Analysis of Impact of Aral Sea Catastrophe on Anomaly Climate Variables and Hydrological Processes

Berdimbetov, T.,[1] Ma, Z.,[1] Nietullaeva, S.[2] and Yegizbayeva, A.[3]
[1]CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China, E-mail: b_timur_1984@mail.ru
[2]Nukus branch of Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi, Nukus 230100, Uzbekistan, E-mail: s.nietullaeva@yandex.ru
[3]National Center for Space Research and Technology, No. 15 Shevchenko, Almaty 050010, Kazakhstan
E-mail: asset@spaceres.kz

Abstract

Since 1960, water level began to decline considerably due to anthropogenic impact of the Aral Sea (AS), and it is continued to this day, which has led to dramatic changes in the climate around the AS, including ambient temperatures and sharp increases in evapotranspiration. Although, it isn't possible to see normal trend in this precipitation. Time series analysis of the FTI (First Time Interval 1901-1960) and STI (Second Time Interval, 1960-2015), highlighting climate change around the AS, based on Global Climate Data, suggests that there is a significant negative difference between precipitation and evapotranspiration during the drying of the AS. It is possible to see the logical compatibility of the air temperature and difference between precipitation and evapotranspiration observed around the AS, i.e. the temperature fluctuation trend is positive and contrary to the difference between precipitation and evapotranspiration negative trend, which means that the annual hydrological budget was reduced according to the time scale. In this article, determining the AS as the central point, we analyze the changes in the thermal and hydrological processes observed on the AS, as well as the impact to the environment of anomalous climate change observed on and around the sea like the drying out of the AS.

1. Introduction

Until 1960, the AS was the fourth largest lake in the world and the surface area was 65,000 km^2. Considered as a terminal lake, the AS is the principal source of water in Amu Darya and Syr Darya rivers (Small et al., 2001 and Gaybullaev et al., 2012). After 1960, due to irrigation actvities in the AS, the disbalance in the water occurred and caused declining of the sea (Micklin, 2000). Due to the large volumes of surface water evapotranspiration, the main source of water supply to the AS was sharply reduced. As a result of the decline in the inflow of the AS water balance after 1960, a significant negative indicator was reversed, i.e. the evapotranspiration volume on the Aral was larger than the amount of precipitation. As a result 1) the lake surfase area decreased by 60%, 2) the average depth was from 15 to 8 meters, 3) the lake volume decreased to 80% 4) the salinity increased from 10 ppt up to 100 ppt. The drying up of the AS caused a spatially large change in the land surface. In 1998, 48,000 km^2 of the lake were rare sandy plants, evaporating deposits, leading and important thermal changes, and moisture and radiation. Until 1998, 25,000 km^2 was preserved prior to relocation. The temperature of the lake surface increased due to thermal capacity, which influenced the rate of evapotranspiration and reduction of water levels. In Small et al., (2001) it is arugued that the drying of the AS is accompanied by a climatic change and a unique isolation of the temperature change trend. Based on global climate records, the dramatic temperature change around the AS was observed in the 1960-1997 period.

Several scientific studies have been conducted, and many are still continued in the AS region, including through integrated mathematical models to integrate climate change around the AS region and to explore the region's radiation processes (Abdurahimov and Kurbanov, 2015), hydrological and hydro meteorological (Bortnik and Chistyaevaya, 1990), water management (Micklin, 2000, Micklin, 2014 and Berdimbetov et al., 2020), one of the main causes of the AS basin, the AS water balance change based on data from satellite remote sensing (Cre´taux and Berge´-Nguyen, 2014) Assessment of the volumes of atmospheric precipitations (1986-2001) on Amu Darya and Syr Darya, based on the Global Weather Climatology Center (GPCC) (Nezlin et al., 2004), the hydrophysics of the AS in the first decade of the

21st century research on chemical and hydrobiological changes (Zavialov et al., 2003 and Zavialov et al., 2011) and other aspects.

2. Study Area, Data and Methodology

2.1 Study Areas

In this paper, the concerned study area is the AS region (Figure 1). The AS region, geographic location of the AS and the surrounding area are within a radius of 500 km (Abdurahimov and Kurbanov, 2015). The full study territory consists of the southern part of Kazakhstan (43^{0}00′N, 68^{0}30′E), the northwest part of Uzbekistan (38^{0}00′N, 68^{0}00′E) and northern part of Turkmenistan (41^{0}49′N, 60^{0}16′E). In terms of geographical aspects, the territory is predominantly a desert region and is 56 meters above sea level. The AS and the AS Region are administratively located in Uzbekistan (Karakalpakstan) and Kazakhstan. The AS includes the lower reaches of the Amu Darya and Syr Darya rivers, as well as the AS region, and the Aral desert (Aral-Kum) as well, which emerged in the north-eastern and southern parts due to the reduction of sea water level.

Ecological state: The middle latitudes in the region during the cold season are subjected to continental climate because it is a desert zone, and it is characterized by high temperature, relative humidity and low rainfall. Summer is very hot in the area with the average temperature in July around 24 or 25.5°C and the maximum temperature around 40-45°C. But, winter months are very cold, and in the southern Kazakhstan during the month of January, the average temperature falls to -12-(-15°C). Winds in the east prevail in the winter. They bring cold masses from East Asia. Here the absolute minimum is -30-(-35°C). After winter cold, warm spring and hot summer begin quickly. The cold period lasts for 180-200 days. Climatic conditions of the desert zone, occupied by the territory, are characterized by extreme drought, summer heat, cloudlessness and poor precipitations. During the period of March and April in the spring, precipitation is most likely to occur during the cyclonic activity. These rains moisturize the soil with dissolved water and create conditions for the development of transient plants in the spring. These plants disappear with hot and dry summers. The annual precipitation is about 100-120 mm, in some places 50 mm or less.

