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DISTRIBUTION OF RIVER RUNOFF AND ITS CLIMATE FACTORS IN AVERAGE AND EXTREME YEARS

ABSTRACT

Schematic maps of spatial distribution of seasonal precipitation amounts and average air temperatures were obtained for the areas studied in years with normal and extreme values of annual river runoff. Data on precipitation for January-December (I–XII) and on average air temperatures for June-September (VI-IX) during 1961–1990 collected at 93 meteorological stations located along 30.20–44.08°N and 67.20–82.98°E, altitude 122–4169 m above sea level, were used in the maps' compilation. For each point-element (i.e. a meteorological station with proper data), the ordinates of an integral empirical function of distribution of probabilities P were calculated from these data for a 30-year sample period and for each year were received average values and standard deviations of P. In characteristic years were revealed, significant differences of spatial distribution of climatic factors and runoff. It was found out also that the spatial distribution of the total volume of glaciers melting is less variable in the years with extreme water yields compared to the average years. This peculiarity is very beneficial for hydropower and agriculture sectors because it provides additional natural ability to stabilize water balance of reservoirs. Piecewise multi-factor linear equations were obtained to calculate the statistical probability of glaciers' total melting in low and high flow years as a function of geographical coordinates and the average altitude of firn boundary.

KEY WORDS: river runoff, Central Asia, spatial distribution, precipitation, air temperature, extremes, glaciers melting

THE RESEARCH PROBLEM AND OBJECTIVES

Spatial and temporal variability of river runoff and its climatic factors (i.e., precipitation, air temperature, etc.) play a significant role in understanding of past, current, and future environmental conditions. It is especially true in extreme cases, such as low-water or high-water years that influence strongly water management and consumption and the needs of the population. The essence of the problem may be easily seen after calculating the correlation matrix for river runoff in different watersheds within a certain region. Such matrix describes spatial change of correlation independently from the distance between watersheds and other hydrographic parameters. A matrix obtained for some time interval reflects average conditions of runoff formation in different river basins. It is an essential but limited characteristic. More important is studying: (a) regional homogeneity of climate fields and (b) spatial variability of climate factors in years with extreme and normal volumes of runoff. These were the main objectives of our work. Regular or standard data measurement of precipitation and air temperature at the regional meteorological network were used for the tasks (a–b). Analysis of spatial variability of river runoff, glacier runoff, and their climate factors have to be done in a common system of units. This was achieved by transforming all studied variables into ordinates of integral distribution of probabilities P for the corresponding function X, i.e. $P(X) = 1 - F(X > x)$.

THE RESEARCH AREA AND BACKGROUND DATA

The studied region is located within of a closed basin of the Aral Sea and includes the Syr Darya, Amu Darya, Tedjen, and Murgab rivers' watersheds. It also incorporates a number of smaller rivers draining the western part of Tien Shan. With regard to administrative divisions, the region embraces the entire areas of Uzbekistan, Tajikistan, Kirghizstan, and parts of northern Afghanistan. The region belongs to the Central Asian territory with the total area of 1765.9 thousands km^2 and 41.686 millions population (Data of 1996). The territory receives considerably more solar energy than any other part of the former USSR. Temperatures during remarkably long summer are high (the average temperature in July is 25–33°C). On the plains of the Aral region, annual precipitation is 90–120 mm. In the piedmont areas, it is 400–500 mm, while it is over 2000 mm on the western slopes of Tien-Shan.

Hydrology

The rivers Syr Darya and Amu Darya are the principal water sources of the Aral Sea. The areas of these rivers' basins are 692.3 and 493.0 thousands km^2, respectively. The surface water resources of the region also include the runoff of the blind drainage rivers Kashka Darya, Zarafshan, Murgab, Tedjen, Chu, Talas, and other smaller rivers flowing within the territory of the former USSR and of the rivers flowing from Afghanistan. The long-time average river runoff is about 116-120 km^3 per year. The primary source of all rivers in the Aral Sea drainage basin is mostly snow/glacier runoff. The runoff formation area is about 25% of the Aral Sea basin. Eighty percent of this area is located in the Amu Darya and Syr Darya river basins. Their runoff formation zones can be estimated at approximately 200 thousands km^2 for Amu Darya and 160 thousands km^2 for Syr Darya. The Amu Darya, a product of the confluence of the Piandj and Vakhsh rivers, is 1,445 km long. The main part of its water resources (72.8%) forms on the territory of Tajikistan and the rest comes from the Afghanistan and Iran (14.6%) and the Uzbekistan (8.5%) territories. Low-water periods of the Amu Darya occur every 4-5 years and high-water periods occur every 6–10 years. The Syr Darya is the longest river in Central Asia (2,790 km). Its average annual runoff is 40.8 km^3.The low-water period is October-March, while the highest water discharge is in June-July. The low-water periods occur every 3–4 years and last 5–6 years. The annual and seasonal runoff of the basins Amu Darya and Syr Darya has multiyear variations. For example, the annual runoff in the Amu Darya basin in 1969, the high-water year, was about 110 km^3. In the low-water year of 1974, it was about 65 km^3. In the Syr Darya basin, in the same high-water year of 1969, the annual runoff was about 70 km^3, and in the low-water year of 1983, it was about 20 km^3. The Aral region has considerable ground water resources. At present, the ground water discharge is 14.7 km^3/yr. The annual water intake in the Aral Sea basin is 117.7 km^3 and irrigation consumes over 90% of this volume.

