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Interannual variations of the discharge of Amu Darya and Syr Darya estimated from global atmospheric precipitation

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Abstract

The discharges of two main rivers of the basin of the Aral Sea (Amu Darya and Syr Darya) was estimated from two global data sets of monthly atmospheric precipitation (GPCP, collected in 1979–2001 and GPCC, collected in 1986–2001) integrated over the areas of formation of the discharge of these two rivers. Both seasonal and interannual variations of atmospheric precipitation are evident. A decreasing trend is evident in Amu Darya discharge; the discharge of Syr Darya did not decrease since 1985. Both trends well correspond to interannual variability of the sea level of two independent basins of the Aral Sea (the Large Sea and the Small Sea) derived from the TOPEX/Poseidon satellite altimetry (1992–2002).

Keywords: Aral Sea; Amu Darya; Syr Darya; Discharge; Precipitation; Satellite altimetry; 35–50°N; 55–75°E

1. Introduction

The Aral Sea is a terminal lake (no outflow) located in Central Asia (Fig. 1). It receives inflow from two rivers only: Amu Darya and Syr Darya. The surface area of the Aral Sea was 68,320 km^2 in 1960, making it the fourth largest inland water body on Earth. It existed in that form during the past 8000–10,000 years (Boomer et al., 2000).

Amu Darya is the most important river within the Aral Sea basin. Originating among glaciers and snowfields of the Pamir mountains of Tajikistan, Kyrgyzstan, and Afghanistan, it flows nearly 2400 km from the mountains across Kara-Kum desert and into the Aral Sea. Average annual flow from the drainage basin is around 79 km^3 (Micklin, 2000). This includes not only the flow of the Amu Darya and its tributaries but several "terminal" rivers (Zeravshan, Murgab, Tedjen) that disappear in the deserts.

All the flow of Amu Darya originates in the well-watered Pamir mountains. This flow is substantially diminished by evaporation, transpiration from vegetation along the banks, and bed filtration as the river passes across the Kara-Kum desert to the Aral Sea.

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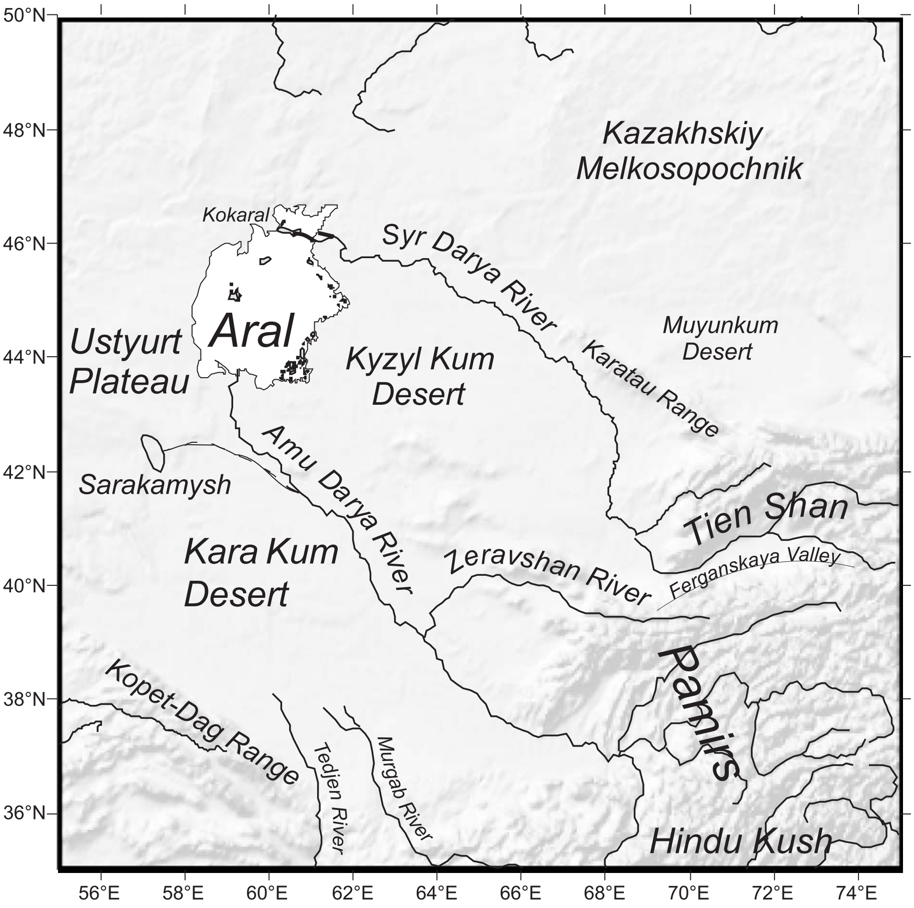