2.2 Data

This article uses information from the Climatic Research Unit (CRU) and NOAA global meteorological network. Meteorological data on monthly humidity from NOAA for 1960-2015 were obtained from CRU TS 4.0 (Harris et al., 2014) through 1901-2015, when monthly average temperature, monthly precipitation and daily potential evapotranspiration were obtained.

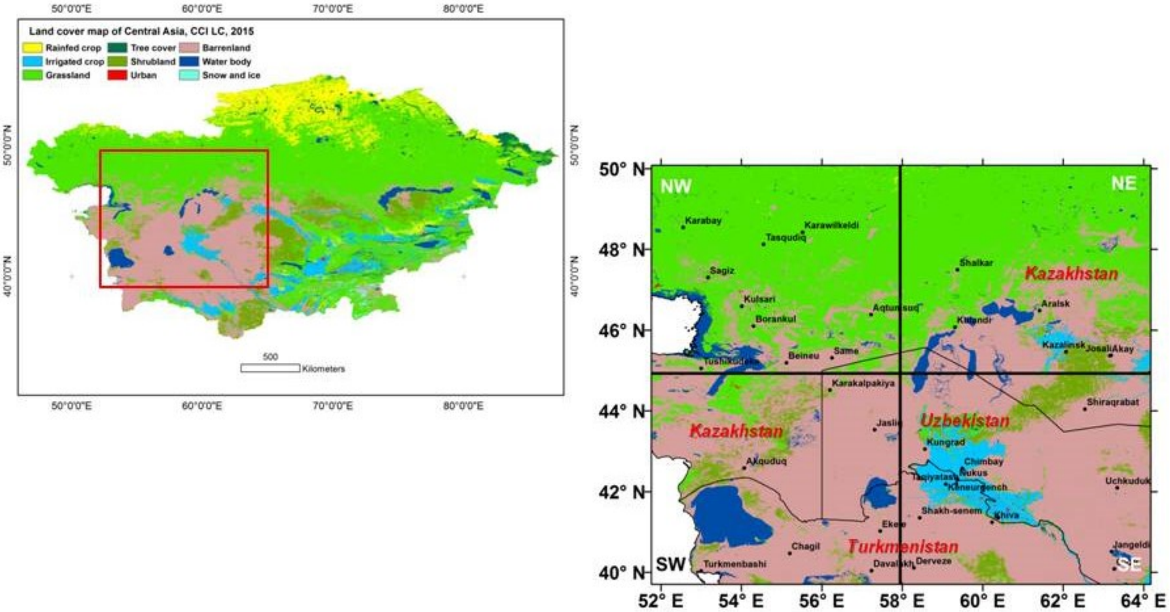

Figure 1: Study area: Territory of the Kazakhstan, Uzbekistan and Turkmenistan with land cover categories (left), territory of the AS region with meteorological station (right)

2.3 Method

In this article, several methods have been used to analyze the data. The Climatic Research Unit gridded Time Series (CRU TS) 4.0 and NOAA global meteorological data were originally identified by the coordinates of the study area. NCL/NCAR software capabilities were used to analyze the obtained meterological data including MAM (March, April, May), JJA (June, July, August), SON (September, October, November) and DJF (December, January, February), and the climatic and anomalous distribution (Climate) of air temperature and precipitation were observed for the last 56 years between 1960-2015 on and around the AS. Secondly, the Mann-Kendall (MK) test (Mann, 1945 and Kendall, 1975) was used to calculate the climate change trend around the AS in the last 115 years. It is possible to evaluate the monotonous uptake or reduction process using the MK test. The monotonic trend determines a gradual increase (decrease) of this up (down) time, which can be either curly or non-linear. In addition, the Sens Slope test analyzed the trend of deviation level. The presented statistical data are based on FTI (First Time Interval: 1901-1960) and STI (Second Time interval: 1960-2015) for the two phases of AS transformation and anomalous change in climate variables. We have divided (Figure 1) the study area into four segments relative to the seas, namely NW (North-West), NE (North-East), SW (South-West) and SE (South-East). The main purpose of the division is to analyze which parts of the AS are more or less affected by climate change in the sea. In addition, a hydrological balance equation was introduced to assess the impact of the AS level change and P-E over the AS to the Sea budget.

3. Results

3.1 Analysis of Anomaly Climate Variables in the AS Region

3.1.1 Spatial distribution of temperature

The AS region has strong continental climate with a geographically flat desert. The annual temperature fluctuations around the AS have been observed in the MAM season $2\text{-}2^0$C (Figure 2), with an average annual temperature drop of North-South to South-East relative to the AS, and average temperatures around the AS are around 10-12˚C. Annual anomalous temperatures range from -10-(+10˚C) to around 0.7° degrees Celsius. The most hot weather in the JJA season is the average annual temperature around 18-32°C, which is the highest temperature in Kyzylkum, in the South-East territories of the AS (Dashoguz 28-30°C) and northern Uzbekistan (Bukhara and Navoi 30-32°C). Relatively warm air temperate (26-28°C) was observed in the northern part of Uzbekistan (Karakalpakstan and Khorezm), the closest to the AS, and the normal air temperature (24-26°C) was observed around and over the AS.