Hydrometeorological network

The National Hydrometeorological Services of the Central Asia's states carry out collection of operational information on many characteristics of environment including river runoff and climate. The additional source of hydrological data is observations in the network, conducted by the Ministry of Melioration and Water Economy. The longest range of data exceeds 100 years. Like in many other countries, the structure of network, a number of points, methods and technique of measurements are not stable during of 20th century and later. The distribution of sites for measurement of precipitation and air temperature within the Syr Darya and Amu Darya river basins and adjacent territories are shown on Fig. 1.

The highest number of network measurements in the Aral Sea basin was reached by 1985 (Table 1). Since that, there began a constant reduction of the number of observational sites [Chub, 2000].

The time interval 1961–1990 was chosen for our analysis on spatial variability of seasonal (April-September) river runoff, annual precipitation, and mean seasonal values (June-September) of air temperature. The main sources for the data on runoff were [Bodo, 2000] and [Main Hydrological Characteristics 1967–1980]. Minimal and maximal parameters of the watersheds in the sample used are related to the very different conditions of river runoff formation. Thus, the geographical coordinates of the

Table 1. Hydrometeorological network in Central Asia

Measurement types	Number (N), percentage, and density of measurement points				
	years				
	1975	1980	1985	1990	1995
(a) runoff (N)	412	505	530	478	366
(b) suspended sediments (N)	181	270	291	245	108
(c) water level (N)	453	540	558	486	397
(a) relative to 1985 (%)	77.7	95.3	100.0	90.2	69.1
(b) relative to 1985 (%)	62.2	92.8	100.0	84.2	37.1
(c) relative to 1985 (%)	81.2	96.8	100.0	87.1	71.1
density of (a) per 1000 km^2	1.306	1.310	1.313	1.316	1.320
density of (b) per 1000 km^2	0.273	0.334	0.351	0.316	0.242
density of (c) per 1000 km^2	0.120	0.179	0.192	0.162	0.071
(d) precipitation (N)	355	365	361	331	282
(e) air temperature (N)	333	341	335	312	273
(f) soil surface temperature (N)	302	312	306	283	248
(g) vapor pressure (N)	303	313	307	284	248
(h) snow cover (N)	348	354	350	324	255
(d) relative to 1985 (%)	98.3	101.1	100.0	91.7	78.1
(e) relative to 1985 (%)	99.4	101.8	100.0	93.1	81.5
(f) relative to 1985 (%)	98.7	102.0	100.0	92.5	81.0
(g) relative to 1985 (%)	98.7	102.0	100.0	92.5	80.8
(h) relative to 1985 (%)	99.4	101.1	100.0	92.6	72.9
density of (d) per 1000 km^2	0.235	0.241	0.239	0.219	0.187
density of (e) per 1000 km^2	0.220	0.226	0.222	0.206	0.181
density of (f) per 1000 km^2	0.200	0.206	0.202	0.187	0.164
density of (g) per 1000 km^2	0.200	0.207	0.203	0.188	0.164
density of (h) per 1000 km^2	0.230	0.234	0.231	0.214	0.169

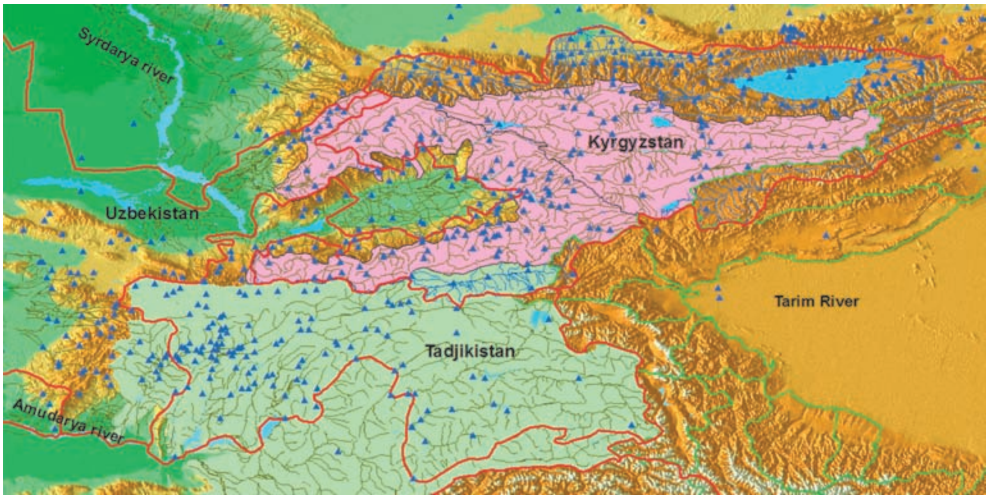

Fig. 1. Points of observation on precipitation and air temperature (blue triangles), red lines – state boundaries. Pink color – the Syr Darya River basin, light green – the Amu Darya River basin

