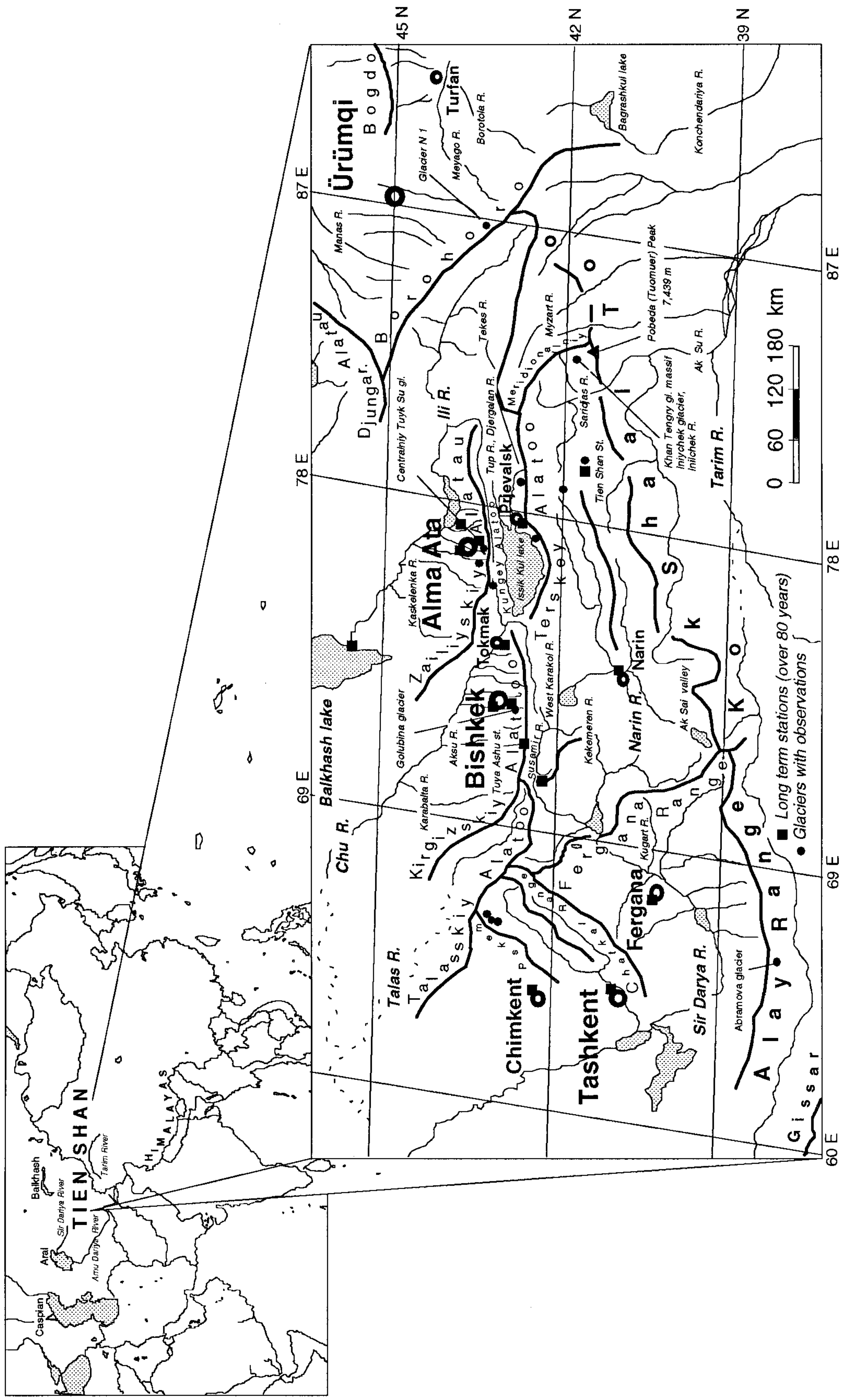

FIG. 1. Map of the Tien Shan.

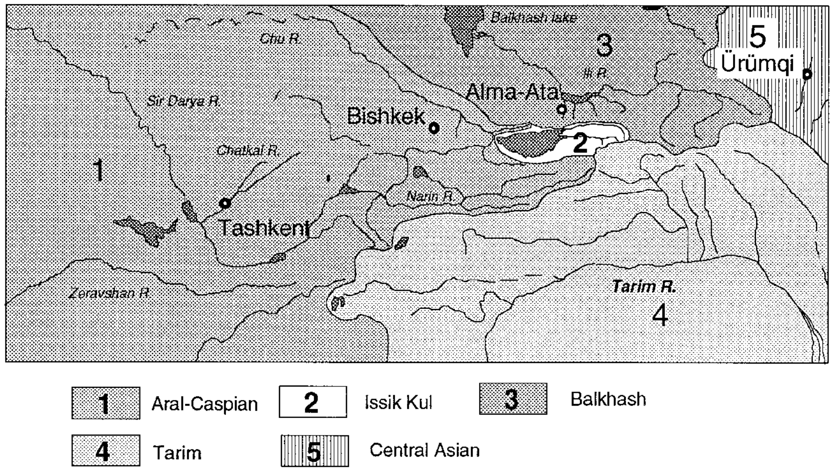

FIG. 2. Hydrographic regions of the Tien Shan.