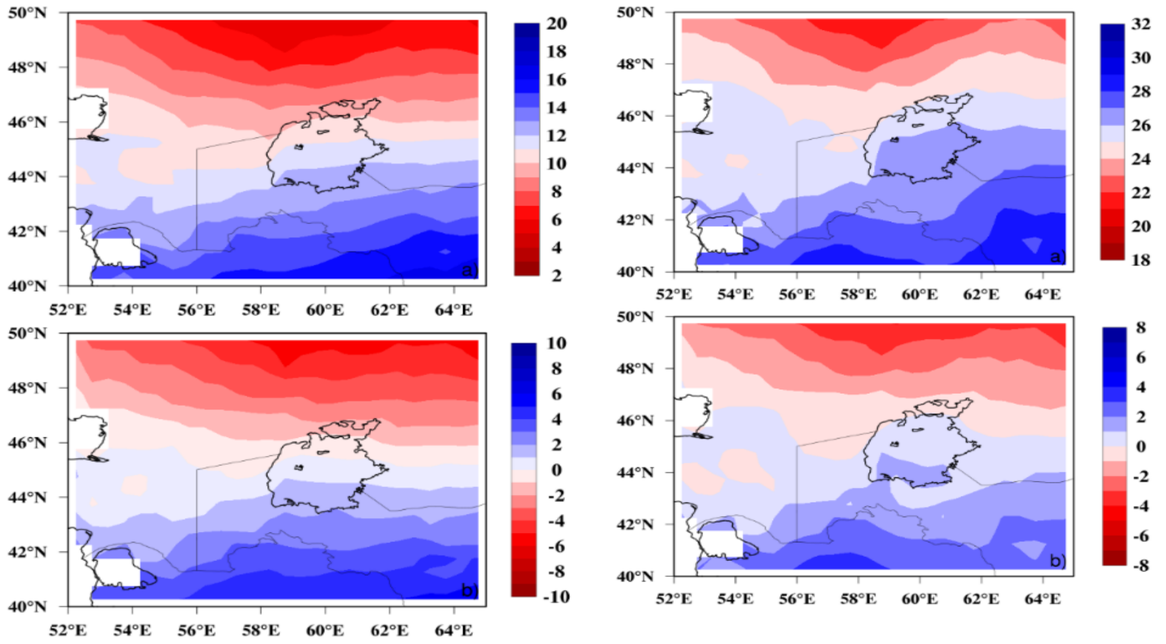

Figure 2: Temperatures Changes in the territory of AS Region from 1960-2015, MAM (left) and JJA (right) seasons, a) temperature climatology, b) anomaly temperature

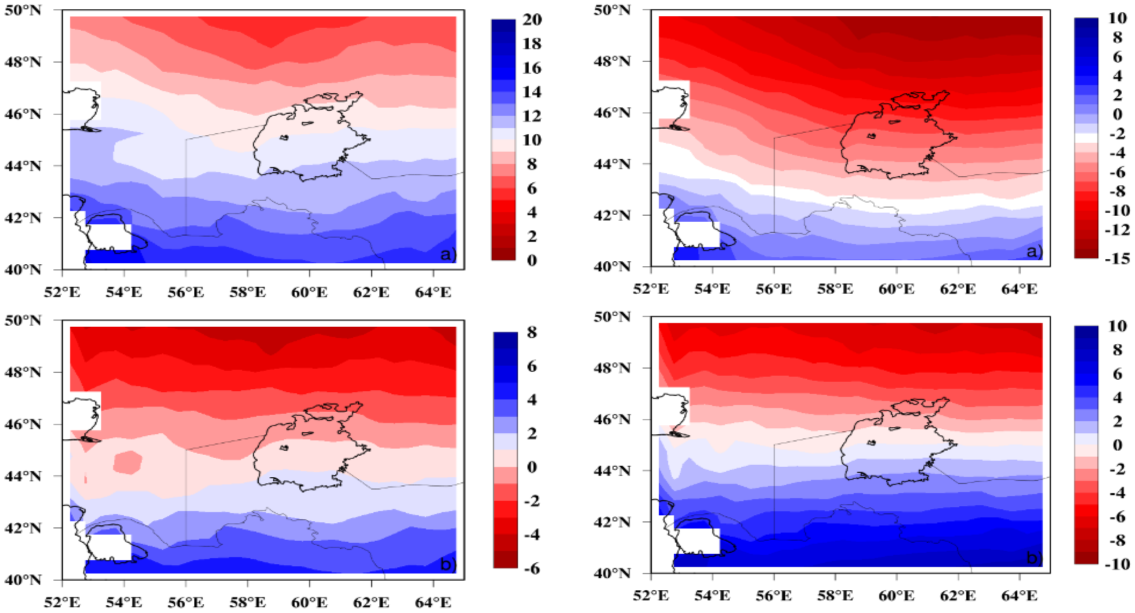

Figure 3: Change temperatures in the territory AS Region from 1960-2015, SON (left) and DJF (right) seasons, a) temperature climatology, b) anomaly temperature

