

RESEARCH ARTICLE

Generation of cyclonic gyre in large saline lake through differential warming

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Abstract

Circulation model of Lake Issyk-Kul is compiled based on Princeton Ocean Model with real bathymetry and atmospheric and river runoff forcings. According to the model, the cyclonic circulation develops in the lake from May to January, when a seasonal thermocline is present, while in February through April it vanishes or changes for a weak anticyclonic circulation. Wind-driven coastal jets and internal Kelvin waves intensify vertical mixing at a lateral periphery of the lake over sloping bottom. Due to enhanced vertical mixing and reduced depth, the water column warms up and cools down faster at the lateral periphery of the lake than in the deep central part. This, in view of geostrophic balance, causes cyclonic circulation in the period from late spring to early winter and the anticyclonic circulation during the rest of the year. River runoff does not play a primary role and only moderately contributes to the cyclonic circulation through the geostrophic adjustment of buoyant coastal discharges to the lake whose salinity is about 6 ppt. At the end of winter and beginning of spring, when river runoff is minimal, it is nevertheless capable of maintaining weak hydrostatically stable stratification in the coastal zone and thereby significantly weakening the development of cascading and deep-water ventilation. Model simulations showed that the cyclonic circulation prevailing in Lake Issyk-Kul would develop even without positive wind stress curl attributed to local winds.

The Issyk-Kul is a large mountain lake located in Kyrgyzstan. It is the tenth largest by volume (1730 km³) and the sixth-deepest (~668 m) lake on Earth (Zavialov et al. 2018). From the south and the north, the lake is framed by the Terskey-Alatau and the Kungey-Alatau mountain ridges. Along the entire perimeter, rivers and creeks flow into the lake (see Fig. 1), fed mainly by melt water from the glaciers of these mountain ridges. Due to the surrounding mountain ridges, not a single river or creek flows out of the lake. Since the precipitation regime in different mountainous regions is different and there is a relatively flat area to the east of the

lake between the ridges, where the rivers are fed mainly by melting snow cover rather than glaciers, floods on different rivers occur at different times of the year from May to August. One of the largest rivers, the Tyup, which flows through the flat area to the east of the lake, has its maximum discharge in May, the southern rivers in June, July, or August, and the northern ones in August (see Supporting Information Table S1; Fig. S1). Despite the fact that a large number of rivers flowing into the lake bring nutrients, the lake is oligotrophic and is characterized by low levels of primary production and concentration of phytoplankton, which in turn is the reason for low biodiversity throughout the entire trophic chain. The total nutrient load reaching the lake is estimated to span from 1300 to 1800 tons yr⁻¹, mainly represented by forms of nitrogen (The State Agency on Architecture and Construction of the Kyrgyz Republic 2006). However, only a fraction of the nutrients is retained in the upper euphotic layer where it can boost primary production, while an unknown and, hypothetically, major part of the nutrient supply is eventually removed from the euphotic zone and distributed through the deeper portions of the water column where no primary production is feasible (Zavialov et al. 2018). Hence, the biological

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Data Availability Statement: The Princeton Ocean Model code is free available on the site <http://www.ccpo.odu.edu/POMWEB/userinfo.htm>. The atmospheric forcing data from the NCEP Climate Forecast System Version 2 (NCEP2 Reanalysis) were downloaded through <https://rda.ucar.edu/datasets/ds094-1/>. The river discharge data were taken from the Global Runoff Data Center (https://www.bafg.de/GRDC/EN/Home/homepage_node.html), from Wikipedia and literary sources mentioned in the paper. The modeling data that support the findings of this study are available from the corresponding author upon reasonable request.