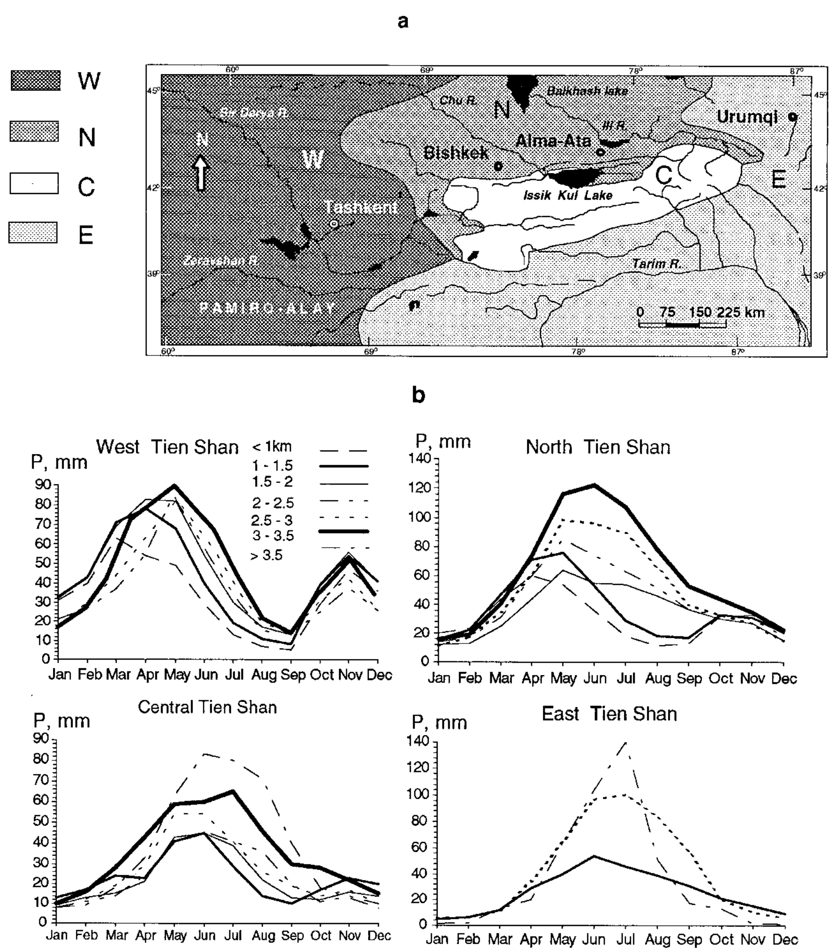

FIG. 3. (a) Classification of the Tien Shan by precipitation regime: W—western Tien Shan, N—northern Tien Shan, C—central Tien Shan, and E—eastern Tien Shan. (b) Annual variation in precipitation through altitudinal zones in the Tien Shan.

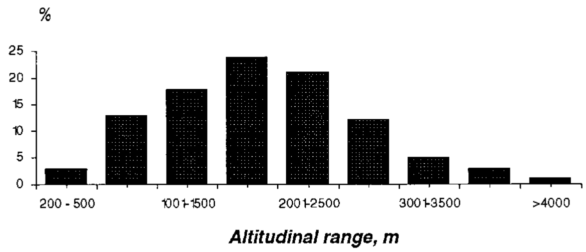

FIG. 4. Distribution of hydrometeorological stations throughout altitudinal zones.

of meteorological stations located at different altitudes; and A_{Z_0} is ablation at the Z_0 in meters, calculated by empirical equations obtained during expeditionary observations (Suslov 1980; Avsuyk 1984; Aizen and Aizen 1994, 1995). Data from 110 (Fig. 4) hydroclimatic stations, gauges, and sites with long records were used to evaluate hydroclimatic variability and patterns of climatic change in the Tien Shan. We required that all stations have data through a common period (1940–91) to calculate average annual anomalies for each region.

We assessed changes in climatic and hydrologic characteristics by calculating a linear trend, standard errors, coefficients of determination, and *F* tests for each region and altitudinal belt (Table 1). The average annual anomalies for each region were smoothed by the elementary binary filter (3-yr moving average with weights 1/4, 1/2, and 1/4).

3. Results

a. Air temperature

During the period 1940–91, there is no significant trend of decreasing air temperatures in any season, and mean annual air temperature rose by an average rate of 0.01°C per year over the entire Tien Shan (Table 1). According to coefficients of determination (Table 1), on average, 11% of interannual air temperature variability is described as a linear trend. The rise in all regions but the northern Tien Shan was about the same. In the northern Tien Shan above 2000 m, the increase of annual temperature was smaller and was associated with a rise in summer temperatures only.