The lowest air temperature in this season is around 20-22°C in the North-West and North-East parts of the AS, in the southern part of Kazakhstan (Atyrau and Kyzyl-Orda). The annual anomalous air temperature is in the range of -8-(+8°C), as in the MAM season, anomalous air temperature is not observed. SON season is very important for the region, because the region's economy is mostly agricultural. In this season, air temperature falls below 0-20°C in the region, 16-20°C in the southern part of the Aral, and 0-8°C in the northern part of the country. From the Ustyurt Platou to the Caspian Sea and the AS, the relative air temperature is below 10°C (Figure 3). By the analysis of the DJF season, we can observe that the zero isotherm is mainly observed on the territory of Turkmenistan, whereas the air temperature in the season is south-east 0-2°C to North-East -12- (-15°C) and minus temperature in the Aral is -4-(-6°C) is the most extreme air temperature at the North-West coast of the AS, which is 8-10°C around the Caspian Sea. By When we analyzinge the annual average abnormal temperature fluctuations on and around the AS, we can say that in all the seasons, there were almost no anomalous temperatures in the AS (zero isoterms), anomalous air temperature downstream from North East, anomalous air in spring and summer seasons temperature was -10-(+10°C). The West-to-East longitude (52°E-64°E) is a cylindrical isoline that has been changed from North to South. In accordance with the obtained results, we offer several theoretical factors. On the continents, large lakes reduce the annual amplitude of air temperature and thus soften the climate. For example, the annual amplitude of the temperature in the middle of Lake Baikal (53°13N, 107°45E) is 30-31°C, while on its banks, it is about 36°C, and at the same latitude, Yenisei River's (71°49N, 82°42E) temperature amplitude is 42°C.

Other lakes, such as, Issyk-Kul (42°26N, 77°11E) and Ladoga (60°50N, 31°33E), show a similar effect on the temperature of the air. With the help of the notions of the marine and continental climate, a relatively small annual amplitude of sea-climate air temperature and sea air masses is described. The continental climate is formed in parts of the ocean, which are characterized by a high frequency of air masses intervention into the interior parts of the continent. Here, the annual amplitude of the air temperature is usually very high. In tropical latitudes, the high values of annual amplitudes on land are not due to the cold winter climate, but its because of to the higher summer temperature. Therefore, with the continental climate, the average annual temperature is much higher than the temperature in the marine climate. Due to the sharp reductioning of the AS area, the former positive climate impact has decreased, which high summer temperatures and very low winter temperatures. Therefore, the continental climate of AS zone is characterized by low humidity, precipitations regime and other factors.

3.2 Spatial Distribution of Precipitation

By the analysis of precipitation from 1960 to 2015, we can observe the highest precipitation in the

MAM season (Figure 4). The results of the analysis show that the similar volumes of 16-20 mm precipitations were observed (Karakalpakstan and Khorezm) over and around AS region, and relatively low in the territory of Kazakhstan (Kyzylorda) on the North-East of the AS. The largest positive anomaly observed in North and West over the AS and around the AS was observed in North-West and South East. There is almost no anomaly in the territory of Turkmenistan and smaller AS.

The JJA season is the warmest and most dry season in the region with almost 80% of the region recorded in the low seasonal precipitation during this season, and with a record of 0-4 mm in the South-East part of the AS, 10-12 mm over the AS and on 48°N-50°N latitude (Kazakhstan), the highest monthly pecipitation was observed at <30 mm (Figure 4). In the SON season, almost the JJA season's scenario was repeated, i.e., in all the territory, the lowest precipitation of 4-16 mm was observed (Figure 4). During the DJF season, the lowest volumes of precipitations were observed on the South West part of the AS at 8-10 mm in the territory near to the Caspian Sea (Figure 5). There was almost no anomaly at the 44-46°N latitude over the AS. The territory of the Aral Region suffers from a severe lack of natural hydration, which is the main reason for the invalid use of its very large thermal resources. The territory of the AS region, within all the parts of whole of Asia, is characterized by the smallest annual amount of precipitation.

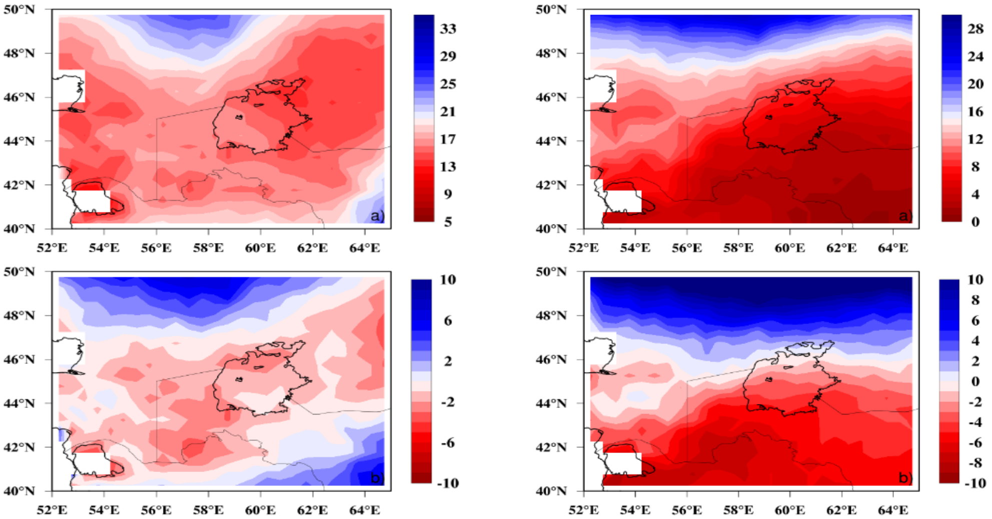

Figure 4: Precipitation change in the territory AS Region from 1960-2015, MAM (left) and JJA (right) seasons, a) precipitation climatology, b) anomaly precipitation