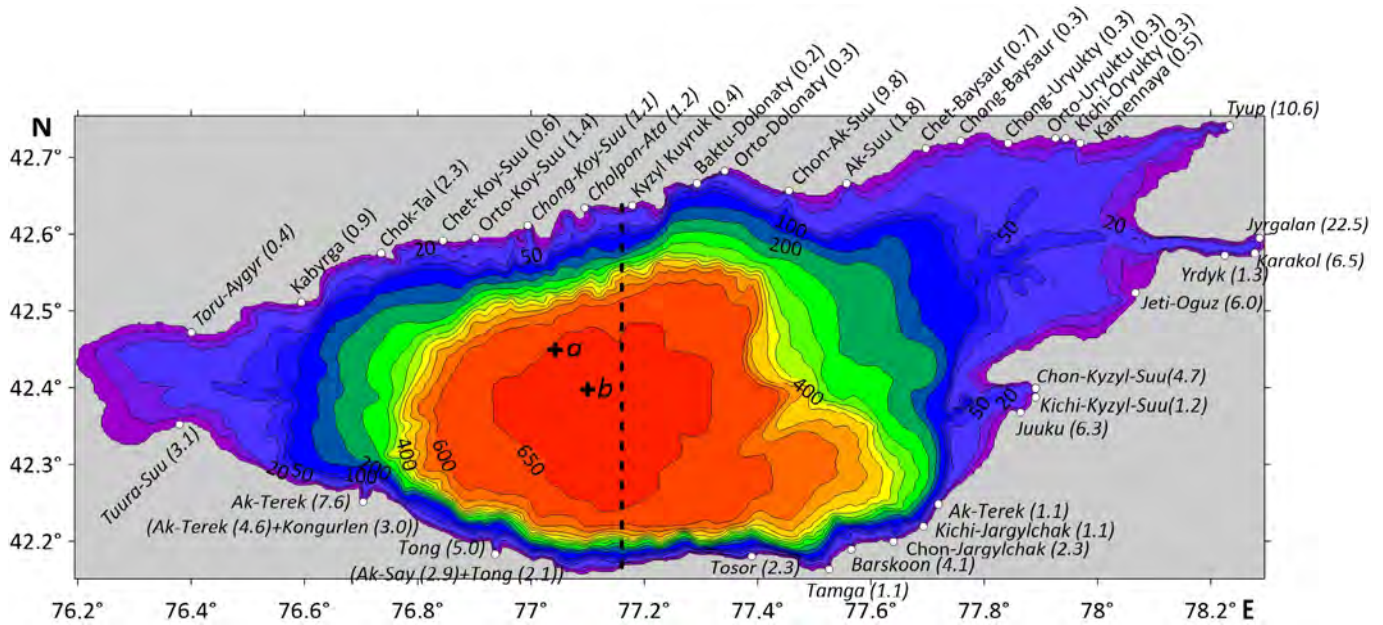


Fig. 1. Bathymetry of Lake Issyk-Kul. Indicated are names and locations of rivers flowing into the lake, taken into account in the numerical model. Average annual river discharges ($\text{m}^3 \text{s}^{-1}$) are given in parentheses. The crosses marked as *a* and *b* are the points at which the CTD profiles used for the model validation were obtained.

productivity of the lake is likely controlled by physical processes taking place in the upper layer and modulating availability of nutrients in the euphotic zone. In this study, we mainly focus on the dynamics of the upper layer as driven by wind stress, river discharges, and lake-air fluxes.

At present, information about the hydrodynamics of the lake is based mainly on sparse field observations (Romanovsky 1991; Peeters et al. 2003; Zavialov et al. 2018). Field studies of the lake have been rather fragmentary and consisted mainly of temperature and (sometimes) salinity profiles at individual points. Relatively recent surveys aimed at measuring temperature and salinity profiles in a significant part of the lake water area were described in Zavialov et al. (2018). The results of a number of experiments carried out in different years, including some episodic deployments of mechanical current meters at a limited number of locations as well as launching improvised surface drifters (Romanovsky 1991) showed that a cyclonic circulation and a dome of cold water are formed in the central part of the lake. CTD surveys in August 2001 (Peeters et al. 2003) confirmed the existence of the dome-like structure of temperature field in the lake.

A few attempts were also made to simulate the lake circulation pattern in numerical models (e.g., Arkhipov and Revyakin 1986; Kochergin, Klimok, and Bokovikov 1990). Three-dimensional numerical hydrodynamic models were used based on the traditional system of equations in the Boussinesq, hydrostatics, and beta-plane approximations (or f-plane approximation in one of the papers), taking into

account the bottom topography and the upper turbulent layer. No equation describing change in salinity was used. The initial temperature was set either horizontally uniform, changing with depth, or a dome of cold water in the center of the lake known from observations (Shabunin 1982) was taken into account. As an external forcing, a stationary, spatially nonuniform wind was set as a combination of the westerly wind (locally dubbed as the “Ulan”) and the easterly wind, the “Santash.” In particular, in the work by Kochergin, Klimok, and Bokovikov (1990), an uneven distribution of wind over the water area was taken into account: the weakening of the “Ulan” from west to east and the “Santash” from east to west; deviation of the “Ulan” to the south coast and “Santash” to the north coast; strengthening of the meridional components of both winds towards the center of the lake, and other features were prescribed through analytical expressions. The heat flux through the lake surface and river runoff were not taken into account. Expectedly, the specified system of winds generated a cyclonic circulation cell in the center of the lake with annual mean velocities up to 10 cm s^{-1} covering the upper 150- to 200-m layer.

However, the cyclonic circulation in a lake can be also generated by river runoff provided that the density of inflowing river water is smaller than water density in the lake (e.g., Yankovsky and Chapman 1997). Since salinity of Lake Issyk-Kul is approximately 6 ppt, its density always exceeds the density of the inflowing fresh river water and thus holds potential to form cyclonic circulation in the lake due to geostrophic adjustment of buoyant coastal discharges.

Several decades have passed since the above-described numerical experiments were conducted. Since then, public databases based on global atmospheric reanalysis models have appeared, containing a wide variety of characteristics of the state of the atmosphere and surface fluxes. It became possible to create a state-of-the-art hydrodynamic model of the lake, taking into account the realistic atmospheric forcing and river runoff and capable of reproducing the seasonal cycle of hydrological parameters. This paper presents the results of numerical modeling of Lake Issyk-Kul over a 10-yr period of 2013–2023 taking the heat, momentum, and mass fluxes calculated using NCEP/DOE AMIP-II Reanalysis (NCEP2), as well as a detailed set of river runoff data assembled by the authors from various available sources as the external forcing. The objective of this study is to assess relative effects of atmospheric forcing and river runoff on circulation in Lake Issyk-Kul.

Materials and methods

River runoff assessment

To set the seasonal cycle of river runoff, data on average monthly discharges ($\text{m}^3 \text{s}^{-1}$) were used, which were linearly interpolated for each day of the year under assumption that the values of average monthly discharges fell in the middle of the month. The names of the rivers, average annual discharge values and locations of the mouths for the rivers taken into account in numerical modeling, are shown in Fig. 1. The discharge data for the majority of rivers flowing into the southern part of the lake, and for several rivers flowing into the northern part of the lake, were taken from (Kadyrov 1986). For the Tyup, the second largest river of the lake, the data were taken from the Global Runoff Data Center, (https://www.bafg.de/GRDC/EN/Home/homepage_node.html), which closely match the data given by Kadyrov (1986). However, for the vast majority of the northern rivers, the discharge data could not be found either in the literature or on the Internet. The total annual discharge of all northern rivers was estimated based on the information that the total annual discharge of the northern rivers is 20% of that of the southern rivers (Rukavishnikov 1970). Further, the total annual discharge of all northern rivers was distributed among individual rivers based on the ratio of the areas of glaciers that feed these rivers (Zabirov and Sydykov 1976). Finally, according to the available data on the monthly discharges of the Ak-Terek River, a relatively large river flowing into the southwestern part of the lake and having the maximum discharge in August, similar to that of the northern rivers, a template was created to distribute the average annual discharges of the northern rivers by months. A summary containing information about the rivers taken into account in the numerical model, including the mouth coordinates, average annual discharge, maximum and minimum average monthly discharges with indication of the corresponding months, is given in

Supporting Information Table S1. Supporting Information Fig. S1 presents the seasonal cycle of the total river discharge to Lake Issyk-Kul and that for Tyup and Jyrgalan as an example of rivers that have a maximum discharge in May and August, respectively. The total annual discharge of the 35 rivers included in the model is $109.2 \text{ m}^3 \text{s}^{-1} = 3.4 \text{ km}^3 \text{yr}^{-1}$.

