

An Investigation into the Hydro-Climate Processes Impacting Aral Sea Region in Central Asia

**Sahibjamal Nietullaeva^{1,2*}, Bayram Fayzullaev^{1,2}, Aykerim Karimova^{1,2},
Nurmuxamed Shaudenbayev^{1,2}**

¹Nukus branch of Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi, Nukus 230100, Uzbekistan. E-mail: snietullaeva@bk.ru, karimovaaajikerim4@gmail.com, nshaudenbaev@gmail.com

²Department of Telecommunication Engineering, Nukus branch of Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi, Nukus 230100, Uzbekistan. E-mail: fayzullaevbayram@gmail.com

*Correspondence: snietullaeva@bk.ru

ABSTRACT

Since 1960, the anthropogenic activities had severely impacted the hydrological balance of the Aral Sea (AS), which has led to dramatic changes in the climate around the AS, likewise changes in ambient temperatures and potential evapotranspiration. Moreover, the rainfall patterns are not homogenous in the study region. Trend analyses are performed on the monthly gridded climate data of rainfall and temperature, potential evapotranspiration, and relative humidity using the Mann-Kendall (MK) test for the period 1901-2017 years. The outcomes of this study investigated a significant difference (negative) between precipitation and evapotranspiration in AS region, during the analysis period of 1901-1960, and 1960-2017. Analysis of air temperature around the AS further suggests the positive trend of air temperature contrary to a significant difference between precipitation and evapotranspiration negative trend, which means that the annual hydrological budget remarkably decreased in the regional analysis. The present study investigates the changes in hydro-climate processes observed over the AS region, as in recent few decades global warming impacted the socioeconomic and environmental conditions of this region.

Keywords

Aral Sea, Mann-Kendall test, temporal climate change, water.

1. Introduction

Since 1960, the AS was the fourth largest lake in the world with a surface area equals 65×10^3 km². Considered as a terminal lake, the AS is the principal source of water in the Amu Darya and Syr Darya rivers (Gafforov et al., 2020; Gaybullaev, Chen, & Gaybullaev, 2012; Small, Sloan, & Nychka, 2001). After 1960, the anthropogenic activities in AS has severely affected the hydrological cycle 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.

Due to the rate of evapotranspiration (<1000 mm per year) over the Aral region was found larger than the amount of precipitation. The (Zavialov et al., 2011; Zavialov et al., 2003) research found out following points: 1) the lake surface 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 (Zavialov et al., 2011; Zavialov et al., 2003). In 1998, 48×10^3 km² of the lake were rare sandy plants, evaporating deposits, leading and important thermal changes, and moisture and radiation. The temperature of the lake surface increased due to thermal capacity, which influenced the rate of evapotranspiration and reduction of water levels (Micklin, 2007).

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 & Kurbanov, 2015; T.

Berdimbetov, Nietullaeva, & Yegizbaeva, 2021; T. T. Berdimbetov, Zhu-Guo, Chen, & Sana, 2020), hydrological and hydro-meteorological (Bortnik & Chistyaevaya, 1990), water management (Micklin, 2000), one of the main causes of the AS basin, the AS water balance change based on data from satellite remote sensing (T. T. Berdimbetov et al., 2020; Cre'taux & Berge'-Nguyen, 2014; Lioubimtseva, 2014). Assessment of the volumes of atmospheric precipitations (1986-2001) on the Amu Darya and the Syr Darya, based on the Global Weather Climatology Center (GPCC) (Nezlin, Kostianoy, & Lebedev, 2004), the hydro physics of the AS in the first decade of the 21st century research on chemical and hydro-biological changes (Zavialov et al., 2011) and other aspects.

2 Study area, data, and methodology

2.1 Study area

The research, consider in AS, in the Central Asian region (Fig.1). The AS region, geographic location of the AS, and the surrounding area are within a radius of 500 km (Abdurahimov & Kurbanov, 2015). The full study territory consists of the southern part of Kazakhstan (43°00'N, 68°30'E), the northwest part of Uzbekistan (38°00'N, 68°00'E) and the northern part of Turkmenistan (41°49'N, 60°16'E). In terms of geographical aspects, the territory is a predominant arid region and its elevation is 56 meters above the mean sea level (source). The AS and the AS Region are administratively located in Uzbekistan and Kazakhstan. The AS covers the lower reaches of the Amu Darya and the Syr Darya rivers (Gafforov et al., 2020), as well as the AS region, and the Aral desert (Aral-Kum) as well, which emerged in the north-eastern and southern parts.