Fig. 1. Map of the study region.

Even prior to the development of modern large-scale irrigation, average inflow of the river to the Aral Sea decreased to around 40 km^3 from the 62 km^3 coming from the mountains (Micklin, 2000).

The Syr Darya river flows from the Tien Shan mountains, located to the north of the Pamirs. It is chiefly fed by glaciers and snowmelt. Its total length is 2500 km. The average annual flow of the Syr Darya River is 37 km^3 (Micklin, 2000). In parallel to Amu Darya, even prior to modern age of irrigation, the diminution of Syr Darya flow was substantial during its long journey across the Kyzyl-Kum desert, with less than half (around 15 km^3 on the average annual basis) of the water coming from the mountains reaching the Aral Sea.

The zone of the Aral Sea is classified as an “Arid-Temperate Climate” zone (West, 1983). The main part of this zone is covered by dry steppes, semi-deserts and deserts. In the plain area around the Aral Sea, cyclonic rain is still received from the Atlantic Ocean, falling in the winter in the southern parts, and mostly in the spring in the north. The winters are cold, hence evaporation at this time of year is very small. In summer potential evaporation is 10–15 times of precipitation due to hot and dry weather (Walter, 1985).

After 1957, the Aral Sea began to dry up as more and more water was directed to irrigate cotton and other thirsty crops. The sea used to receive 50–60 km^3 of water a year from its two main feeder rivers. By the mid-1980s, river flow into the sea had shrunk to 2–5 km^3 a year (Keyser et al., 1999). As a result of the reduced inflow, the water balance of the Aral Sea became negative after 1960; evaporation from the lake surface was greater than the sum of on-lake precipitation and the reduced streamflow. As a result, the lake surface area decreased ~60%, the mean depth decreased from 15 to 8 m, the water volume decreased by 80%, and salinity increased from 10 to >35 ppt (Small et al., 2001b). Now the Aral Sea consists of two separate basins: the Large (Big) Sea fed by Amu Darya in the south and the Small Sea fed by Syr Darya in the north. A substantial part of the Amu Darya discharge flows to Sarakamysh Lake located in the northern part of Kara Kum desert. Desiccation has weakened the "lake effect" of the Aral Sea influencing climate over a distance of several hundred kilometers; air temperature near the Aral Sea changed by up to 6 °C (Small et al., 2001a).

In the 1990s the sea level had dropped by 16 metres. As a result the shallow (less than 2 m deep), dried-out Auzykokaral Strait in 1968 caused the Kokaral, a little island stretching from the west to the east, to joined up with the western borders of the Aral. In 1990 after the deeper Berg Strait (about 13 m) had also dried out, this land mass finally got linked to the eastern coast of the Aral Sea, thus cutting the once large water body into two–the Small Aral Sea to the north and bigger Large Aral Sea to the south. The total volume of water in the Aral Sea then had fallen to 370 km^3 and covered a total area of 40,394 km^2; Small Aral Sea accounted for a volume of under 30 km^3 and an area of 3500 km^2. Small Aral Sea was 11 times smaller in volume and 10 times smaller in area than the Large Aral Sea.