Model setup and validation

In order to investigate the dynamics of Lake Issyk-Kul, numerical hydrodynamic modeling based on the Princeton Ocean Model (POM) (Blumberg and Mellor 1987) was implemented for the 10-yr period from March 1, 2013 to February 28, 2023. Princeton Ocean Model is a primitive equation, free surface, hydrostatic, sigma-coordinate model, which uses the time splitting with an explicit computational scheme for the barotropic mode and implicit one for the baroclinic mode. Vertical and horizontal diffusivities are calculated by means of a second moment turbulence closure sub-model (Mellor and Yamada 1982) imbedded into Princeton Ocean Model and the Smagorinsky parameterization (Smagorinsky 1963), respectively. The gridded bathymetry of the lake with $360 \text{ m} \times 360 \text{ m}$ resolution was taken from Zhurbas et al. (2022); see also De Batyst et al. (2002). The horizontal step of the model grid was 720 m. In the vertical direction, 24 sigma layers were adopted with an increased resolution toward the lake surface. In the lake center at 600 m depth, the uppermost six sigma layers were 2, 4, 8, 11, 15, and 20 m thick, while below 60 m depth the sigma layers were uniform at 30 m. The initial temperature and salinity distributions were taken homogeneous at $T = 4.3^\circ \text{C}$ and $S = 6.0 \text{ ppt}$, respectively, which is typical for the end of winter (Romanovsky 1991). The same seasonal cycles of river discharge compiled for each of 35 major rivers were applied consistently each year. The momentum advected by the river inflows was neglected. The temperature of inflowing river water was assumed to be equal to the temperature of the surrounding lake water. The last assumption could not significantly affect the buoyant jet dynamics and the lake in general, since the difference in salinity of lake and river waters (about 6 ppt) contributed to the density much more than the possible temperature difference. The atmospheric forcing components including momentum, heat and mass fluxes were calculated from the 10-m wind vector, solar radiation, air temperature, total cloudiness, relative humidity, sea level pressure and precipitation data generated by the operational model NCEP2 and the lake surface temperature data generated by the circulation model. The NCEP2 data with the spatial resolution of approximately 0.2° and temporal resolution of 6 h were downloaded from <https://rda.ucar.edu/datasets/ds094-1/> (last assessed July 19, 2024) and interpolated to the circulation model grid. The fluxes were calculated using bulk formulae taken from the general estuarine transport model Documentation at <https://getm.eu/doc.html> (last assessed July 19, 2024). Both the atmospheric forcing components with 6-h

time step and the river runoff time series with 1-d time step were linearly interpolated to the circulation model time step of 75 s. Another possibility was to use ERA5 reanalysis (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>), which had better spatial and temporal resolutions. However, we preferred the NCEP2 reanalysis because it produced wind velocity magnitudes more consistent with measurements at the Issyk-Kul International Airport weather station and more accurately captured wind field attributed to local winds such as the westerly Ulan and the easterly Santash. For example, the annual mean value of the 10-m wind velocity magnitude at the Issyk-Kul International Airport weather station site, estimated from ERA5, NCEP2, and the observations, in 2017 was 1.21, 2.89, and 2.66 m s⁻¹, respectively (see Supporting Information Fig. S2). Wind map obtained by averaging the NCEP2 reanalysis data over 2013–2022 does capture the westerly Ulan over the western part of the lake and the easterly Santash over the eastern part of the lake (Fig. 2). However, Fig. 2 contains some discrepancy in the wind direction displaying a NE wind over the eastern part of the lake, while the Santash is an E-NE wind blowing from the mountain pass of the same name San-Tash.

The equation of state for Lake Issyk-Kul water, $\sigma_{t_Issyk}(T, S, p)$, was obtained by Peeters et al. (2003) by modifying the equation of state for seawater $\sigma_{t_sea}(T, S, p)$ (UNESCO et al. 1981) to account for the ionic composition of Lake Issyk-Kul water which differs from that of ocean water. Our estimates based on the empirical formula by Peeters et al. (2003) and that of UNESCO et al. (1981) showed that the relative difference in density between the Issyk-Kul water and the seawater for equal values of temperature, salinity, and pressure, $[\sigma_{t_Issyk}(T, S, p) - \sigma_{t_sea}(T, S, p)] / \sigma_{t_sea}(T, S, p)$, is positive but does not exceed 7.6%. Such a difference is not large enough to introduce significant bias to the simulated Lake Issyk-Kul dynamics, while the change of $\sigma_{t_sea}(T, S, p)$ for $\sigma_{t_Issyk}(T, S, p)$ in the model code would result in considerable increase in computer time consumption. We, therefore, opted for retaining the conventional seawater equation of state in the model.