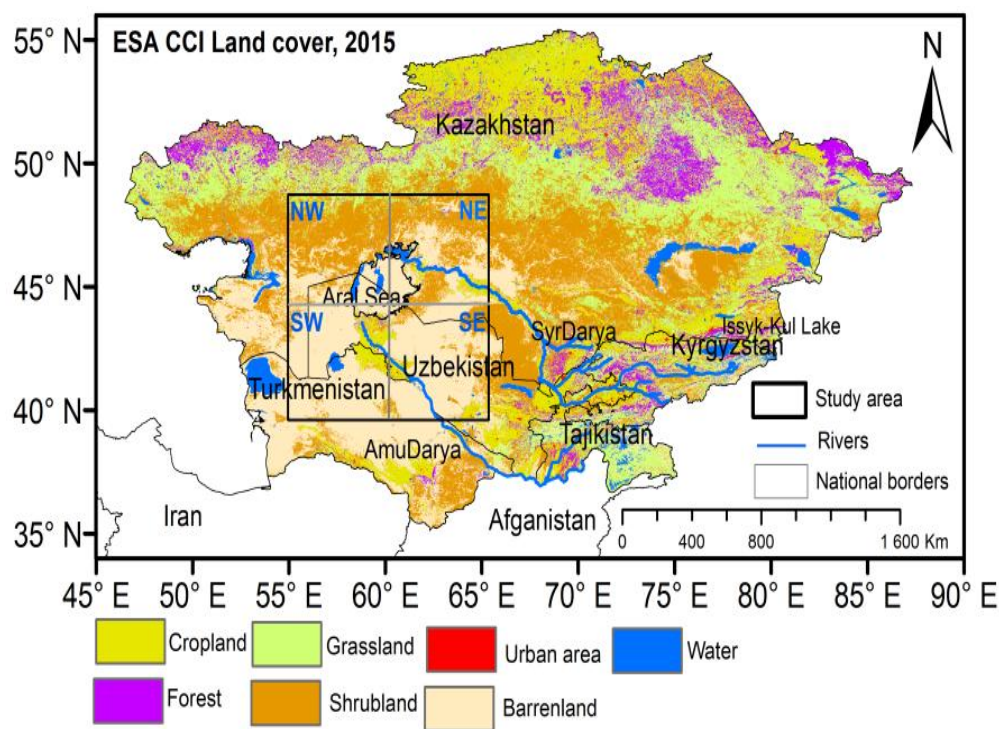


Figure 1. Study area: North-West (NW), North-East (NE), South-West (SW), South-East (SE). The territory of Kazakhstan, Uzbekistan, and Turkmenistan with major seven land cover categories (300 m spatial resolution). Land cover data from ESA CCI (European Space Agency, Climate Change Initiative) database

2.2 Data

This article uses a dataset from the Climatic Research Unit (CRU, 0.5°x0.5°) and National Oceanic and Atmospheric Administration (NOAA's, 0.5°x0.5°) global meteorological network. Meteorological data of monthly relative humidity (RHM) was archived from NOAA during 1960-2015. While we used the monthly climatic variables of average temperature (TMP), precipitation (PRE), and potential evapotranspiration (PET) using CRU TS 4.0 (Harris, Osborn, Jones, & Lister, 2020) ranging from 1901-2015.

2.3 Method

In this article, several methods have been used to analyze the data. The Mann-Kendall (MK) test (Faustin Katchele, Ma, Yang, & Batebana, 2017; Kendall, 1975; Mann, 1945) was used to calculate the climate change trend around the AS in the last 117 years. It is possible to investigate the monotonous changes in trend using the MK test. The monotonic trend determines a gradual increase (decrease) changes over time, which can be either non-linear (Kendall, 1975; Xu, Takeuchi, & Ishidaira, 2003). In addition, the Sen's Slope test analyzed the trend deviation level. The presented statistical data are based on FTI (First Time Interval: 1901-1960-give this interval in the abstract) and STI (Second Time interval: 1960-2017) for the two phases of AS transformation and anomalous change in climate variables. We have divided (Fig. 1) the study area into four segments relative to the sea's, 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 the difference in $P - E$ over the AS to the Sea budget (Benduhn & Renard, 2004; Zavialov et al., 2011). Here, the monthly evapotranspiration (E) is calculated based on the Penman-Monteith equation (Beven, 1979).