Until 1989, the water level decreased evenly over the entire Aral Sea, because the Berg Strait connected the northern and southern water bodies. Later, after their isolation the water levels in the Large and the Small Aral Seas changed at different rates. The Large Aral continued to shrink while the Small Aral Sea swelled as water poured in from Syr Darya. Water from the Small Aral flowed to the Large Aral through the man-made canal built in the shallow Berg Strait in early 1980s to facilitate navigation. To prevent the decreasing of the level of the Small Aral Sea (this area is most populated) the canal was dammed in 1992, but the water broke and washed away the dam several times. The most serious damage of the dam happened in April 22, 1999; by September 1999 the level of the Small Sea decreased on 2.5 m.

Analyzing the dramatic changes in the Aral Sea hydrology, it is important to discern the difference between catastrophic anthropogenic impact we observe around the Aral Sea and natural trends in climate change, which manifests themselves in changes of the amount of atmospheric precipitation.

The goals of this paper are:

- to estimate the amount of water precipitated from the atmosphere over the catchment areas of Amu Darya and Syr Darya;
- to analyze seasonal and interannual variations of atmospheric precipitation feeding river discharge to the Aral Sea;
- to compare these variations with the changes of the Aral Sea level derived from satellite altimetry.

2. Data and method used for analysis

Monthly data on atmospheric precipitation were obtained from two sources: Global Precipitation Climatology Project (GPCP) and Global Precipitation Climatology Centre (GPCC).

The monthly digital maps of precipitation produced as a part of the Global Precipitation Climatology Project (GPCP) were derived from satellite remote-sensed observations (Huffman et al., 2002). We obtained these data from the Distributed Active Archive Center at Goddard Space Flight Center (NASA GSFC DAAC). The data are based on the measurements of Special Sensor Microwave/Imager (SSM/I) multi-channel passive microwave radiometers on Defense Meteorological Satellite Program (DMSP) satellites, infrared (IR) sensors on Geosynchronous Operational Environmental Satellites (GOES, USA), Geosynchronous Meteorological Satellite (GMS, Japan), Meteorological Satellite (METEOSAT, European Community), the NOAA-series low-earth-orbit satellite (LEO, USA), and the TIROS Operational Vertical Sounder (TOVS) data derived from the High-Resolution Infrared Sounder 2 (HIRS2), Microwave Sounding Unit (MSU), and Stratospheric Sounding Unit (SSU) instruments on the NOAA series of polar orbiting meteorological satellites. The monthly averaged data are interpolated to a global grid of 1° spatial resolution. We extracted for analysis the data from the area located between 35°N and 50°N and 55°E and 75°E for the period from 1979 till 2001.

The Global Precipitation Climatology Centre (GPCC) in Germany collects and analyzes the data on atmospheric precipitation all over the world. The rainfall data are based on completely quality-controlled data from globally exchanged synoptic weather reports and monthly climate reports from totally 6000–7000 stations. The products of GPCC are gridded datasets of monthly total precipitation derived from observed data measured by raingauges. These products cover the entire earth's land surface. The spatial resolution is 1° by 1° geographical latitude and longitude. We used the data (35°N–50°N; 55°E–75°E) for the period from January 1986 to November 2001.

The data on monthly precipitation was integrated over the areas where the river runoff is formed. The hatched areas at Fig. 2 show the zones which 1° by 1° grid nodes were included into the catchment areas of Amu Darya and Syr Darya.