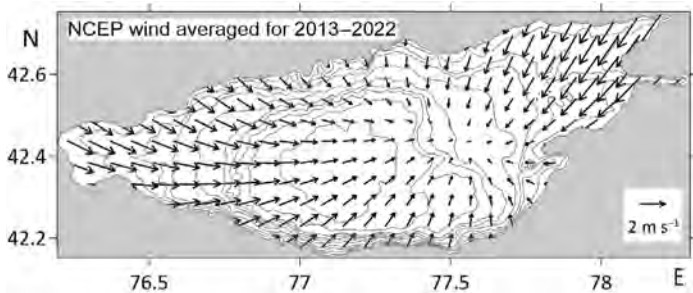


Fig. 2. Wind map averaged for 2013–2022 (NCEP/DOE AMIP-II Reanalysis [NCEP2]). Local winds, the westerly Ulan and the easterly Santash, are clearly identified.

Preliminary model runs showed that the simulated deep-water temperature gradually increased by approximately 0.15°C yr⁻¹ (see Supporting Information Fig. S3) in disagreement with the observed approximately constant value close to $T_{bot} = 4.3^\circ\text{C}$. To ensure a correspondence between the modeled and measured temperature profiles and adequately reproduce seasonal cycles during the entire 10-yr period of modeling, the modeled temperature profile $T(x, y, z, t)$ was forced to keep an exponential tendency towards the observed climatic value of the bottom temperature $T_{bot} = 4.3^\circ\text{C}$ with a characteristic time τ . That is, after performing each time step of calculations in the course of the prognostic run of the model, the updated value of temperature $T(x, y, z, t)$ was additionally updated according to the equation

$$\frac{\partial T}{\partial t} = -\frac{T - T_{bot}}{\tau} \quad (1)$$

Using the trial-and-error method, we specified τ as

$$\tau = \begin{cases} \tau_0 = 180 \text{ days at } z \geq z_0 = 300 \text{ m} \\ \tau_0 \frac{z_0}{z} \text{ at } z < z_0 \end{cases} \quad (2)$$

The above definition of τ implies that it is inversely proportional to the depth z at $z < z_0 = 300 \text{ m}$ thus making the tendency towards the climatic value vanish at small depth.

The model was validated against temperature profiles measured on October 31, 2016 and June 29, 2017 in the central part of the lake (Zavialov et al. 2018). The locations of the stations where the temperature profiles were obtained are shown by crosses marked as *a* and *b* in Fig. 1; the *a* and *b* crosses correspond to the October 2016 and June 2017 stations, respectively. It can be seen from Fig. 3 that the model reproduced satisfactorily the vertical structure of temperature with a steep thermocline, where temperature dropped from 12.0°C to 5.2°C in the layer of 0–60 m on October 31, 2016 and from 16.8°C to 5.7°C in the layer of 0–80 m on June 29, 2017. Below the thermocline, the temperature was almost vertically uniform, decreasing by only 0.9°C and 1.4°C in a 600-m layer to 4.3°C at the bottom. The only perceptible difference between the modeled and measured temperature profiles is a noticeable overestimation of the lake surface temperature by the model on June 29, 2017; however, the heat content of the water column in the model is quite consistent with the observations. The overestimation of surface layer temperature in summer and poor reproduction of the upper mixed layer is typical for ocean circulation models with the second-order turbulence closure. It can be cured by, for example, an explicit treatment of turbulent entrainment to mixed layer (Hong, Noh, and Dudhia 2006) and parameterization of mixing due to wind wave breaking, Langmuir circulation, and other processes specific to mixed layer which were not realized in Princeton Ocean Model.

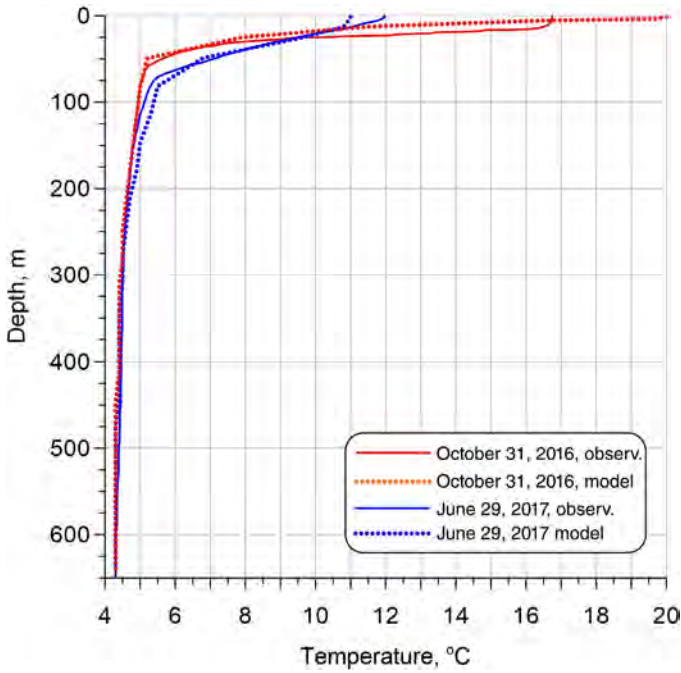


Fig. 3. Temperature profiles measured in the central part of the lake on October 31, 2016 and June 29, 2017 and the corresponding modeled profiles.

The change in salinity in the vertical direction in both the measured and modeled profiles (not shown) did not exceed 0.05 ppt so that the effect of salinity on density stratification was negligible.

Results

According to the model output, the seasonal cycle of temperature in Lake Issyk-Kul is characterized by a weak, hydrostatically stable temperature stratification at the end of winter and beginning of spring with the temperature difference below 1°C in the entire water column (Fig. 4). Development of seasonal

thermocline starts in mid-March, and the maximum temperature stratification is attained in August. During this period of surface heating, the thermocline layer thickens to approximately 60 m. Then the autumn–winter cooling begins accompanied by a progressive increase in the thermocline thickness until almost complete mixing of the water column occurs at the end of winter. Note that the model reproduces seasonal cycle with no trend in the near bottom temperature (see also Supporting Information Fig. S4), which confirms the efficiency of the procedure described by Eqs. 1, 2.