The rate of mean annual temperature rise in the northern Tien Shan below 2000 m was 0.006°C yr^{-1}, or about one-half of those rate increases estimated for the range as a whole (Fig. 5). Analysis of air temperature deviations (Figs. 5a,b) reveals a pattern of similarity throughout the Tien Shan regions. For example, there are synchronous periods of positive and negative de-

TABLE 1. Linear trends (β) of hydroclimatic variables in the northern, central, and western Tien Shan (1940–91) and their standard errors (σ_β), coefficient of determination (r^2), and F test ($p = 0.95$, $df = 1$, $\mu - 2 = 50$, where μ is number of years) for $F' = 4.04$; * if $F > 4.04$ then linear trend is statistically significant during last 52 yr.

		Temperature (°C)		Precipitation (mm)		Snow cover		Runoff ($m^3\ s^{-1}$)	
Regions		June–August	Annual	March–October	Annual	Duration days	Accumulted cm	March–October	Annual
Northern	β,yr^{-1}	0.008*	0.006*	2.03*	2.44*	−0.25*	−0.16*	−0.003	−0.002
<2000 m	F	4.360	5.217	11.93	13.84	9.78	4.51	0.338	0.344
	σ_β	0.004	0.003	0.59	0.66	0.08	0.07	0.007	0.007
	r^2	0.08	0.094	0.19	0.22	0.16	0.08	0.006	0.004
Northern	β,yr^{-1}	0.009*	0.008*	0.84	0.84	0.06	−0.012	−0.01	0.00
>2000 m	F	4.008	5.138	1.85	2.23	0.38	0.021	1.50	2.46
	σ_β	0.005	0.004	0.62	0.56	0.10	0.084	0.01	0.00
	r^2	0.074	0.093	0.04	0.04	0.01	0.000	0.03	0.05
Central	β,yr^{-1}	0.013*	0.012*	0.67	0.71	−0.29*	−0.26*	−0.10*	−0.06*
<2000 m	F	4.021	5.321	3.95	3.84	14.51	8.95	4.51	4.45
	σ_β	0.007	0.005	0.34	0.36	0.08	0.09	0.05	0.03
	r^2	0.074	0.096	0.07	0.07	0.23	0.15	0.08	0.08
Central	β,yr^{-1}	0.011*	0.012*	0.41	0.42	−0.21*	−0.12*	−0.06*	−0.04*
>2000 m	F	4.500	7.852	1.15	1.07	6.55	5.06	4.12	4.45
	σ_β	0.005	0.004	0.38	0.40	0.08	0.05	0.03	0.02
	r^2	0.084	0.177	0.02	0.02	0.12	0.09	0.08	0.08
Western	β,yr^{-1}	0.010*	0.010*	1.94*	2.46*	−0.15*	−0.26*	−0.04	−0.02
<2000	F	4.026	4.026	4.55	4.84	4.46	5.76	1.23	1.02
	σ_β	0.005	0.005	0.91	1.12	0.07	0.11	0.04	0.02
	r^2	0.075	0.075	0.08	0.09	0.08	0.10	0.02	0.02
Western	β,yr^{-1}	0.013*	0.011*	0.06	0.35	−0.20*	−0.36*	−0.05*	−0.03*
>2000 m	F	6.553	8.406	0.01	0.23	8.53	11.56	4.38	4.32
	σ_β	0.005	0.004	0.61	0.72	0.07	0.11	0.02	0.01
	r^2	0.116	0.144	0.00	0.01	0.15	0.19	0.08	0.08
Ave	β,yr^{-1}	0.011*	0.010*	0.99	1.20*	−0.17*	−0.2*	−0.04	−0.03
	F	4.578	5.993	3.91	4.34	7.37	5.24	2.62	2.79
	σ_β	0.005	0.004	0.575	0.64	0.08	0.09	0.02	0.03
	r^2	0.116	0.144	0.00	0.01	0.15	0.19	0.08	0.08