The altimetric analysis of the temporal variations of the Aral Sea level was based on the data of the TOPEX/Poseidon (T/P) satellite. The precision of the measurements of sea surface height by T/P is 1.7 cm (Fu and Pihos, 1994) and is higher than in other altimetry programs (Chelton et al., 2001). The position of the tracks of the satellite orbits is shown at Fig. 3; it is optimal for the analysis of the variations of both the Large Sea (including its eastern and western parts) and the Small Sea. The period between orbits (~10 days) enables the analysis of interannual, seasonal, and subseasonal variability of the sea level. The T/P data represent the longest time-series of satellite altimetry; we operate the data obtained from September 1992 to August 2002. Unfortunately, in the end of August 2002 the orbit of T/P satellite was changed and the area of the Aral Sea was excluded from the satellite measurements. The new satellite JASON-1 was launched in January 2002; its orbit was designed to obtain altimetry data along the tracks of T/P. Thus, the altimetric time series of the Aral Sea level could be extended into future.

Two approaches are conventional in the studies of altimetric sea level time series. The first one implies the analysis of variations of the anomalies of the sea surface height related to its mean value or the geoid height; the latter one is estimated averaging the observations along one or several tracks during the time period of one cycle. The second approach is based on the analysis of variations of sea level in the intersection point of two tracks; this approach enables the studies of the regional variations of sea level. The first approach is not applicable for the Aral Sea because the concept of its mean surface is arbitrary: first, the area of the sea is not constant, and second, during winter season a substantial part of the sea is covered by ice and the altimetric data are absent. The geoid height also cannot be used as a reference surface, because the precision of its estimation in this

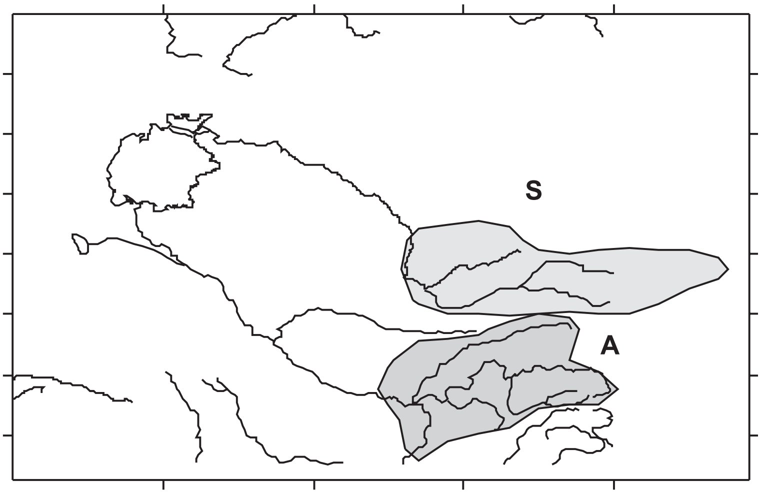

Fig. 2. The catchment areas of Amu Darya (A) and Syr Darya (S).