The modeled seasonal cycle of salinity in the central part of the lake is characterized by an increase of salinity by 0.01–0.05 ppt in a very thin surface layer of approximately 5 m depth during warm season of the year (from April to September) when the seasonal thermocline develops (see Supporting Information Fig. S5). The salinity increase is likely caused by intense evaporation in summer. The trend in the near-bottom salinity on the multiyear scale does not exceed 0.001 ppt yr⁻¹. In any case, the contribution of salinity to the vertical stratification of density is negligible in comparison with that of temperature.

Maps of monthly mean currents at 40 m depth in Lake Issyk-Kul averaged over 10 yr of 2013–2022 are presented in Fig. 5 for the basic model run with the NCEP2 atmospheric forcing and the river runoff included. The 40 m depth was chosen because it had the highest velocities which, in contrast to the near-surface velocities, are not biased by the Ekman spiral. The vertical distribution of currents will be exhibited later. The spring season is characterized by a weak cyclonic circulation in the central part of the lake (Fig. 5a). In May–June, with the beginning of the formation of the seasonal thermocline, a gyre cyclonic current is formed, confined approximately to the 100-m isobath (Fig. 5b). The gyre cyclonic current eventually shifts towards the lake center approximately following the 200-m isobath in August (Fig. 5c) and 600-m isobath in December (Fig. 5d). It is remarkable that detrending the deep-layer temperature by Eqs. 1 and 2 did not

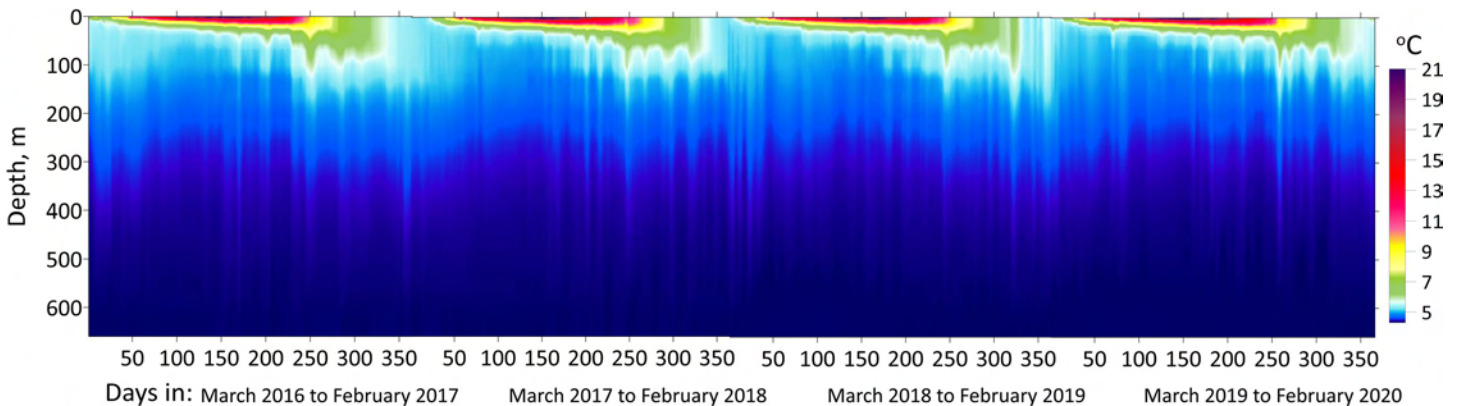


Fig. 4. Simulated temperature vs. time and depth for a 4-yr period from March 1, 2016 to February 29, 2020 in the center of Lake Issyk-Kul (the location is shown by a black cross marked as *b* in Fig. 1).

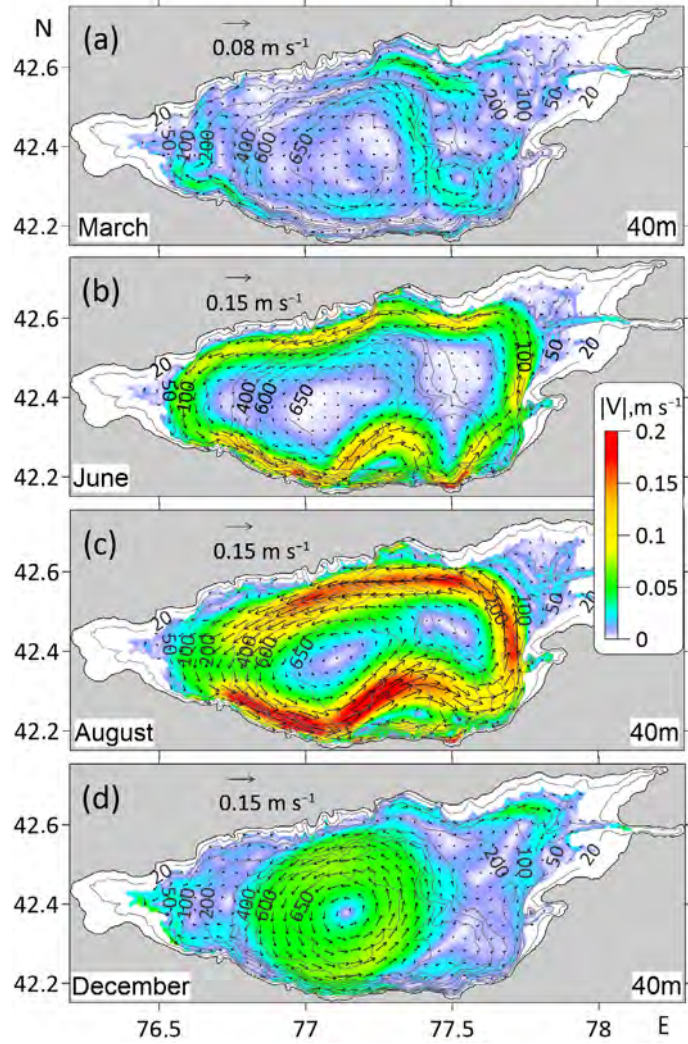


Fig. 5. Average monthly currents in Lake Issyk-Kul at 40 m depth for March, June, August, and December over a period of 10 yr (2013–2022) according to a model run with NCEP/DOE AMIP-II Reanalysis (NCEP2) and river forcings.

significantly affect the above described circulation patterns (cf. Fig. 5; Supporting Information Fig. S6).