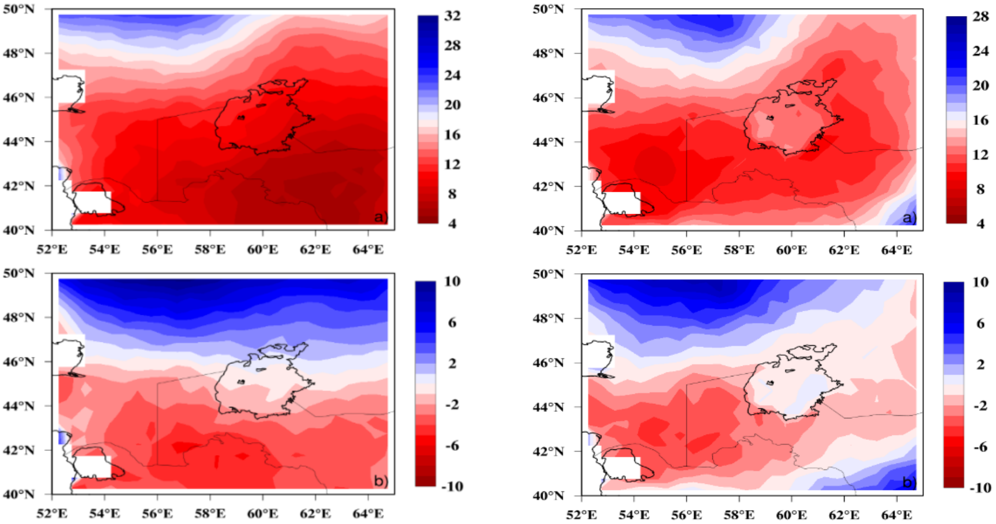

Figure 5: Precipitation change in the territory of AS Region from 1960-2015, SON (left) and DJF (right) seasons, a) precipitation climatology, b) anomaly precipitation

The intra-annual distribution of precipitation possesses all the characteristic features characteristic of the climate of the Republics of Central Asia: about half of their annual amount falls in the spring months and about 1/3-in the winter; sStill there are some precipitation in autumn; For the summer, there is an insignificant part of the annual amount of precipitation, less than 10%. The territory of the AS is characterized not only by a not significant very less amount of precipitation, but also by their extreme instability. So, for example, in the South-Eastern territory of the AS, there was a case when in the wettest month of March, there was more than 50 mm (1982) precipitation. At the same time, there mayight be some years when there iwas very little precipitation in March, like it was, for examplesimilar to 13 mm in 1981, and 19 mm in 1983.

3.2 Detection Trend

An analysis of trend momentary and trend slope were analyzed using two-time intervals (FTI and STI), anomaly climatic changes (temperature, precipitation, evapotranspiration and moisture), MK test (95% confidence level) and Sen's Slope methods, observed on and around the AS (Table 1 and Figures 6-9). Table 1 shows the tendency of anomaly climatic changes observed around the AS for two periods. In the initial analysis of the anomaly temperature change trend, we can see the same homogeneity trend in either of the four surrounding parts of the AS (NW, NE, SW, SE), but they differ from each other in time intervals. The lowest negative trend recorded in the FTI was recorded for all segments (z = -0.916 to -0.131), and the largest negative trend was observed in SE (Sen's Slope: -0.007), NE and SW, with the same negative trend, (z=3.653 to 4.162), while the average recorded trend in the southern AS increased to 7.73% over the northern part. When compared with the anomaly temperature trend in the southern part of the island (Sen's Slope: 0.034) and North (Sen's Slope: 0.031), we can see a large slope change in the southern part of 8.82%. FTI was not significant (p>0.05), whereas STI was significantly recorded in all parts (p<0.005). Since, evapotranspiration changes are proportional to the change in air temperature (H. Penman 1948), the abnormal evapotranspiration has been as abnormal as the temperature in the two different intervals. We can see an unusual tendency in STI for abnormal precipitation, as the three regions of the AS were positive (z=0.686 to 1.039), whereas negative correlation was observed in the NE part (z=-1.025), also FTI recorded negative anomalous precipitation trends z =-1.007 to -0.183). The moisture fluctuation trend was only analyzed for one time interval, in STI, where the negative trend was observed in all parts of the AS, and the largest negative trend was observed in the Southeast part of the lake (z=-2.113, p-value = 0.035), while the relatively small negative trend (z=-0.615, p-value=0.539) belonged to the Northeast part of the lake.