The following formula is given for the MK trend analysis:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(x_j - x_i)$$

$$\text{sign}(T_j - T_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

Where S is statistical trend, n is the length of the time series data set and $x_i \dots x_j$ stand for the observations at times i to j , correspondingly.

According to the hypothesis of independent and randomly distributed random variables, the S statistic is approximately normally distributed when $n \geq 8$, as follows:

$$E(S) = 0$$

The variance (σ^2) for the S -statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i(i-1)(2i+5)}{18}$$

Where j is the number of tied groups and is the size of the i th tied group. As a result, the standardized Z (calculated in the case of MK) test statistics follow a normal standardized distribution:

$$Z_s = \begin{cases} \frac{s-1}{\sigma} \text{ for } S > 0 \\ 0 \text{ for } S = 0 \\ \frac{s+1}{\sigma} \text{ for } S < 0 \end{cases}$$

A significance test is determined based on the result of the Z value. The sign of Z either positive or negative is indicating an upward or downward trend of the tested variable (Faustin Katchele, Ma, Yang, & Batebana, 2017).

The time series of hydro parameters were calculated to attain the slope coefficient based on the trend line. Precisely, the slope coefficients of the linear regression were worked out by employing the following equation (Faustin Katchele, Ma, Yang, & Batebana, 2017):

$$Slope = \frac{n \times \sum_{i=1}^n X_i Y_i - \sum_{i=1}^n X_i \sum_{i=1}^n Y_i}{n \sum_{i=1}^n X_i^2 - (\sum_{i=1}^n X_i)^2}$$

Where X_i and Y_i were the values of the independent variable and the dependent variable in the i^{th} year, respectively, and n is the average number of years during the study period. Generally speaking, if $slope > 0$, the fluctuation of the dependent variable reveals an upward tendency, whereas if $slope < 0$, the fluctuation of the dependent variable reveals a downward tendency.

3 Results

3.1 Temporal trend of climate variables between 1901 and 2015 years

An analysis of trend was performed on two-time intervals (give the time) (FTI and STI), of the anomalous climatic variables (TMP, PRE, PET, and RHM), using MK test (95% confidence level) and Sen's Slope methods (Tab. 1 and Fig. 2-3). Table 1 shows the tendency of anomaly climatic changes observed around the AS for two periods. In the initial analysis of the anomaly TMP 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 TMP trend in the southern part of the sea (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 ($\rho > 0.005$), whereas STI was significantly recorded in all parts ($\rho < 0.005$). Since, evapotranspiration changes are proportional to the change in air temperature (Beven, 1979), these homogenous PET changes are found robust in the above-mentioned two-time intervals.

Table 1. MK test (Z) and Sen's slope (Sen Slope) of time series of from anomaly climate variables over territory AS. Temperature (TMP), Precipitation (PRE), Potential evapotranspiration (PET), Relative humidity (RHM)

| Climate variables | Region | FTI | | STI | |
|-------------------|--------|---------|-------------|--------|-------------|
| | | Z | Sen's slope | Z | Sen's slope |
| TMP | NW | -0.392 | -0.003 | 3.653* | 0.031 |
| | NE | -0.144 | -0.001 | 3.936* | 0.031 |
| | SW | -0.131 | -0.001 | 4.036* | 0.034 |
| | SE | -0.916 | -0.007 | 4.162* | 0.034 |
| PRE | NW | -0.549 | -0.005 | 1.039 | 0.009 |
| | NE | -1.007 | -0.008 | -1.025 | -0.009 |
| | SW | -0.876 | -0.005 | 1.025 | 0.010 |
| | SE | -0.183 | -0.002 | 0.686 | 0.005 |
| PET | NW | 0.075 | -0.001 | 2.918* | 0.023 |
| | NE | -0.445 | -0.004 | 3.201* | 0.024 |
| | SW | -1.072 | -0.009 | 3.498* | 0.031 |
| | SE | -1.753* | -0.013 | 4.671* | 0.038 |
| RHM | NW | | | -1.053 | -0.009 |
| | NE | | | -0.615 | -0.006 |
| | SW | | | -1.819 | -0.013 |
| | SE | | | -2.113 | -0.018 |

Note: *Indicates the two-tailed significance level (0.005) of the trend.