To separately assess the effects of atmospheric forcing and river runoff on water circulation in Lake Issyk-Kul, the basic 10-yr model run was repeated with no river runoff, and a 2-yr run from March 1, 2013 to February 28, 2015 was performed with no river runoff and the NCEP2 atmospheric forcing except for the wind, which was instead taken horizontally uniform and periodic in time:

$$W_x(x, y, t) = W_0 \sin\left(\frac{2\pi t}{T_0}\right), W_y(x, y, t) = 0 \quad (3)$$

where W_x and W_y are the x and y components of the wind velocity at 10 m height, $W_0 = 8 \text{ m s}^{-1}$, and $T_0 = 6 \text{ d}$. The

physics for choosing periodic in time spatially uniform wind specified analytically by Eq. 3 (hereafter referred to as sin wind) is that it has zero curl and zero mean velocity components. Therefore, it can produce transient upwelling/downwelling coastal jets and internal Kelvin waves (Csanady 1975) but is not able to generate long-term mean annular circulation in the lake by wind stress curl and/or by combined effect of wind stress and bottom slope (Ezer and Mellor 1994; Schwab and Beletsky 2003; Lips et al. 2016).

Surprisingly that the sin wind, no-rivers (hereafter SWNR) run reproduced fairly well cyclonic circulation in Lake Issyk-Kul in summer (see Fig. 6b,c). In winter, the circulation in the lake lost its integrity, breaking up into several individual, mainly anticyclonic cells (Fig. 6a,b).

Monthly mean distributions of temperature, salinity, and current velocity in the bulk of the lake averaged over 10 yr are

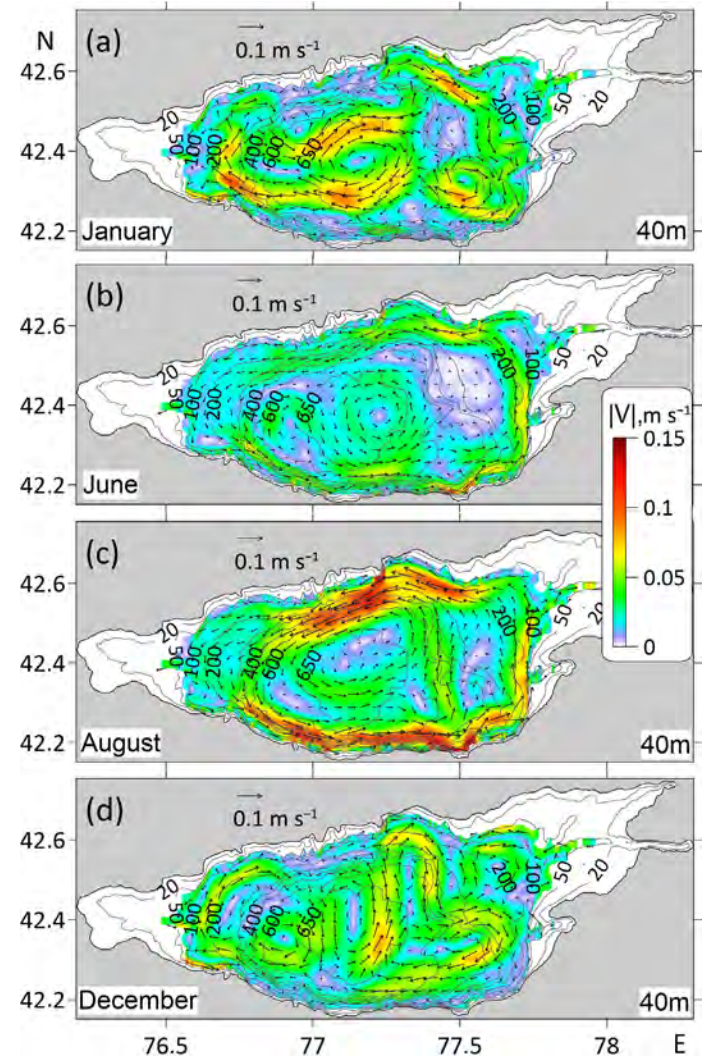


Fig. 6. Same as in Fig. 5 but for January 2015, June, August, and December 2014 according to the sin wind, no-rivers (SWNR) run.

demonstrated in Figs. 7–9 where these parameters are presented vs. depth and latitude for a South–North section across the lake center shown by a dotted line in Fig. 1. Summer is characterized by a well-pronounced cold-water dome in the lake center below the 40 m depth and a warm water cap above it in the surface layer (Fig. 7a,b). In view of geostrophic balance, such temperature distribution corresponds to a baroclinic cyclonic gyre current with maximum velocities in the thermocline layer (Fig. 7e,f). It is remarkable that the basic model run and the SWNR run produce essentially similar temperature and velocity patterns with maximum velocity of approximately 0.15 and 0.12 m s^{-1} , respectively. Salinity values in the SWNR run exceeded those of the basic run by approximately 0.02 ppt (cf. Fig. 7c,d), which was caused by evaporation in the absence of river runoff.