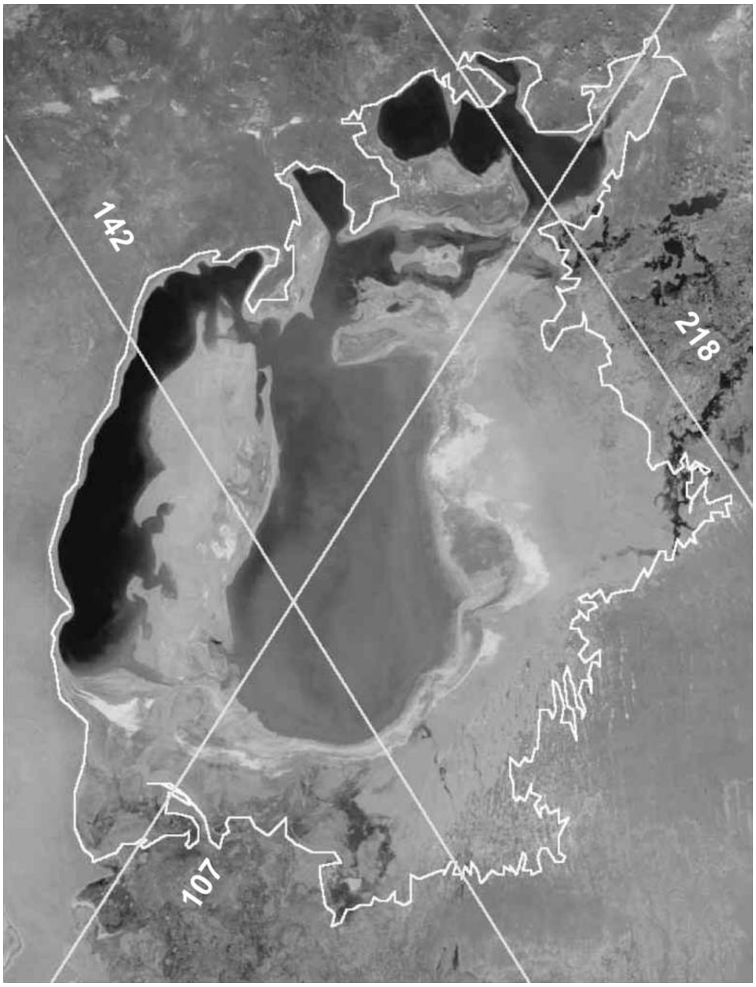

Fig. 3. Ground track TOPEX/POSEIDON before maneuver of the orbit in August 2002. The MODIS images from 18 May 2002 (Credit: Jacques Descloitres, MODIS Land Rapid Response Team, NASA/GSFC) and coastline 1962 (white line).

region does not exceed 50 cm. That is why the second method was selected. We analyzed the variations of sea level in the point of intersection of the 107 ascending and 142 descending tracks in the Large Sea and the intersection of the tracks 107 and 218 in the Small Sea. The level of the Sarakamysh Lake was obtained from track 107. The sea level was related to reference ellipsoid (in m).

The TOPEX/POSEIDON data were obtained from the NASA Goddard Space Flight Center (GSFC) Ocean Altimeter Pathfinder Project and the Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory of California Institute of Technology. For data analysis we used the Information and Software integrated satellite Altimetry Data Base (ISADB) designing in the Russian Academy of Sciences Geophysical Center (Medvedev et al., 1997).

3. Results and discussion

Fig. 4 illustrates the interannual variations of the Amu Darya runoff derived from the precipitation data obtained from different sources, and the level of the Large Sea and Sarakamysh Lake measured by satellite