We can see an unusual tendency in STI for irregular PRE, as the three regions of the AS were positive ($z = 0.686$ to 1.039), whereas a 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 RHM fluctuation trend was only investigated for the 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 ($z = -2.113$, $\rho\text{-value} = 0.035$), while the relatively small negative trend ($z = -0.615$, $\rho\text{-value}=0.539$) belonged to the Northeast part of the lake.

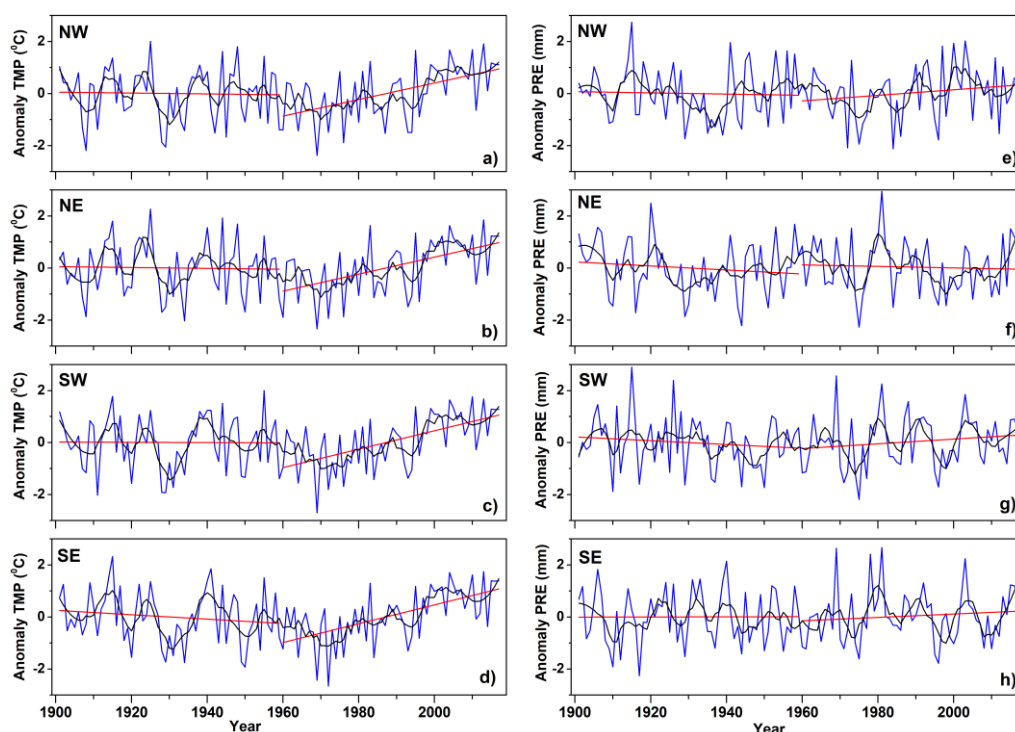


Figure 2. Comparison of change anomaly annual mean (a, b, c, d) Temperature (TMP, °C) and change anomaly annual (e, f, g, h) total precipitation (PRE, mm) for two-time intervals FTI and STI over territory around AS.