hydrological stations are between 37.20–41.80°N and 66.00–74.00°E, and their elevations vary from 327 m to 3,576 m above sea level (a.s.l.). Most of the hydrological stations located in sub-mountain and high-mountain areas provide the data on runoff not distorted by water management. The area of the watersheds varies from 362 km^2 to 113 thousands km^2, and their mean weighted altitude varies from 1.80 km to 4.20 km above sea level. As climate factors for river runoff, we used precipitation for January-December (here and further this season is abbreviated as I-XII) and the average air temperature for June-September (abbreviated as VI–IX) during 1961–1990 at 93 meteorological stations located along 30.20–44.08°N, 67.20–82.98°E at altitudes of 122–4,169 m a.s.l. The sources of the data were [Former Soviet Union Monthly Precipitation Archive, 1891–1993; Global Historical Climatological Network Database, GHCN, Version 2; Williams, and Konovalov, 2008].

SPATIAL HOMOGENEITY OF AIR TEMPERATURE AND PRECIPITATION

A well-known feature of the Central Asian natural environment, i.e. vertical zonation of landscapes and climate characteristics complicated by latitudinal differences and local peculiarities [Balashova, et al, 1960; Muminov and Inagamova, 1995; Murzaev, 1958], was used to address the research objectives. Let us consider as homogeneous such samples of air temperature *T* and precipitation *Pr* that present objectively the features mentioned above. The coefficient of determination (R^2) for the multifactor equations of linear regression *T* = *T*(Long, Lat, Alt) and *Pr* = *Pr*(Long, Lat, Alt) was adopted as the criterion of spatial homogeneity. Furthermore, these equations were applied to determine spatial variability of norms of the mean monthly air temperature during January-December and the total yearly precipitation. The time interval 1961–1990 was used as a reference period. Here: Long (longitude) and Lat (latitude) – are geographical coordinates of the measurement points and Alt – is their altitude a.s.l.

The samples of 179 meteorological stations for air temperature and 215 meteorological stations for precipitation were selected for determination parameters of regression equations. The contribution of each independent variable for describing variances of the functions *T* = *T*(Long, Lat, Alt) and *Pr* = *Pr*(Long, Lat, Alt) was calculated by formula (1) from [Alexeev, 1971].

$$\beta_j = \frac{|r_{0j}\alpha_{0j}|}{|r_{01}\alpha_{01}| + |r_{02}\alpha_{02}| + |r_{03}\alpha_{03}|}, \qquad (1)$$

where

$$\beta_1 + \beta_2 + \beta_3 = 1. \qquad (2)$$

Table 2. Statistical characteristics of equation *T* = *T* (Long, Lat, Alt)

Index	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
R^2	0.70	0.75	0.84	0.93	0.97	0.97	0.95	0.93	0.91	0.88	0.82	0.73
β_1(Long),%	6.5	3.2	1.0	2.7	0.8	0.3	2.4	3.1	2.4	0.6	5.0	7.4
β_2(Lat),%	36.3	41.1	27.3	8,1	2.0	1.9	2.1	4.3	7.4	16.6	23.1	30.9
β_3(Alt),%	57.2	55.7	71.7	89.3	97.2	97.7	95.6	92.6	90.2	82.8	71.9	61.8

Note: R^2 – the coefficient of determination (the explained part of variance of dependent variable for the regional equations *T* = *T*(Long, Lat, Alt); T – mean monthly air temperature, β_1(Long), β_2(Lat), β_3(Alt) – are monthly contributions of longitude, latitude, and altitude in R^2 of multifactor equations *T* = *T* (Long, Lat, Alt)

Here, r_{0j} are the coefficients of correlation of the function with each argument and α_{0j} are the coefficients of the normalized multifactor linear regression. Table 2 contains estimations of homogeneity for air temperature in the selected sample of data.

The coefficients of determination in Table 2 show that linear equation *T* = *T*(Long, Lat, Alt) describes, in 9 cases out of 12, more than 80% of spatial variability of the mean monthly air temperature in the Central Asia region. Moreover, the value of R^2 is $\geqslant$ 0.93 during April-August. The characteristics obtained for equation *T* = *T*(Long, Lat, Alt) fully correspond to the seasonal conditions of formation of the air temperature field within Central Asia [Balashova et al, 1960]. The main factor in the spring-summer period here is powerful local warming from solar radiation at the local scale and practical absence of latitudinal gradients. Arctic intrusions together with southern cyclones play an essential role during October-March; their influence specifies the latitudinal differentiation of the air temperature field. Equation *T* = *T*(Long, Lat, Alt) adequately describes these processes. Thus, the field of mean monthly air temperature in May-September at all altitudes should be considered as rather homogeneous inside the Central Asia region.

The analogous analysis for the general formula of precipitation, i.e. *Pr* = *Pr*(Long, Lat, Alt) showed that its coefficient of determination was only 0.23 and the contributions of longitude, latitude, and altitude were 27.8%, 3.6%, and 68%, respectively. This confirms, once more, significant spatial variability of even mean annual precipitation and inefficiency of the regional empirical formula in the form of a linear function of geographical coordinates and altitude. The search for local dependences for precipitation as a function of altitude and geographical coordinates revealed better estimations of homogeneity and representativeness for initial information. Coefficients of determination for the equation *Pr* = *Pr*(Long, Lat, Alt) calculated separately for the Chirchik, Naryn, and Zeravshan river basins equaled 0.70, 0.87 and 0.94, respectively. Many examples of similar dependences of satisfactory quality for the Amu Darya and Syr Darya river basins could be found in [Resources…, 1969, 1971].