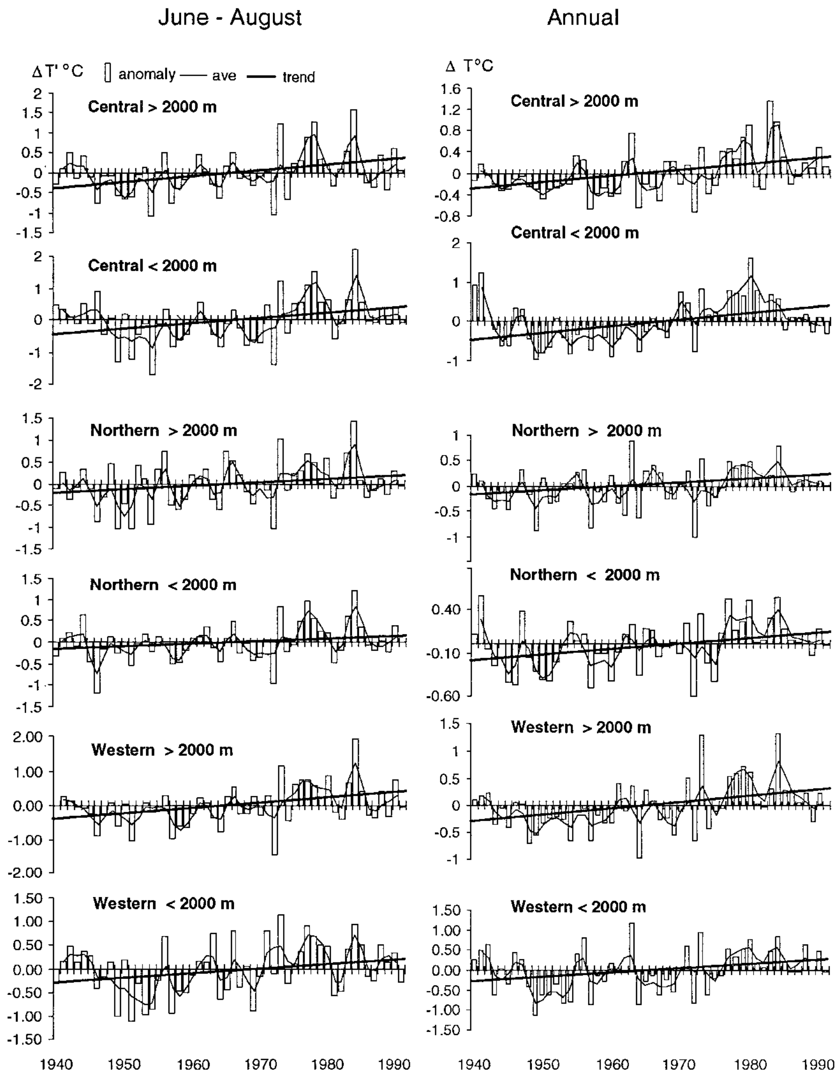

FIG. 5. Long-term anomalies of summer and annual mean air temperature, their centrally weighted moving averages, and statistically significant linear trends in the Tien Shan.

TABLE 2. Years with positive and negative deviations in changes of average annual air temperatures, total precipitation, accumulation/maximum snow thickness, glacier mass balance, and runoff.

	Deviation	
	Positive	Negative
Temperature	1940–43	1947–55
	1976–87	
Precipitation	1957–61	1940–46
	1963–71	1973–78
	1979–83	
Accumulation	1947–56	1973–84
	1965–72	
Glacier mass balance		1940–47
		1973–85
Runoff	1948–56	1940–46
	1967–72	1973–85

viations from the long-term mean annual air temperature, as is chronologically depicted in Table 2. The greatest deviations from long-term mean annual air temperature are observed in the high-mountain belts of the central Tien Shan.

b. Precipitation

Statistically significant changes in precipitation during the period 1940–91 had, on average, a positive trend. At altitudes below 2000 m, the magnitude of the trend is larger than that observed above 2000 m, especially in the northern and western Tien Shan. During the period 1940–91, the rise in total annual precipitation was 1.2 mm per year (Table 1). A linear trend of warm season