Table 1: MK test (Z) with probability (P) and Sen's slope (Sen Slope) of time series of climate variables over territory AS. Note: *Indicates the two-tailed significance level (0.005) of the trend

Climate variables	**Region**	**FTI**			**STI**		
		Z	**P-value**	**Sen's slope**	**Z**	**P-value**	**Sen's slope**
Anomaly temperature	NW	-0,392	0,695	-0,003	3,653*	0,000	0,031
	NE	-0,144	0,886	-0,001	3,936*	0,000	0,031
	SW	-0,131	0,896	-0,001	4,036*	0,000	0,034
	SE	-0,916	0,36	-0,007	4,162*	0,000	0,034
Anomaly precipitation	NW	-0,549	0,583	-0,005	1,039	0,299	0,009
	NE	-1,007	0,314	-0,008	-1,025	0,305	-0,009
	SW	-0,876	0,381	-0,005	1,025	0,305	0,010
	SE	-0,183	0,855	-0,002	0,686	0,493	0,005
Anomaly evapotransporaion	NW	0,075	0,937	-0,001	2,918*	0,004	0,023
	NE	-0,445	0,657	-0,004	3,201*	0,001	0,024
	SW	-1,072	0,284	-0,009	3,498*	0,000	0,031
	SE	-1,753	0,008	-0,013	4,671*	0,000	0,038
Anomaly humidity	NW				-1,053	0,292	-0,009
	NE				-0,615	0,539	-0,006
	SW				-1,819	0,069	-0,013
	SE				-2,113	0,035	-0,018

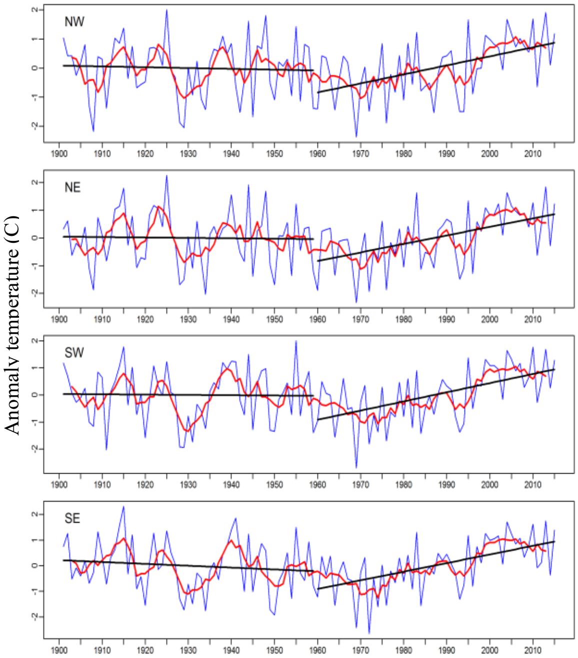

Figure 6: Comparison of change trend anomaly annual mean temperature for two time intervals FTI and STI over territory around AS

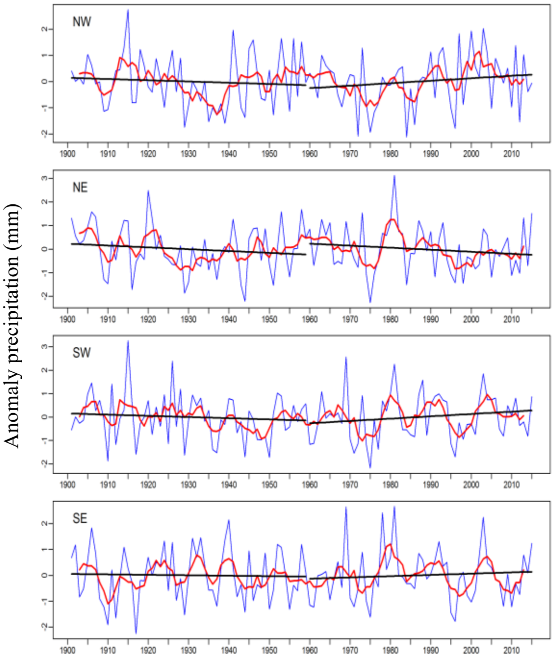

Figure 7: Comparison of change trend anomaly annual total precipitation for two time intervals FTI and STI over territory around AS

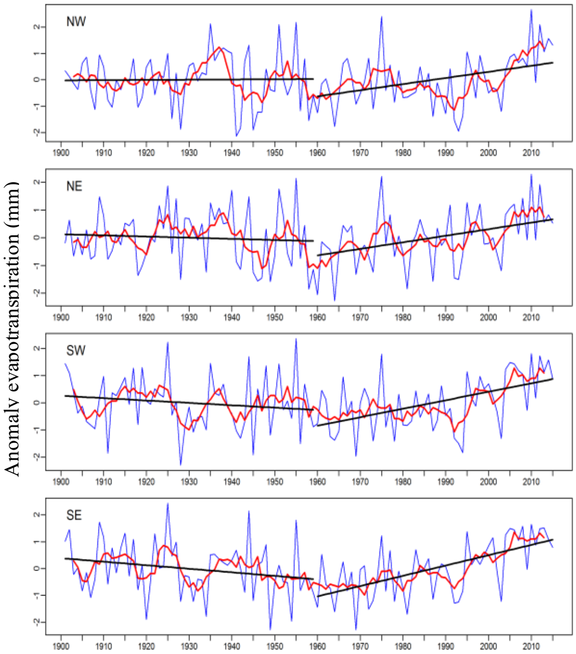

Figure 8: Comparison of change trend anomaly annual mean evaporation for two time intervals FTI and STI over territory around AS