SPATIAL VARIABILITY OF RIVER RUNOFF AND ITS CLIMATE FACTORS

In hydrological computations, the empirical probabilities of exceeding $X > x_i$ is determined by a rather simply and known procedure [Alexeev, 1971]:

$$p_i(x_i) = \frac{m(x_i) - 0,25}{N_i + 0,5} \cdot 100, \qquad (3)$$

where $m(x_i)$ = 1, 2,..., N_i are ordinal numbers of the x_i values after their disposition in the descending order.

All temporal ranges of R_{IV-IX} – seasonal runoff for April-September on the selected

Table 3. Parameters of seasonal river runoff within the Amu Darya and Syr Darya watersheds

Index	Probability of R_{IV-IX} in characteristic years and their standard deviation SD		
	1969 – max (high-water)	1974 – min (low-water)	1985 – normal
Mean (%)	11.33	88.19	52.31
Limits (%)	2.46–48.36	61.48–97.54	12.30–84.43
SD	13.95	9.49	17.51

33 hydrological stations in 1961–1990 were processed according to the formula (3). Then, we determined $P(R_{IV-IX})$ which is the mean probability for the 33 values in each year. Years when 15% ⩾ $P(R_{IV-IX})$ ⩾ 85% were subsumed to extreme; and when 45% ⩽ $P(R_{IV-IX})$ ⩽ 55% they were considered as normal or average. Table 3 presents the results of identification of average and extreme years and their statistical parameters. Fig. 2, *a*, *b* illustrates

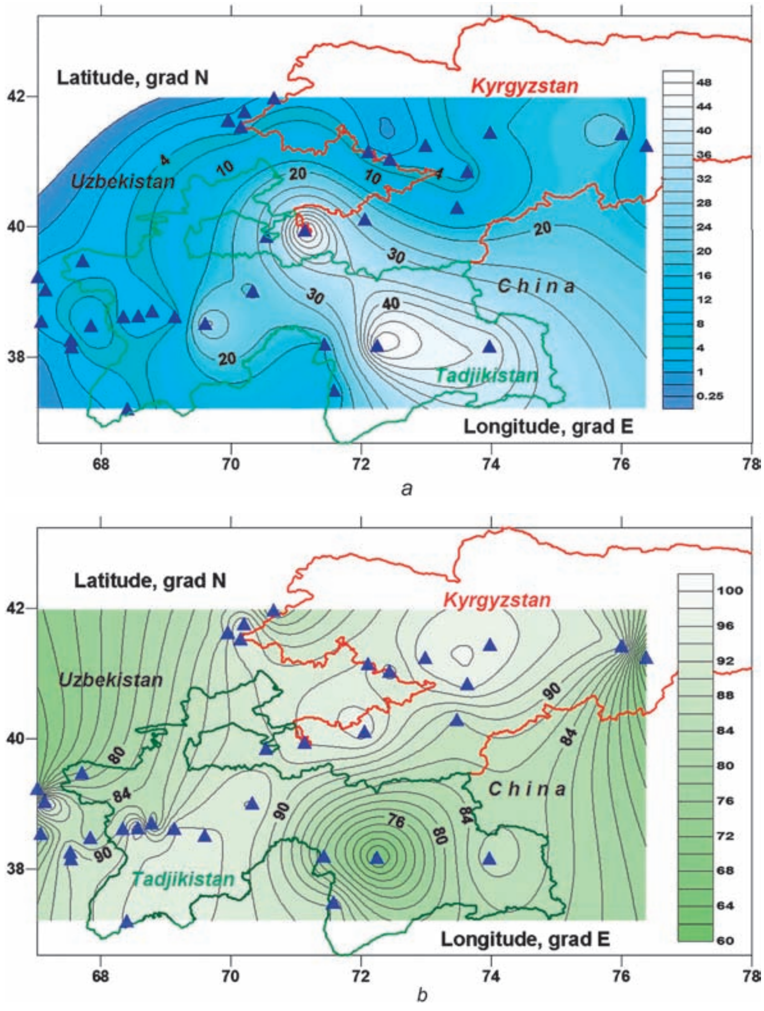

Fig. 2. The spatial distribution of seasonal (April-September) river runoff probability within the Amu Darya and Syr Darya watersheds in 1969 – high-water (*a*) and in 1974 – low-water (*b*) years. Blue triangles are the hydrological stations