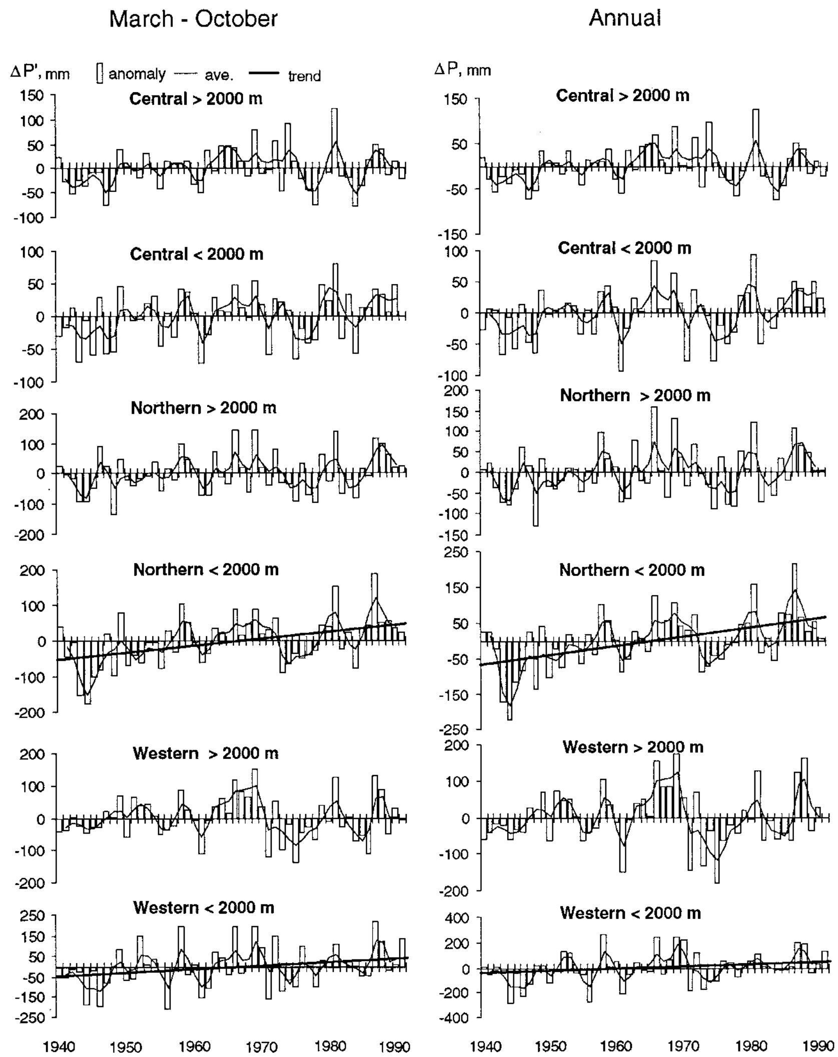

FIG. 6. Long-term anomalies of seasonal and annual sum of precipitation, their centrally weighted moving averages, and statistically significant linear trends in the Tien Shan.

and annual precipitation was statistically significant and positive only in the northern and western Tien Shan below 2000 m (Fig. 6, Table 1). Annual mean precipitation has increased about 100 mm, or about 12%–14%, during the past 52 yr.

In spite of the complicated character of long-term precipitation changes, analysis of the time series throughout the Tien Shan indicates (Fig. 6) the following. 1) There is a general pattern of variability in annual precipitation throughout the Tien Shan, which is confirmed by the cycles of positive and negative deviations shown in Table 2 and Fig. 6a. 2) Changes in annual and warm season (from March to October) precipitation are similar across the Tien Shan. 3) The largest deviations of annual and warm season precipitation are observed in the western Tien Shan, and the smallest deviations are typical of the central region (see Figs. 6a,b). 4) Deviations from the linear trend showed an inverse relation between deviations in mean annual air temperature and annual precipitation (see Table 2 and Figs. 5a and 6a).

c. Snow cover

During the period 1940–91, a decrease in snow occurred almost everywhere in the Tien Shan. The maximum snow thickness and snow duration decreased, on average, 10 cm and 9 days, respectively. At altitudes below 2000 m, the maximum snow thickness decreased 8–14 cm, and above 2000 m decreased 6–19 cm. The northern Tien Shan over 2000 m was exceptional during the past 52 yr because there are no significant changes in maximum of snow thickness and snow duration. This corresponds to an absence of significant changes in winter–autumn precipitation in the region. The results for snow seem compatible with the previous conclusions