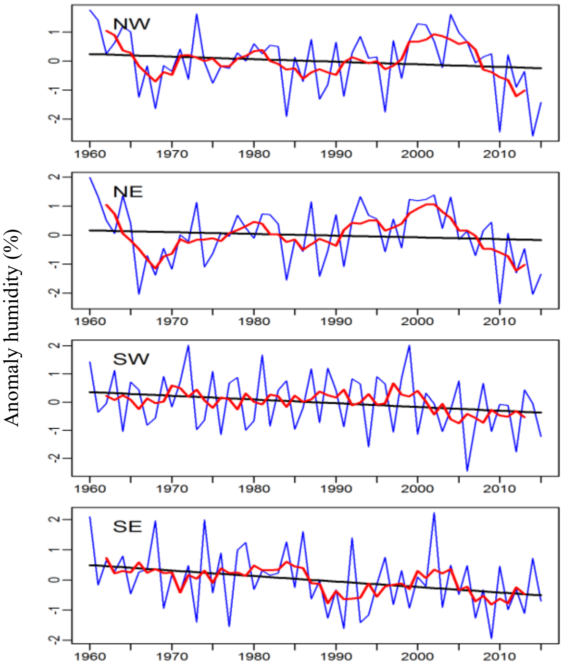

Figure 9: Change trend anomaly annual mean humidity from STI over territory around AS

3.3 Observed Hydrologic Changes

The change in the AS water volume over the time (dV/dt) is due to several parameters such as river discharge (R), groundwater inflow (G), precipitation per unit area (P), evapotranspiration per unit area (E), sea area (S) and A - lake's surface area (Zavialov et al., 2011).

$$\frac{dV}{dt} = (R + G) + A(P - E)$$

Equation 1

Here, we consider the underground water change (G) to be zero as research findings show that the contribution of groundwater around the AS to the Aral hydrological budget is extremely low (Roget et al., 2008), and in other scientific sources this parameter is constant or equal to zero (Benduhn and Renard, 2004). The Amu Darya and Syr Darya water supply sources in the AS, which was 63 km^3 in 1960, have dropped continuously each year and calculated to be 3.2 km^3 in 2003 (CAWater-Info, 2015). Direct measurements of precipitation (P) and evapotranspiration (E) during the AS do not exist. Therefore, we calculated the cumulative contribution of precipitation and evapotranspiration to the lake, with $P-E$ as the residual above the water balance equation.

Initially, monthly precipitation and evaporption were observed on the AS (44°48′N, 59°36′E) and ranged from two intervals in terms of AS water volumes change (FTI, 1901-1960, STI.1960-2015) The change in $P-E$ was analyzed. In the linear regression analysis (95% confidence interval estimate), variations in two time intervals, i.e., FTI, were recorded in the low positive trend (Slope: 0.4749, R-square: 0.0152), whereas STI maintained strong negative trend (Slope: -1.8816, R-square: 0.1387). The minimum and maximum values were observed in STI in two intervals, in 1975 (-1304.5 mm), in 1981 (-935.9 mm) (Figure 10). By analyzing the annual (intra-annual) $P-E$ change over the two interval periods, negative pees were monitored for almost every month in both periods (Figure 11), and the minimum values were typically ≤200 in summer (June, July) mm, maximum negative indicator ≥-50 in February, March and November. Only in winter months (December and January) p positive was $P-E>0$. The results of the P-E transformation were approximate, as other factors contributed to the change in the AS water balance. Amu Darya and Syr Darya hydrometric stations are located 50-100 km far from the AS coast (Small et al., 1999). Most of the water is consumed until the river flows into the AS (agriculture, evapotranspiration, groundwater).

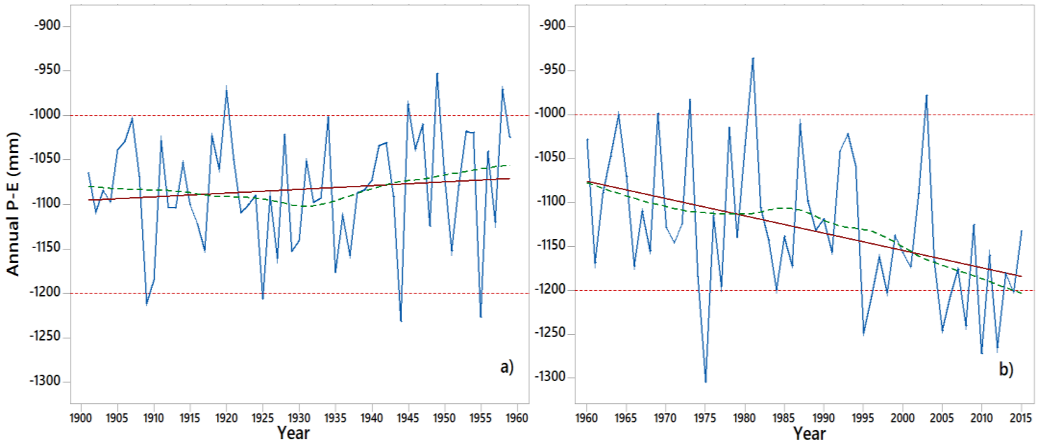

Figure 10: Annual values of $P-E$ over the AS for two time intervals, a) FTI b) STI