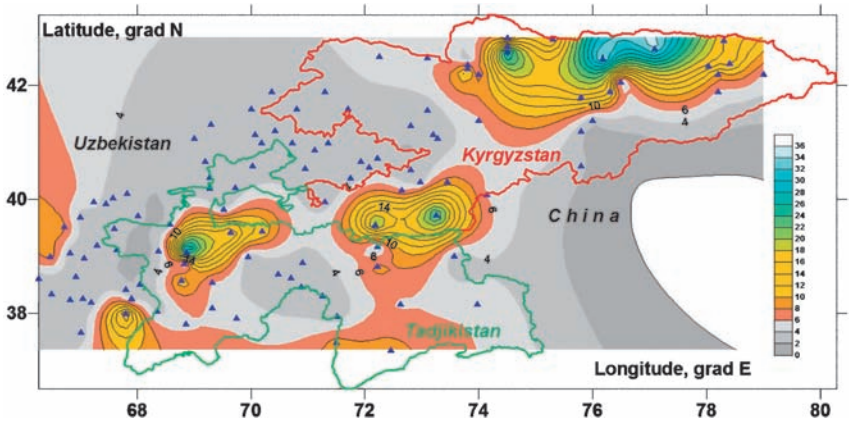

Fig. 3. The spatial distribution of $P(Pr_{I-IX})$ within the Amu Darya and Syr Darya watersheds in high-water year (1969). Average $P(Pr_{I-IX})$ equals 6.14%. Blue triangles are the measurement sites

the spatial distribution of probability of seasonal river runoff within the Amu Darya and Syr Darya watersheds in high-water and low-water years.

For the rivers of the Aral Sea basin, both precipitation and air temperature are used as predictors in order to forecast seasonal and monthly runoff from the upper watersheds. Identification of their role in formation of extreme values of river runoff would help improving methods of hydrological forecasts in critical situations for water users.

Only in 1969 the mean values of probabilities for both runoff – $P(R_{IV-IX})$ and precipitation – $P(Pr_{I-IX})$ could be treated as extremely high, but the same phenomenon is not true for probability of air temperature – $P(T_{VI-IX})$. Below is the example of the regional distribution of extreme precipitation (Fig. 3).

Tables 4–5 contain the probabilities of annual precipitation and seasonal air temperatures and their standard deviation (SD) related to the years that have been previously identified as low, average, and high water based on R_{IV-IX} values (see Table 3). Data in Tables 4–5 are presented as all together (ALL), sorted by Central Asian states (here, KYR – Kyrgyzstan, UZB – Uzbekistan, TAD – Tajikistan), and along altitude Z a.s.l.

In assessing the probabilities of precipitation and air temperatures in the Table 4–5 as climate factors of river flow formation, we may note the following:

- Probabilities of yearly precipitation correspond completely to $P(R_{IV-IX})$ of runoff in high-water, low-water, and normal years. This conclusion is correct not only for the entire territory of the Amu Darya and Syr Darya river basins, but also for its different parts and altitudinal zones. Standard deviation of $P(Pr_{I-IX})$ is significantly less in high-water year compared to low-water and normal years. This feature of precipitation is important for obtaining a generalized estimation of the regional water resources and for improvement of hydrological forecasts and computations.
- Probabilities of seasonal air temperature $P(T_{VI-IX})$ in Table 5 demonstrate the absence of rather evident relationship with seasonal runoff in characteristic years. We may only note a rather cold summer season in the high-water year of 1969. Standard deviation of $P(T_{VI-IX})$ is also significantly less in the high-water year compared to the low-water and normal years.

Thus, in the high-water year, we see rather good synchronism between probabilities of precipitation and runoff, but for the low-water year, the extreme value of the regional mean $P(Pr_{I-IX})$ was in 1971 but not in 1974. Asynchronism between

Table 4. Probabilities (%) of yearly precipitation in the characteristic years of runoff

Data	Index	1969	1974	1985	1969	1974	1985	1969	1974	1985
		$380m \leqslant Z \leqslant 4169m$			$Z \geqslant 2000m$			$Z \geqslant 3000$ m		
ALL	Mean	6.14	67.92	58.37	7.92	58.53	68.03	8.81	58.61	62.30
	Min	2.46	2.46	9.02	2.46	2.46	22.13	2.46	5.74	18.85
	Max	35.25	97.54	97.54	31.97	94.26	97.54	31.97	94.26	94.26
	SD	7.04	26.21	21.94	8.01	28.75	24.28	9.00	31.10	24.61
KYR	Mean	9.09	55.00	63.35	8.70	50.86	80.37	9.02	49.59	77.46
	Min	2.46	2.46	9.02	2.46	2.46	48.36	2.46	5.74	61.48
	Max	35.25	97.54	97.54	28.69	90.98	97.54	25.41	87.70	94.26
	SD	9.15	29.24	20.51	8.35	28.90	16.97	8.76	29.16	13.17
UZB	Mean	3.20	75.56	62.82	2.46	80.33	51.64	–	–	–
	Min	2.46	18.85	22.13	2.46	71.31	31.97	–	–	–
	Max	18.85	97.54	94.26	2.46	87.70	71.31	–	–	–
	SD	2.82	18.60	19.50	0.00	7.27	16.93	–	–	–
TAD	Mean	6.30	75.04	44.40	8.31	63.82	54.22	8.61	67.62	47.13
	Min	2.46	12.30	12.30	2.46	12.30	22.13	2.46	12.30	18.85
	Max	31.97	97.54	90.98	31.97	94.26	97.54	31.97	94.26	90.98
	SD	6.38	24.87	22.12	8.35	29.11	26.08	9.83	32.19	24.47