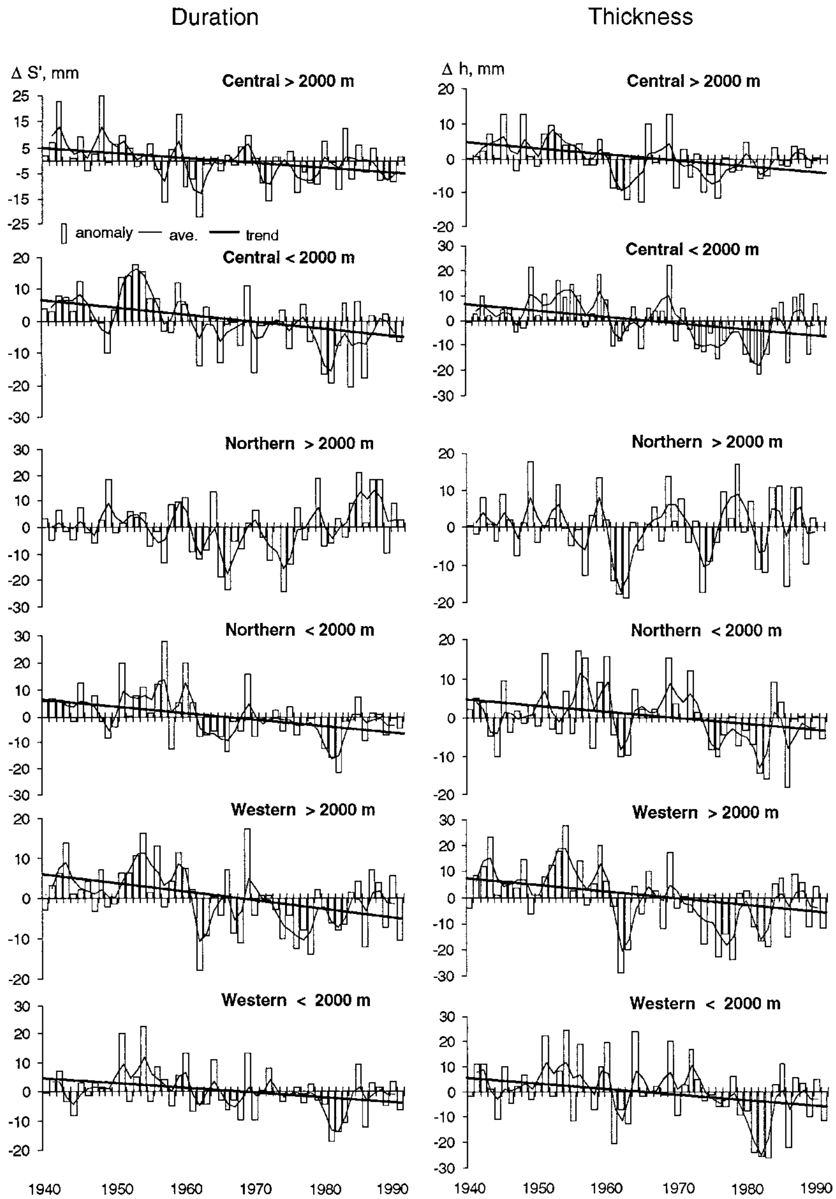

FIG. 7. Long-term anomalies of snow duration and snow thickness, their centrally weighted moving averages, and statistically significant linear trends in the Tien Shan.

about air temperature and precipitation during the last half of this century. An increase in air temperature is consistent with more liquid precipitation, leading to a decrease in snow resources.

There is a similarity in the long-term changes of snow regime in the Tien Shan (Fig. 7). Positive values of deviations occurred during 1947–57 and 1965–72. During the period 1973–84, negative deviations of snow thickness occurred.

d. Runoff and glacier mass

According to Akbarov and Suslov (1984) and Aizen and Aizen (1994, 1997), there are synchronous fluctuations in mass balance of the Tien Shan and Pamiro-Alai glaciers (Fig. 8b). From 1940 to 1947 and from 1973 to 1985 the glaciers had a negative mass balance. During 1935–85, the glaciers lost about 5%–27% of their mass. Concomitant with a decrease in glacier area, the glacial runoff in basins with large glaciers increased (Konovalov and Shchetinnicov 1994).

In the northern and western Tien Shan at altitudes below 2000 m, the annual and warm season runoff has not increased during the past 52 yr in spite of an increase in precipitation (Fig. 8). For example, from 1961 to 1991 the mean annual runoff fell 47 m^3 s^{-1} in the Ili River basin and has fallen 35 m^3 s^{-1} in the Saridjaz River