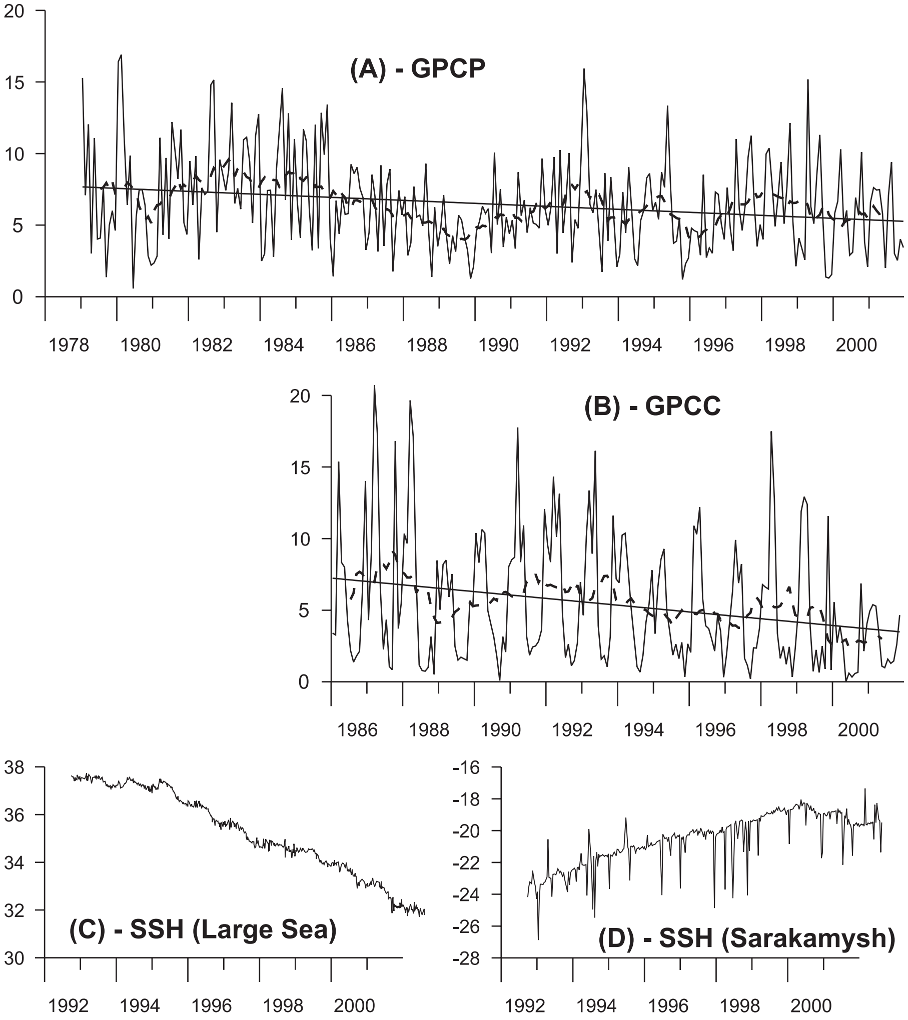

Fig. 4. Interannual variations of the discharge of Amu Darya derived from precipitation integrated over its catchment area. (A) Satellite-measured (GPCP) precipitation (km^3/month); (B) gauge-measured (GPCC) precipitation (km^3/month); (C) satellite-measured (TOPEX) level of the Large Sea (m); (D) satellite-measured (TOPEX) level of the Sarakamysh Lake (m). Dashed line is a moving average of about 1 year (13-point) period.

altimeter. Similar properties of the Syr Darya runoff and the level of the Small Sea are given at Fig. 5.

Both seasonal and interannual variations of atmospheric precipitation are evident. Seasonal maxima are observed in winter–spring and seasonal minima in summer–autumn. The precipitation supplying the discharge of both Amu Darya and Syr Darya exhibit interannual variations of 5- to 9-year period. Minima of discharge of both rivers were observed in 1980, 1989, and 1996; maxima in 1983–1985, 1992–1993, 1995 and 1998.

The total remote-sensed precipitation feeding the discharge of Amu Darya exhibits an evident trend to decrease (Fig. 4A); this trend is especially evident from 1983 to 1990. In 1990–1992 the precipitation over Amu Darya watershed increased, and then continued to decrease. In the gauge-measured precipitation (Fig. 4B) the trend to decrease is more evident. Similar trend is observed in the level of the Large Sea (Fig. 4C). The level of Sarakamysh Lake gradually increased by 2000 and slightly decreased in 2000–2002 (Fig. 4D).