In August, the depth range of simulated cold-water doming (i.e., the depth differences of same isotherms between shore/open water) reached 78, 110, 114, and 103 m for 6.0°C, 5.2°C, 4.9°C, and 4.6°C isotherms, respectively (Fig. 7). The observed depth differences, estimated from fig. 10 of Peeters et al. (2003), reached 51, 76, 83, and 85 m, respectively, which in mean is 27% smaller than the simulated values. Some excess of the simulated depth differences over the observed

ones can be probably caused by an overestimation of vertical mixing at the lateral periphery of the lake above a steep bottom slope and/or too sparse network of CTD stations during the field campaign.

In January, the basic model run and the SWNR run display principally different patterns of temperature (Fig. 8a,b). The cold-water dome in the lake center with a temperature contrast much weaker (less than 2°C) than that in summer is still present in the basic run, while in the SWNR run it is replaced by a warm water cup in the upper 200-m layer. Accordingly, the basic run forecasts cyclonic geostrophic circulation, and the SWNR run forecasts anticyclonic circulation. In the latter case, the temperature is almost vertically uniform near the sloping lateral boundaries, causing cascading or lateral convective motion along the sloping bottom. The cold water in the course of downward convective sliding deviates to the right due to the Coriolis force and a cyclonic circulation near the sloping bottom in the depth range of 200–600 m develops (Fig. 8f). As a result, the SWNR run shows an unusual, double gyring with an anticyclonic inner gyre and a cyclonic outer gyre. Since the double gyring has a clear physical explanation, there is no reason to consider it a modeling artifact.

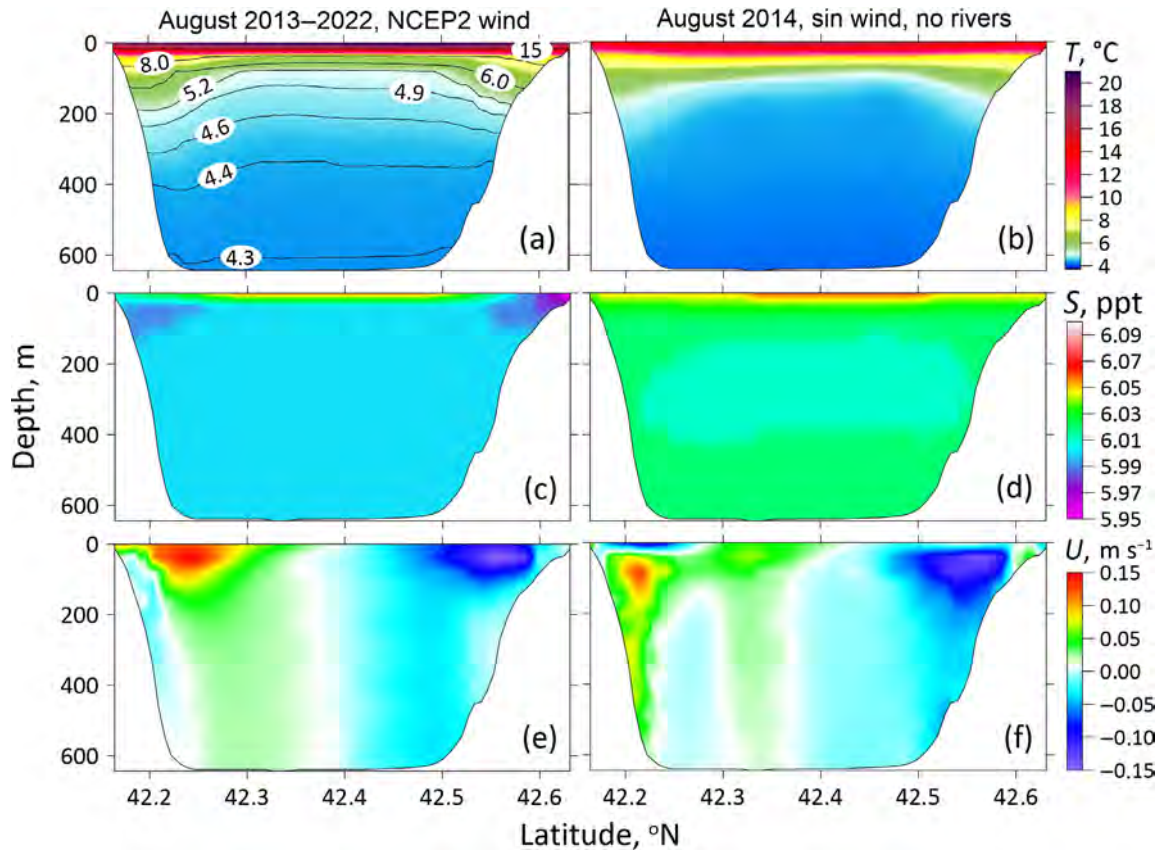


Fig. 7. Vertical section of the simulated monthly averaged temperature (top panels), salinity (mid panels) and u -component of velocity (bottom panels) on a South–North transect across the lake center for August. The left panels correspond to the basic run and the right panels to the sin wind, no-rivers (SWNR) run.