Table 5. Probabilities (%) of air temperatures for VI-IX in the characteristic years of runoff

Data	Index	1969	1974	1985	1969	1974	1985	1969	1974	1985
		380 m $\leqslant Z \leqslant$ 4169 m			$Z \geqslant$ 2000 m			$Z \geqslant$ 3000 m		
ALL	mean	85.74	76.55	34.07	81.64	77.95	31.72	77.66	81.35	33.40
	Min	48.36	9.02	5.74	48.36	9.02	12.30	61.48	12.30	18.85
	Max	97.54	94.26	68.03	97.54	94.26	68.03	90.98	94.26	68.03
	SD	10.18	17.01	13.21	10.72	20.53	10.46	9.46	18.95	12.50
KYR	mean	85.40	70.34	29.13	82.95	73.28	31.48	81.56	84.02	34.84
	Min	48.36	9.02	12.30	48.36	9.02	12.30	74.59	77.87	18.85
	Max	97.54	94.26	68.03	97.54	94.26	68.03	90.98	94.26	68.03
	SD	9.55	19.70	10.52	11.48	21.02	12.33	5.93	5.38	16.39
UZB	mean	93.53	85.88	47.81	90.16	85.25	42.62	–	–	–
	Min	84.43	81.15	22.13	84.43	81.15	38.52	–	–	–
	Max	97.54	90.98	64.75	94.26	87.70	45.08	–	–	–
	SD	3.65	2.31	11.43	4.92	3.14	3.14	–	–	–
TAD	mean	82.30	78.22	32.32	77.87	81.97	29.30	73.77	78.69	31.97
	Min	48.36	12.30	5.74	61.48	12.30	18.85	61.48	12.30	18.85
	Max	97.54	94.26	68.03	94.26	94.26	45.08	90.98	90.98	45.08
	SD	11.04	15.95	12.09	9.50	21.76	7.21	11.05	26.91	7.84

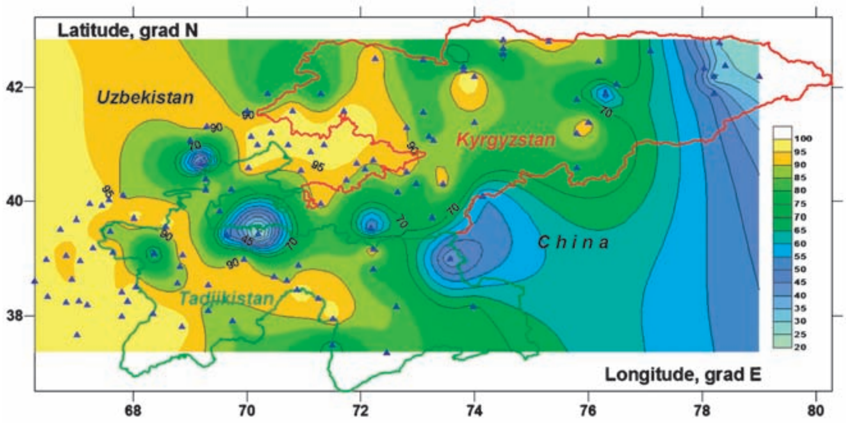

Fig. 4. Spatial distribution of $P(Pr_{I\text{-}IX})$ within the Amu Darya and Syr Darya watersheds in 1971 with minimal mean values of precipitation. Average P(PrI–IX) equals 83.29%. This year was defined as extreme in the sample of $P(Pr_{I\text{-}IX})$ irrespective of runoff

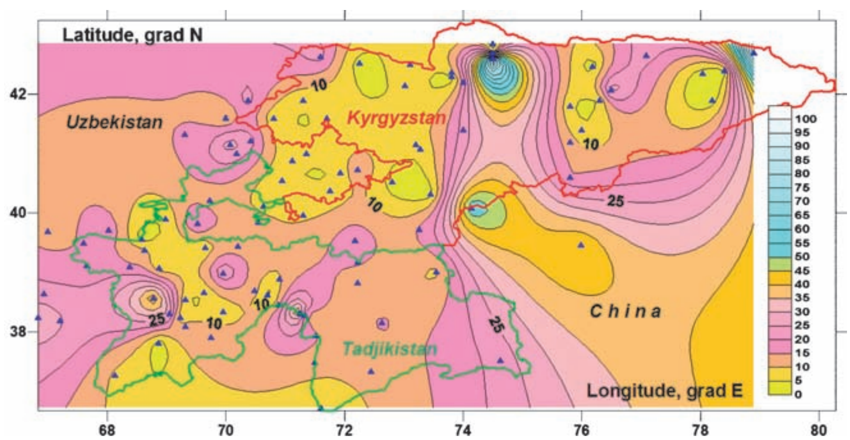

Fig. 5. Spatial distribution of $P(T_{VI-IX})$ inside the Amu Darya and Syr Darya watersheds in 1990 with maximal mean value of air temperature. Average $P(T_{VI-IX})$ equals 15.0%. This year was defined as extreme in the sample of $P(T_{VI-IX})$ irrespective of runoff