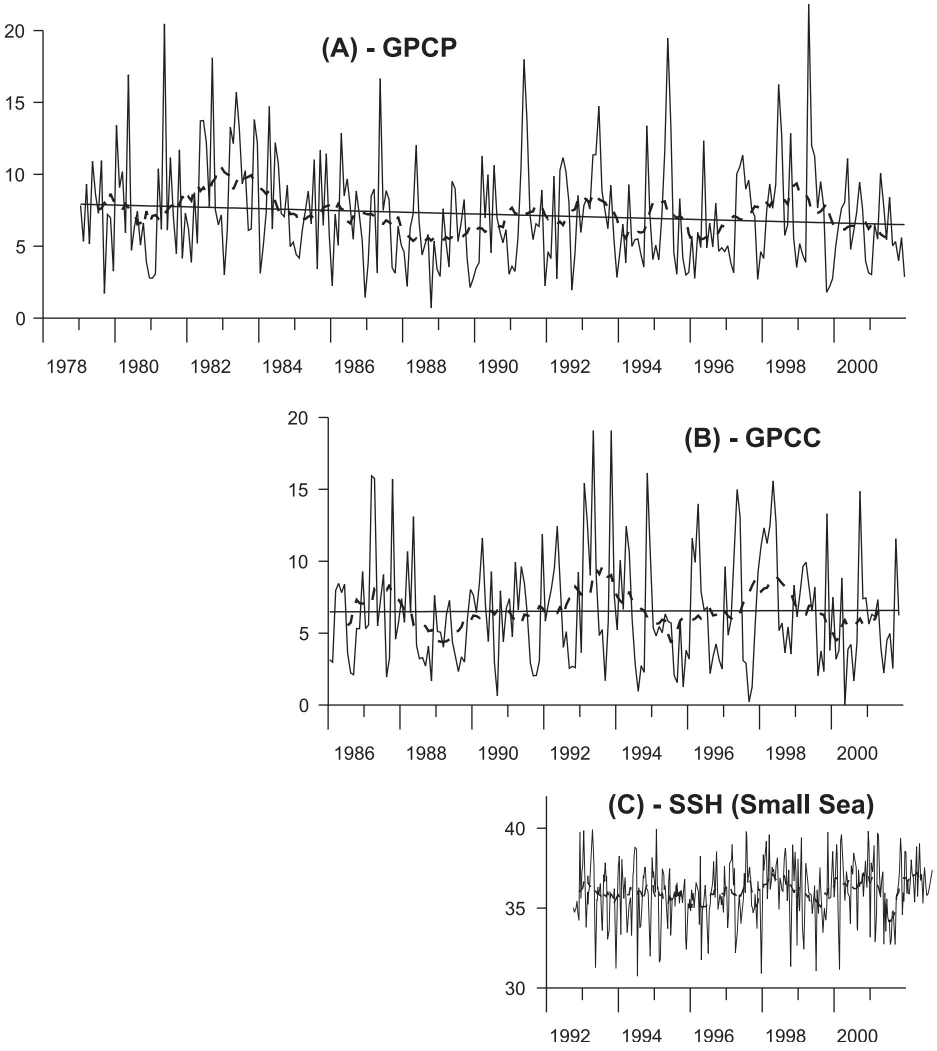

Fig. 5. Interannual variations of the discharge of Syr Darya derived from precipitation integrated over its catchment area. (A) Satellite-measured (GPCP) precipitation (km^3/month); (B) gauge-measured (GPCC) precipitation (km^3/month); (C) satellite-measured (TOPEX) level of the Small Sea (m). Dashed line is a moving average of about 1 year (13-point) period.

The decrease of the remote-sensed precipitation feeding the discharge of Syr Darya (Fig. 5A) was much less pronounced, as compared with the precipitation over Amu Darya. The gauge-measured precipitation over the Syr Darya basin did not show any decreasing trend (Fig. 5B); the level of the Small Sea also did not decrease (Fig. 5C). However, the variability of the level of the Small Sea was very high (Fig. 5C). Obviously, the level of the Small Sea depends mainly on the discharge from the Small Sea to the Large Sea through the Kokaral dam, which varies substantially from year to year (e.g., about 5 km^3/year in 1994 vs. 1 km^3/year in 1996). A gradual decrease in the Small Aral Sea level was observed from the spring of 1998 till mid-1999; it resulted from the break of the Kokaral dam.

We compared the satellite-measured levels of the Large Sea and the Small Sea to the precipitation over the catchment areas of both rivers (Table 1, the upper two rows). The correlation between the precipitation feeding the Amu Darya discharge and the level of the Large Sea was very low; similar correlation was

Table 1

Correlations (r) and their confidence levels (p) between precipitation (GPCP and GPCC) over the Amu Darya and Syr Darya catchment areas and the levels of the Large Sea and the Small Sea

	Amu Darya and the Large Sea		Syr Darya and the Small Sea	
	r	p	r	p
GPCP	0.0556	0.562	−0.0971	0.311
GPCC	0.2362	0.013	0.2246	0.018
GPCP (accumulated)	0.8936	0.000	−0.0800	0.404
GPCC (accumulated)	0.8854	0.000	0.0193	0.841

observed between the precipitation feeding the Syr Darya discharge and the Small Sea level. The correlation was significant only when the precipitation was obtained from the gauge measurements.