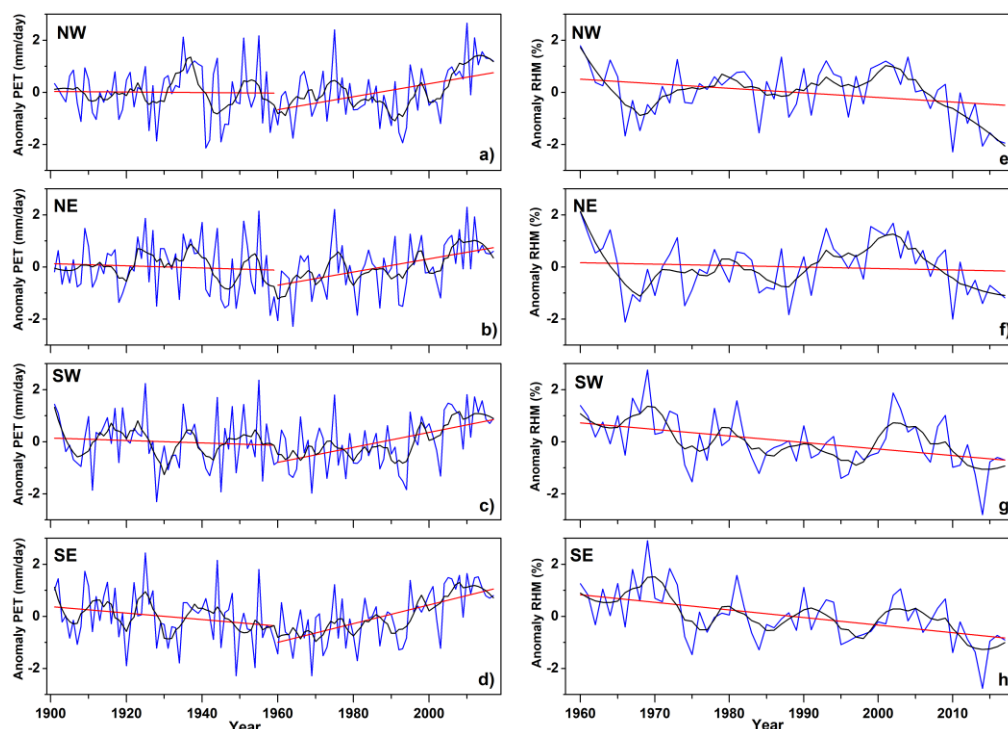


Figure 3. Comparison of change anomaly annual mean (a, b, c, d) Potential evapotranspiration (PET, mm/day) for two-time intervals FTI and STI and change anomaly annual mean (e, f, g, h) humidity (%) from STI over territory around AS. The red line is a trend change for two-time intervals, and the black line is a decadal (10 years) smoothing change.

3.2 An estimate of hydrologic changes over the Aral Sea

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, 2011).

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

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, and in other scientific sources, this parameter is constant or equal to zero (Benduhn & Renard, 2004; Zavialov et al., 2011).

The Amu Darya and the Syr Darya water supply sources in the AS, which was 63 km^3 in 1960, 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 evaporation were observed on the AS ($44^{\circ}48'N$, $59^{\circ}36'E$) and ranged from two intervals in terms of AS water volumes change (FTI: 1901-1960, STI:

1960-2017) The shift in $P-E$ was analyzed using the linear regression analysis (95% confidence interval estimate), variations in two-time intervals, i.e., FTI, were recorded in the low positive trend (Slope: 0.474, R-square: 0.015), whereas STI maintained strong negative trend (Slope: -1.881, R-square: 0.138). The minimum and maximum values were observed in STI during two intervals, of 1995 (-1369.5 mm), and 1981 (-935.9 mm) (Fig. 4a,b).

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 (Fig. 4c), and the minimum values were typically ≤ 200 in summer (June, July) mm, maximum negative indicator ≥ -50 in February, March, and November. Only in the winter months (December and January) was positive $P-E > 0$. The results of the $P-E$ transformation were approximate, as other factors contributed to the change in the AS water balance. The Amu Darya and Syr Darya hydrometric stations are located 50-100 km far from the AS coast (Small et al., 2001). Most of the water is consumed until the river flows into the AS (agriculture, evapotranspiration, groundwater).

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 specific 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.