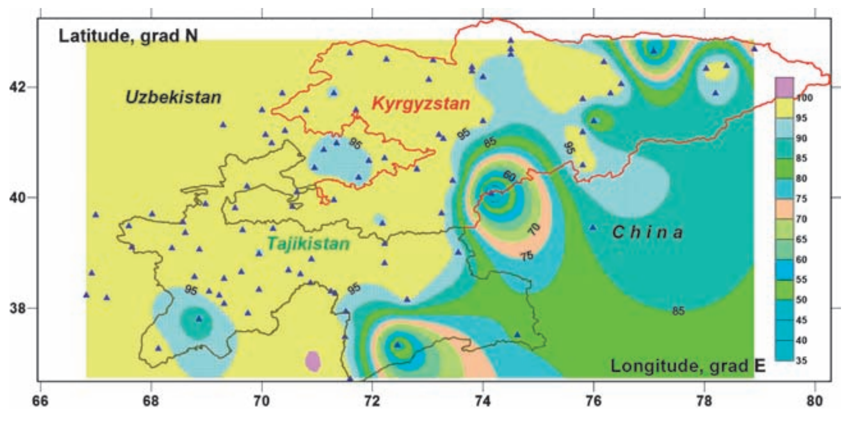

Fig. 6. Spatial distribution of $P(T_{VI-IX})$ in the Amu Darya and Syr Darya watersheds in the 1972 year with minimal air temperature. The average $P(T_{VI-IX})$ equals 94.8%. This year was defined as extreme in the sample of $P(T_{VI-IX})$ irrespective of runoff

the extreme and normal years for runoff and air temperature was identified after calculating $P(T_{vi\text{-}ix})$ independently from $P(R_{IV-IX})$ of runoff in the Table 3. Spatial distribution of $P(T_{VI-IX})$ in the extreme years is shown on Figs. 5, 6.

TOTAL MELTING OF GLACIERS UPSTREAM OF THE AMU DARYA RIVER BASIN

The headwaters of the Amu Darya river basin contains several thousands glaciers [Inventory..., 1971–1978]. These glaciers were regionalized into 138 quasi-homogeneous groups for computing the total volume V_M of their melting, where V_M is the function of meteorological variables and empirical parameters. Each group is characterized by: geographical coordinates; areas of glaciers and solid moraine; altitudinal distribution of area; altitudes of glacier head, terminus and firn boundary; upper limit of solid moraine cover; depth of solid moraine at the end of glacier; and slope and azimuth of glacier surface.

A model, REGMOD, developed as a set of computer programs and data on climate variables [Konovalov 1985, 2006] was used to calculate long-term series of hydrological regime of glaciation. In the model, the formula for determination of total volume of glacier melting v_m in the moment t, has the form:

$$v_m(t) = M_c(\tilde{z}_{im}, t)S_{im} + M(\tilde{z}_i, t)S_i +$$

$$+ M(\tilde{z}_f, t)S_f + M(\tilde{z}_{ws}, t)S_{ws} + M(\tilde{z}_{ss}, t)S_{ss}. \quad (4)$$

Here, M is intensity of melting for open ice or snow, $M_c = Mf(h_c)$ is intensity of ice melting under cover of solid moraine (im) of depth h_c, i is bare ice, f is old firn, ws is winter snow, ss is summer snow, $f(h_c)$ is a function of ice melting decrease under moraine cover of depth h_c, $\tilde{z}$ is mean weighted altitude for the certain S area. In order to obtain the total melt volumes V_M from the equation (4) we used:

$$V_M = \sum_{d_{bp}}^{d_{ep}} v_m(t) \quad (5)$$

where d_{bp} and d_{ep} are the dates of the beginning and the end of the calculation period.

Computations of V_M using the equations (4–5) are based on several numerical methods described in detail in [Konovalov, 1985, 2006]. The REGMOD model and its main subroutines have been successfully tested [Konovalov, 2007]. The total river runoff computed by means of the water balance equation showed a very close coincidence with measured data. The REGMOD model was applied for the selected 138 groups of glaciers during 1935-1994. The set of empirical equations (see below) describing the spatial distribution of volumes V_M in high and low water years was obtained in [Konovalov, 2009] as functions of geographical coordinates (longitude and latitude):

$$V_M(\text{high}) = 7E - 06\text{lat}^5 - 0.0028\text{lat}^4 +$$
$$+ 0.4261\text{lat}^3 - 28.796\text{lat}^2 + 976\text{lat},$$

$$V_M(\text{low}) = -0{,}0001\text{lat}^4 +$$
$$+ 0.037\text{lat}^3 - 3.8553\text{lat}^2 + 186.9\text{lat},$$

$$V_M(\text{high}) = -1E - 06\text{long}^5 + 0.0009\text{long}^4 -$$
$$- 0{,}1825\text{long}^3 + 13.899\text{long}^2 - 115.36\text{long},$$

$$V_M(\text{low}) = -1E - 06\text{long}^5 + 0.0005\text{long}^4 -$$
$$- 0.0801\text{long}^3 + 5.1975\text{long}^2 - 32.441\text{long}.$$

In the headwaters of the Amu Darya river basin, the total volume of glacier melting equals to 7.108 km^3 and 26.888 km^3 in the low and high water years, respectively.