We made an attempt to estimate the amount of water accumulated during each month of the observations. We transformed the time series of the Amu Darya and Syr Darya discharge (derived from precipitation) using the following equation: $Y_t = \int_0^t (X_t - \bar{X}) \cdot \mathrm{d}t$, where X_t is the water income with precipitation at t-th month, Y_t is the water accumulated at t-th month, and $\bar{X}$ is the mean water income and discharge averaged over the entire period of observations.

The water accumulated over the Amu Darya catchment area was strongly correlated with the level of the Large Sea, in contrast to Syr Darya and the Small Sea, where the correlation was small and insignificant (Table 1, the lower two rows). We have two explanations of this difference. First, the volume of water in the Small Sea is much smaller as compared with the Large Sea. Second, the water precipitated over catchment area of Syr Darya flows directly from the Tien Shan mountains to the Aral Sea; relatively small part of water being accumulated in the ground and lost with evaporation. That is why the response of the Small Sea level to the water precipitated over the Syr Darya catchment area is immediate. At the same time, a substantial part of the water precipitated over the catchment area of Amu Darya is accumulated as a ground water in the desert areas along the river bed and around the Aral Sea. The total volume of the Large Sea is much greater than the volume of the Small Sea; this is a second reason why the response of the Large Sea level to rainfall and snowfall in the Pamir mountains where the Amu Darya discharge is formed appears to be much slower.

The level of Sarakamysh Lake was not correlated with the precipitation over the Amu Darya watershed and was negatively correlated with the level of the Large Aral (r=−0.7974; p=0.000). The latter correlation reveals nothing but a gradual increase of the level of Sarakamysh Lake and a gradual decrease of the level of the Large Aral in 1992–2000 (Fig. 4C,D).

Therefore, the correlations between atmospheric precipitation and the levels of different parts of the Aral Sea reveal important features of water balance in this arid zone.

4. Conclusions

The discharges of two main rivers of the basin of the Aral Sea (Amu Darya and Syr Darya) were estimated from the monthly data of atmospheric precipitation integrated over the areas of formation of the discharge of these two rivers. Two global data arrays of atmospheric precipitation were used. The first one is the remote-sensed atmospheric precipitation data produced within the scope of the Global Precipitation Climatology Project (GPCP) from the measurements of microwave radiometers and infrared sensors on different satellite platforms collected during 1979–2001. The second data array is derived from the precipitation measured by rain gauges and processed at the Global Precipitation Climatology Centre in Germany over 1986–2001. Both data arrays are gridded datasets of monthly total precipitation of spatial resolution 1° by 1° geographical latitude and longitude.

A decreasing trend is evident in Amu Darya discharge; the discharge of Syr Darya did not decrease since 1985; the general decreasing trend of Syr Darya discharge was almost insignificant during two recent decades. Both trends well correspond to interannual variability of the sea level of two independent basins of the Aral Sea (Large Sea and Small Sea) derived from the TOPEX/Poseidon satellite altimetry (1992–2000). The level of the Large Sea fed by Amu Darya gradually decreased during 1992–2000 without pronounced interannual oscillations. The Small Sea obtains water from Syr Darya; its level did not decrease during the recent decade of satellite observations. The decrease of the Large Sea volume results from the general decrease of the total rain and snow precipitation over the catchment area of Amu Darya; cyclic interannual variations of atmospheric precipitation do not influence its level. On the contrast, the volume of the Small Sea is much less and its level is sensitive to short-scale interannual variations of Syr Darya river resulting from the oscillations of atmospheric precipitation over the vast region surrounding the Aral Sea.

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