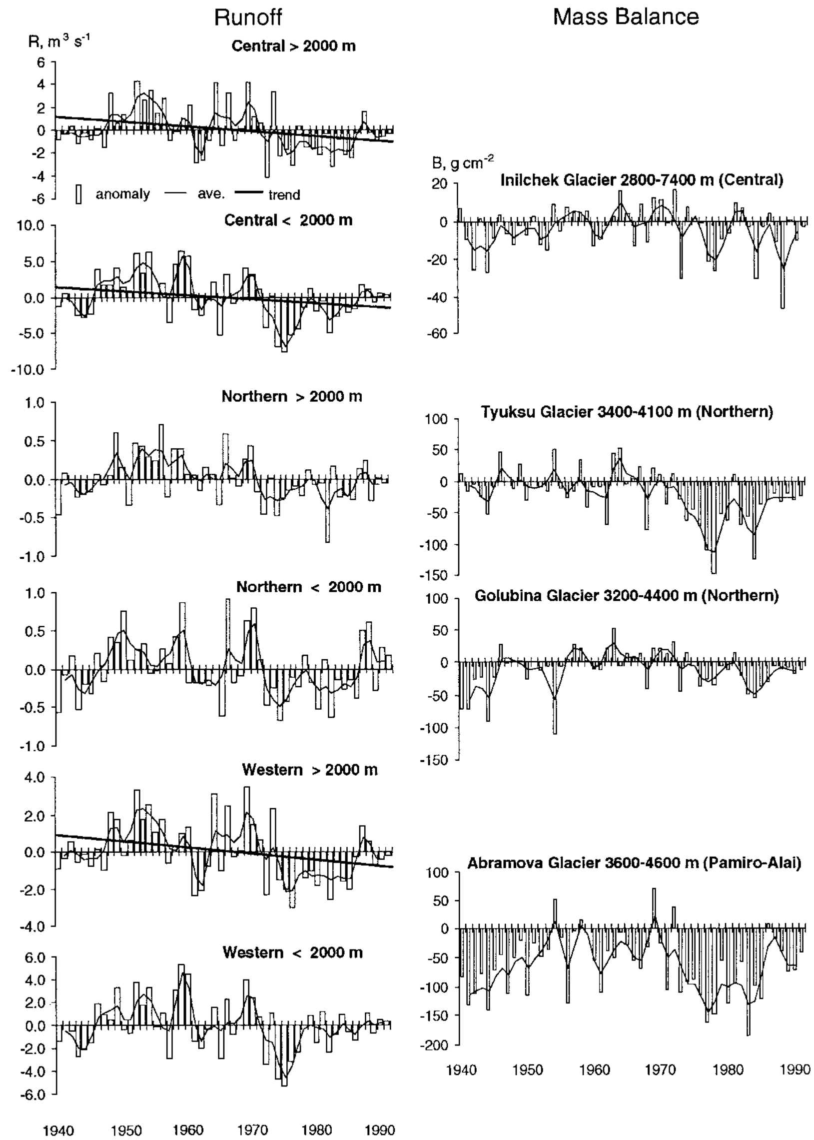

FIG. 8. Long-term anomalies of mean annual runoff and index of glacier mass balance, their centrally weighted moving averages, and statistically significant linear trends in the Tien Shan.

basin. This corresponds to Romanovskiy's (1993) results for Issik Kul Lake's (northern Tien Shan) water balance; increasing precipitation in the basin did not increase surface runoff, but resulted in the increase of the lake level during the last decade. A statistically significant decrease in river runoff is observed in the central and western (above 2000 m) Tien Shan.

River runoff deviations (Fig. 8a) are in phase throughout the Tien Shan. Table 2 identifies two periods with negative deviations in river runoff. These correspond to periods of negative glacier mass balance also shown in Table 2 (see also Fig. 8b for temporal patterns of glacier mass balance). A negative glacier mass balance is typical during dry years with a deficit of warm season precipitation, a decreasing cloudiness, and intense glacier melting.

4. Discussion

There are few studies with which ours can be compared. In the Alps, Fliri (1990) found no significant trends in snow in the Tirol, Austria, despite a warming trend (1895/96–1989/90), whereas in the Austrian mountains Mohnl (1991) reported higher frequencies of snowcover and fresh snow amounts between 1900 and 1920 and lower values between about 1925 and 1975. Beninston et al. (1994) concluded for the Swiss Alps that the annual trends of temperature are in accordance with the increase of global air temperatures and resulted in retreat of glaciers. However, precipitation shows no significant trend between the beginning (1901) and the end (1992) of records, while sunshine duration decreased until the early 1980s. The Tien Shan data have dissimilar tendencies, a decrease in snow thickness and duration during the last 52 yr. Results of our analysis are similar to satellite observations since the early 1970s (Robinson et al. 1991) suggesting a decrease in mean snow depths for spring and summer in Eurasia.

According to historical records in southern Canada (Karl et al. 1993), there is a significant century-scale trend of increasing annual precipitation (1% per decade), and, for the last 4 decades, there is a decreasing trend (−0.7% per decade) in the annual ratio of solid to total precipitation. In the contiguous United States, there is an increase in the annual precipitation during the last 4 decades (2%–3% per decade). Surface ground temperature changes during the last century inferred from geothermal data show 1°–2°C of warming in central and eastern Canada (Beltrami and Mareschal 1992; Wang and Lewis 1992), and 0.6°C warming in the northern basin and range of Utah (Chisholm and Chapman 1992; Chapman et al. 1992). The results of our analysis correspond to these trends for air temperature, solid and total precipitation, and snow resources during recent decades.

Variations in runoff can result from changes in temperature and precipitation. In the Sierra Nevada, since about 1950, the proportion of total annual stream flow occurring during April through July has decreased, while the portion during the autumn and winter has increased (Aguado et al. 1992). Based on 50 yr of historical records for two streams in the northern Sierra Nevada, Pupacko (1993) reported increased winter and early spring runoff during the period from 1965 to 1990 compared to 1939 to 1964, which he attributed to small increases in temperature that increased the rain to snow ratio. Moreover, Karl et al. (1991) and Lins and Michaels (1994) found a pattern opposite to our results for precipitation and runoff in the central United States during the twentieth century. While there do not appear to be statistically significant trends in winter precipitation (Karl et al. 1991), unimpaired winter stream flow has increased in that area (Lins and Michaels 1994). Lins and Michaels (1994) postulate that a regional decrease in evapotranspiration is the likely cause of such anomaly. An analysis by Karl and Riebsame (1989) of decadal climate fluctuations and associated runoff changes over the past 50 yr in the United States indicates that temperature fluctuations are not as great a factor in runoff changes as suggested in previous studies (Langbein's nomogram 1949) where the evaporation is of great importance in formation of runoff under the increase of air temperatures. Karl and Riebsame (1989) reported that the effect of recent temperature fluctuations on stream flow are minimal, but the impact of small fluctuations in precipitation (about 10%) are often amplified.