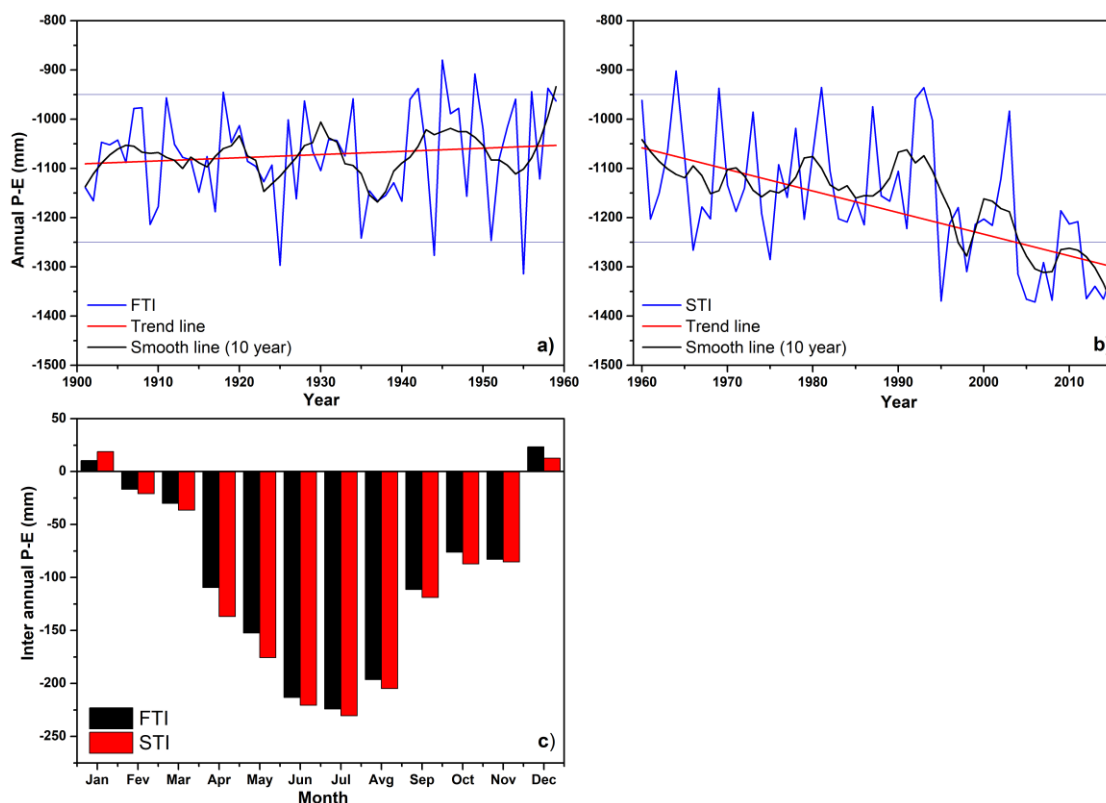


Figure 4. Annual and inter-annual values of $P - E$ over the AS for two-time intervals: a) First-

time interval (FTI), b) Second-time interval (STI) and c) $P - E$ (mm) by month

4 Discussion and conclusion

Having a huge water surface the AS has served as a climate-adjusting reservoir and mitigated sharp weather fluctuations in the Central Asian region (Zmijewski & Becker, 2014). 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 (Akramkhanov et al., 2012; Lioubimtseva, 2014).

The results showing in FTI, there was a decrease in anomalous changes in three climatic parameters (TMP, PRE, and PET), but the STI showed a significant increase in TMP and PET due to uncertainty in PRE and anomalous RHM 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(Figure 2 and Figure 3) of anomalous PET is based on the average annual fluctuation of the anomaly TMP in two-time intervals. The anomalous PRE patterns is almost the same as that of the SE in the STI, but the three parameters are parallel to each other. In contrast, the anomalous RHM change was developed in STI in a non-parallel way. So, as the TMP and PET in the area are reduced, the RHM also decreases. The hydrological state of the AS was assessed based on 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 period 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 seawater volumes have been proven by the conclusions based on numerous experiments (Roget, Muniz, & Zavialov, 2008), statistical data analysis, and expedition (Zavialov et al., 2011). The outcomes of this study indicate that the wind velocity in the region has risen correlating with the AS water volumes. 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 the river, underground sewage, precipitation and evapotranspiration for a long time, so, any deterministic forecast is difficult to construct.

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Author's contributions: All authors agreed to publish this version of the manuscript.

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