It is known [Konovalov 1985, 2006] that V_M depends from the altitude of firn boundary Z_{fg} on glaciers. Therefore, it is necessary to use this parameter for additional studying of changes of V_M. Analysis showed [Schetinnikov, 1998] that the decrease of Z_{fg} along latitude relates to the prevailing (more 76%) concentration of glaciers in the northern part of the region at the altitudes of 3.7 – 4.4 km a.s.l; but in its south, the largest part of the glaciers (62%) are located between 4.0 and 5.0 km a.s.l. The longitudinal increase of Z_{fg} in the same part of the Pamiro-Alai mountain region has been previously shown by [Kotlyakov et al., 1993].

Finally, multi-factor piecewise linear equations were obtained to calculate the statistical probability for the total melting volume of the glaciers in low and high water years as a function of geographical coordinates and average altitude of firn boundary. The general form of the formulae is the following:

$$P(V_m) =$$

$$= a\,Long + b\,Lat + c\,Z_{fg} + \text{Const}\% \qquad (6)$$

Empirical parameters of this formula are given in Table 6.

Principally, enhancing R^2 in the Table 6 is possible by means of using additional independent variables.

CONCLUSIONS

On the presented graphs of the spatial variability for river runoff, precipitation, and air temperature within the Syr Darya and Amu Darya basins, there are certain subareas where the local data are not consistent with the mean value of probability in characteristic years. The reason of such inconsistency is not clear so far. Probably, it is a combined effect of local relief and pattern of atmosphere circulation. Another interesting and important feature of the spatial variability of climatic factors of runoff is their even distribution in high-water years. Both effects have to be taken in consideration at water management, hydrological forecasting, and computations.

Spatial synchronism and asynchronism of air temperature and precipitation extremes are the important characteristics of their fields that strongly influence biota, environment, population, and production. The results presented in Table 7 show high levels of spatial synchronism for minimal air temperature for June-September and maximal precipitation for January-December. This feature of the regional climate has been identified for the first time ever.

Statistics of climatic factors, including integral and differential distributions and spatial

Table 6. Parameters of piecewise multi-factor linear equation for calculation $P(V_m)$

	1-th version of formula (6)				2-nd version of formula (6)				*Br*	R^2
	Const$_1$	a_1	b_1	c_1	**Const$_2$**	a_2	b_2	c_2		
P_1	23.838	–0.196	–0.304	1.084	33.326	0.090	–0.814	0.277	5.085	0.76
P_2	–220.164	1.781	11.804	–70.652	115.416	0.191	–0.933	0.725	91.950	0.88

Note: a_1, b_1, c_1, Const$_1$, a_2, b_2, c_2, and Const$_2$ are parameters for the first and second versions of the formula (6); P_1 – high-water year, P_2 – low-water year, *Long, Lat* – are longitude and latitude in integer and decimal part of degree, respectively; Z_{fg} – firn boundary in km a.s.l., R^2 is explained part of the variance of the function (coefficient of determination), *Br* is the criteria for selection of the empirical equation. When $P_1 \leqslant Br$, computation is performed by the first version of (6), otherwise by the second version, similarly for P_2.

Table 7. The spatial mean of probabilities for $T_{(VI-IX)}$ and $Pr_{(I-XII)}$ in the extreme years

Index	Air temperature				Precipitation			
	Pmax %	**Year**	**Pmin %**	**Year**	**Pmax %**	**Year**	**Pmin %**	**Year**
ALL	15.00	1990	94.80	1972	6.14	1969	83.29	1971
KYR	11.23	1984	92.31	1972	9.09	1969	79.20	1961
UZB	6.47	1988	96.63	1972	3.20	1969	93.22	1971
TAD	9.46	1984	94.62	1972	6.30	1969	73.23	1971

Note: indexes were explained in the text above after Tables 4-5. Pmax and Pmin are maximal and minimal mean values of probabilities.

correlation functions, provide a much more informative assessment of the impact of climate change on the hydrological regime of the Asian river basins, compared to the determination of average values alone. Efficient application of this conclusion requires the same set of parameters for 1931–1960, 1961–1990, and 1991–2020 time intervals that are not available at present. So far, we have such set only for 1961–1990.

Regional determinations of glacier regimes are necessary for solving problems of water consumption and forecasts of runoff. Intra-seasonal distribution of total melting in glacier areas is closely connected with types of the annual water yields. The glaciers' runoff in the headwaters of the river Amu Darya basin in maximal and average years is concentrated in July-August when winter-spring accumulation of snow has been exhausted outside of glaciers area.

It appeared that the spatial distribution of the total amount of the glaciers' melting is less variable in the years with extreme water yield compared to the average years. This peculiarity is very beneficial for hydropower and agriculture sectors because it provides additional ability to stabilize water balance of reservoirs utilizing natural features of the regional climate. However, the stabilizing role of glacier runoff in the Amu Darya basin is becoming less effective due to shrinking of the glacier area by 2,324 km^2 during 1961–2000. This is very significant and undoubtedly influences the sustainable availability and utilization of river runoff in the Aral Sea basin, especially in low water seasons.

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