The Tien Shan data have dissimilar tendencies than those found by Karl and Riebsame (1989), Karl et al. (1991), and Lins and Michaels (1994). One possible explanation for this disagreement is that the Tien Shan is located in the center of the large Eurasian continent. Spring–summer precipitation maxima occur with snow- and ice melt in the Tien Shan, while winter precipitation maxima occur in the central North American areas. The role of evaporation during a period of warming should be more significant in regions with summer maxima of precipitation than in regions with winter maxima. Furthermore, unlike the investigations of Karl and Riebsame (1989), Karl et al. (1991), and Lins and Michaels (1994), we considered only mountainous regions formed mainly by intrusive igneous and sedimentary rocks. Uplifted geological structures, modern relief formed mainly by nival glacial processes, and poor soil have led to the development of deep groundwater circulation systems with large storage capacity in Tien Shan (Chedia 1972). Percolation of river runoff is more likely to be important into the foothills of Tien Shan than on plains.

The patterns of precipitation and surface air temperature change we observed can be reconciled with meso- and synoptic-scale climatic anomalies governing atmospheric circulation over the Tien Shan. A weakening of the local mountain anticyclonic activity and displacement to the northwest of the Siberian anticyclone (Vinnikov 1986) strengthen westerly cyclonic advection to the peripheral, low-altitude, Tien Shan regions. This causes increased cloudiness (Iliak and Porfirieva 1992) and precipitation, and a weakening of surface air temperature increases in altitudinal belts below 2000 m in the northern and western Tien Shan. A similar phenomenon is observed in the low latitudes of the Northern Hemisphere (Budyko 1977; Manabe 1983; Jones et al. 1986; Vinnikov 1986; Hansen and Lebedeff 1987; Waggoner 1990; Folland 1993).

Interestingly, measured increases in precipitation throughout the Tien Shan were not associated with a synchronous rise in river runoff. The evidence suggests that larger amounts of liquid precipitation, which do not correlate with larger spring floods, are being lost as evaporation and perhaps as percolation to deep groundwater circulation systems in the Tien Shan foothills. It is known that greater fraction of liquid than of solid precipitation could be evaporated under the same heat income and that increased air temperatures should increase evaporation. In the Tien Shan during snowmelt, part of the water forms surface runoff, while rain mostly percolated to groundwater. Direct runoff from rain is observed on hydrographs only when storm precipitation with an intensity more than 20 mm day^{-1} occurs (Aizen et al. 1996).

In the mountain basins of the Tien Shan, the main factor controlling changes in river runoff is the impact of air temperature on the type of precipitation throughout altitudinal belts in all seasons. During the past 52 yr a gradual increase of liquid precipitation did not increase surface river runoff. According to the water balance, there are only two ways to explain this: 1) an increase in evaporation and/or 2) an increase in percolation to deep groundwater systems. Furthermore, the decrease in snow resources, with concomitant decrease in snowmelt contribution to river runoff, is apparently compensated by increasing glacier and permafrost melting only in the upper reaches of river basins that exhibit large-scale glaciation, such as in the large Pobeda-Khan Tengry, Saridjaz, and Muzart glaciers of the central Tien Shan. In river basins with smaller glacierized areas, the increase of glacier melting has led to a decline of the glacierized area and, thus, to a reduction in the contribution of glacier melting to river runoff. The combined effect of a larger evaporation of liquid precipitation and changes experienced in the snow and glacier resources, as documented here, are responsible for the observed reductions in river runoff.

5. Conclusions

We have evaluated hydroclimatic changes in the Tien Shan for the period from 1940 to 1991. The rise in air temperature was pronounced particularly in the central Tien Shan and in the high altitudes of the peripheral northern and western regions. In the northern and western Tien Shan, and below 2000 m, the rate of air temperature increase is half that in the central Tien Shan. Statistically significant changes in precipitation have a positive trend. The precipitation increase is larger at low altitudes in the peripheral regions than at altitudes above 2000 m. The annual runoff has dropped or not significantly changed in the Tien Shan rivers. The main factor determining the change in mountain river runoff is the type of precipitation. Increases in liquid precipitation and glacial runoff did not lead to larger river runoff. Larger amounts of liquid precipitation, which do not correlate with larger spring floods, could be lost predominantly as evaporation and, perhaps, as percolation to groundwater circulation systems in the Tien Shan foothills. Another puzzling result is the occasional, though protracted, coincidence over the last few decades of periods of glacier mass decline and declining trends in river runoff.

Further monitoring of water resources in high-mountain watersheds could improve our understanding of the causal mechanisms changing the regional and global water cycle. Hydroclimatic analysis should include evaluation of long-term changes in water balance components of the mountain watersheds (i.e., evaporation, river runoff, type and quantity of precipitation, snow resources), in air temperatures, quantity of cloudiness, regime of solar radiation, glacier mass including the precipitation amount accumulated on the glaciers, atmospheric pressure, atmospheric circulation, levels of closed lakes, and chemical analysis of river and lake water samples. Understanding of the physical dynamics could help to investigate other regional questions such as Aral Sea decline and Caspian Sea level rise.

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