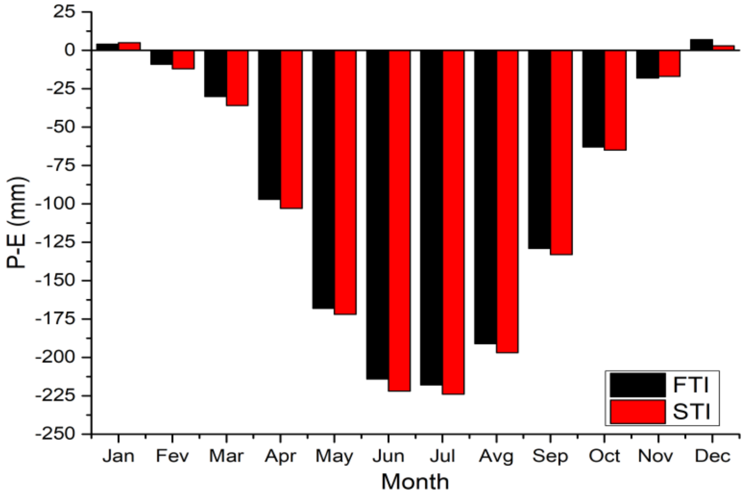

Figure 11: Changes in $P-E$ (mm) over the AS by month

In our approximate calculation, the water allocation has reached the AS and the $P-E$ is the minimum indicator. The minimum value is in line with the estimated value because the Amu Darya and Syr Darya water levels are minimal in most months. Indicators for lake and streamflow have been reduced over time, by percentage and size, and the flow of water has fallen below the delta (Micklin, 1998). If we add the lake flow to this calculation, $P-E$ will have a higher negative value in the second time interval. Therefore, $P-E$ is the minimal estimate of the lake's estimated water volume change.

The equation of water balance can be used for diagnostic assessments of the further development of the situation for different values of the components of the water balance. We do not have the means to reliably predict future changes in river, underground sewage, precipitation and evapotranspiration for a long time, so, any deterministic forecast is difficult.

4. Discussion and Conclusion

Having a significant water surface, the AS has served as a climate-adjusting reservoir and mitigated sharp weather fluctuations in the Central Asian region. The penetrating air masses, mainly from the west to the region during the winter, were warmed up, and in the summer cooled over the water area of the AS. Seasonal distribution of ambient air temperature and precipitation over the AS was examined. In the most observable seasons (MAM, SON) on the island, (44°N-46°N) isotropic process (10°C) observed zero isoteric on the anomalous and almost all the seasons. Air temperature fluctuations were observed in the southern part of the AS, with average air temperatures observed in the north and south, in all seasons. In the southern part of the AS, a major positive difference was observed, as, in the JJA season, 55% of the high temperatures was recorded there. By analyzing the air temperature fluctuations across the range, the air temperature was found out to be around 50 km, which means that the air temperature is dropping to the North, for example, on the AS (-4°C), in the distance of about 200 km the air temperature is -10°C, but longitudinal isolation was recorded. The results show that the distribution of rainfall in and around the AS is relatively small in all seasons, and the south-eastern part of the AS (Karakalpakstan, Khorezm) a very low indicator for autumn. The amount of precipitation is not evenly distributed along the range, i.e., latitude and longitude. The southern and northern parts of the AS are significantly different from the amount of rainfall, especially in the JJA and LAST seasons, with the change sharply declining from north to south but this is not stable in the MAM and DJF seasons. If two points (40°N, 58°E and 50°N, 58°E) are separated from the southern and northern parts of the AS, and the total precipitation observed at these points is almost 90% in the summer and autumn. We can say that there was almost no anomalous rainfall on the AS during the last few seasons and a significant number of negative anomalies (-1-2 mm) were in the MAM and JJA seasons.

The second 115-year fluctuation trend around the second AS was analyzed in two intervals. In FTI, there was a decrease in anomalous changes in three climatic parameters (air temperature, precipitation, and evapotranspiration), but the STI showed a significant increase in temperature and evapotranspiration due to uncertainty in precipitation and anomalous precipitation in three parts of the AS. In contrast to NE, the process is reflected in the NE part. Anomalies were analyzed in terms of STI and a significant decrease in all parts of the AS was recorded, whereas the strongest anomalous negative trend corresponded to SE. The graph of anomaly evapotranspiration is based on the average annual fluctuation of the anomaly temperature in two time intervals (Figure 11). The anomaly precipitation is almost the same as that of the SEA in the STI, but the three parameters are parallel to each other. In contrast, the anomaly humudity change was developed in STI in a non-parallel way. So, as the temperature and evapotranspiration in the area are reduced, the air humidity also decreases. The hydrological state of the AS was assessed on the basis of the change of $P-E$. At first, we will try to estimate the change in the amount of annual precipitation observed on the AS.

In the course of the study period, especially during the desiccation range of STI, the annual evapotranspiration rate is also evolving, with a sharp increase in the process, but also with the wind velocity observed in the region. The wind velocity around the AS and its impact on sea water volumes have been proven by the conclusions based on numerous experiments (Roget *et al.*, 2008) (Roget et al., 2008), statistical data analysis and expedition (Zavialov et al., 2011). The results indicate that the wind velocity in the region has risen and there is a correlation relationship with the AS water volumes.

Acknowledgments

We are grateful to the Chinese Academy of Sciences and the World Academy of Sciences for providing the financial support to advance the scientific research in developing countries (CAS-TWAS) for financial support and University of the Chinese

Academy of Sciences (UCAS) for providing facilities for study and for all other forms of support. Special recognition is to the CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences. We are also grateful to the members of the organization of the GISCA-2019 conference held in Bishkek city. We are also grateful to the Nukus branch of Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi for provinding the opportunity to work on this study

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