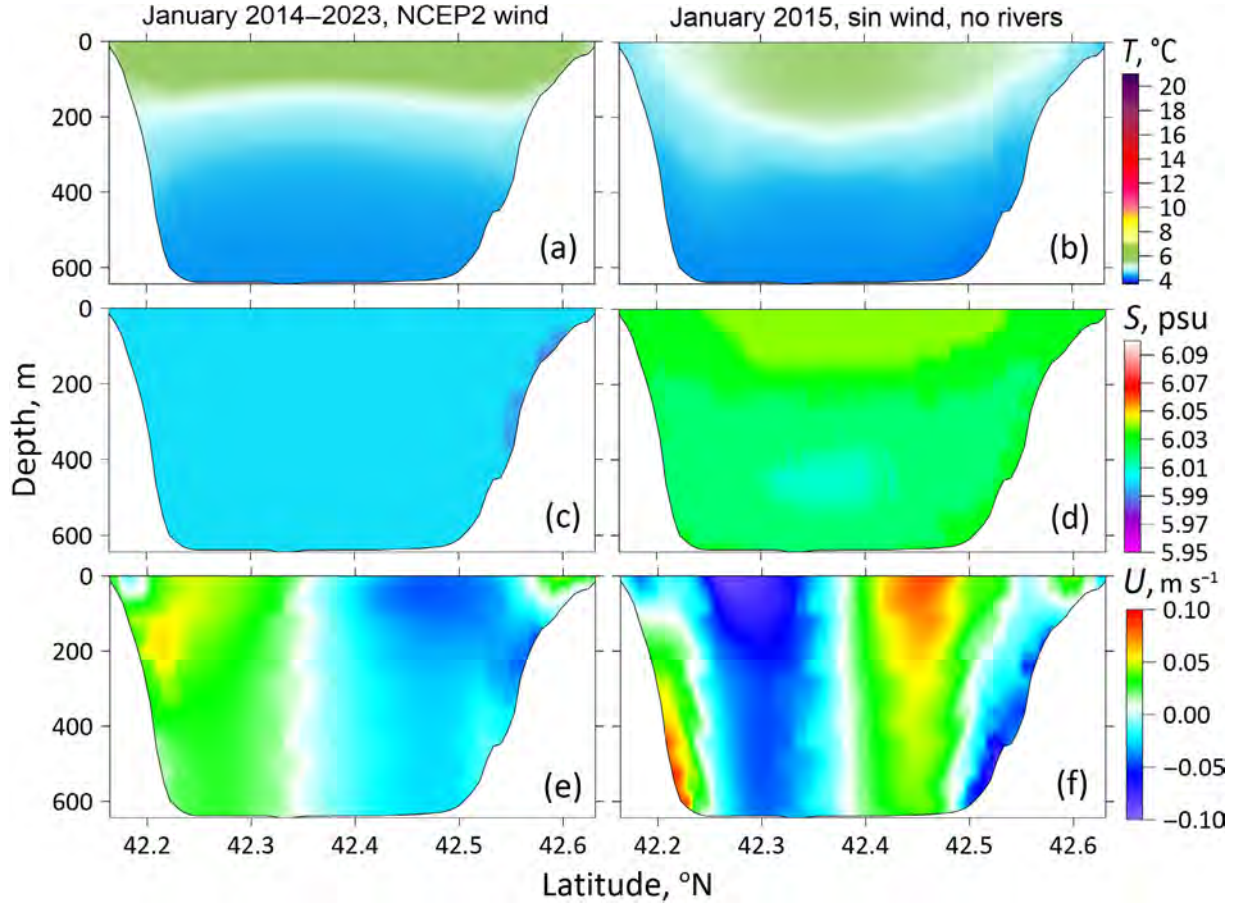


Fig. 8. Same as in Fig. 7 but for January.

The net effect of river runoff on wintertime circulation in Lake Issyk-Kul is demonstrated in Fig. 9. Despite the limited river runoff in February (see Supporting Information Fig. S1), it sufficed to support a weak hydrostatically stable density stratification in the coastal zone and thereby prevented intensive ventilation of the interior layers. The basic run still displays a weakened dome structure of temperature and related weak cyclonic circulation. To the contrary, the no-rivers run displayed no dome temperature structure and, therefore, no cyclonic circulation in the central part of the lake. The dome temperature structure was completely destroyed by February due to enhanced cascading process in the no-rivers run when density stratification near the shore weakened with the absence of river discharge. Similarly to the SWNR run, the enhanced cascading process in the NCEP2 no-rivers run caused enhanced mixing and ventilation of the inner layers and a cyclonic flow by the sloping bottom in the depth range of 200–600 m (cf. Figs. 8f, 9f).

To characterize the overall water circulation in the lake, we calculated a bulk vorticity, $\langle \zeta \rangle = -\langle u_y \rangle + \langle v_x \rangle$, where the bulk velocity gradients $\langle u_y \rangle$ and $\langle v_x \rangle$ were estimated by means of linear regression of the simulated rows of 6-h mean velocity

components u and v at 40 m depth on the meridional and zonal transects across the lake center within the deep part of the lake where $H > 100$ m. The circulation parameter $\langle \zeta \rangle$ was also calculated for the no-river run, $\langle \zeta \rangle_{\text{no rivers}}$, and the SWNR run, $\langle \zeta \rangle_{\text{sin wind, no rivers}}$ (see Fig. 10).

It is seen from Fig. 10a that the cyclonic circulation ($\langle \zeta \rangle > 0$) is maintained throughout the year being maximum in the end of August and minimum in March. The $\langle \zeta \rangle_{\text{no rivers}}$ curve mainly follows the $\langle \zeta \rangle$ curve but the former is slightly below the latter. The difference $\langle \zeta \rangle - \langle \zeta \rangle_{\text{no rivers}}$ is relatively small but positive throughout the year indicating a permanent contribution of river runoff to cyclonic circulation (Fig. 10c). In summer when the river runoff is maximum, it results in approximately 24% increase of $\langle \zeta \rangle$. In winter when the river runoff is minimum, it nevertheless results in a qualitative consequence changing a weak anticyclonic circulation for a weak cyclonic circulation (cf. Fig. 10a,b). The shapes of the low-pass filtered $\langle \zeta \rangle_{\text{sin wind, no rivers}}$ and $\langle \zeta \rangle$ curves are almost identical from May to November (cf. Fig. 10a,d) suggesting that cyclonic circulation in the lake in the warm season can develop regardless of the specifics of the local wind field. Finally, the seasonal cycle of the wind stress curl $\overline{\text{rot}(\tau/\rho_0)}$

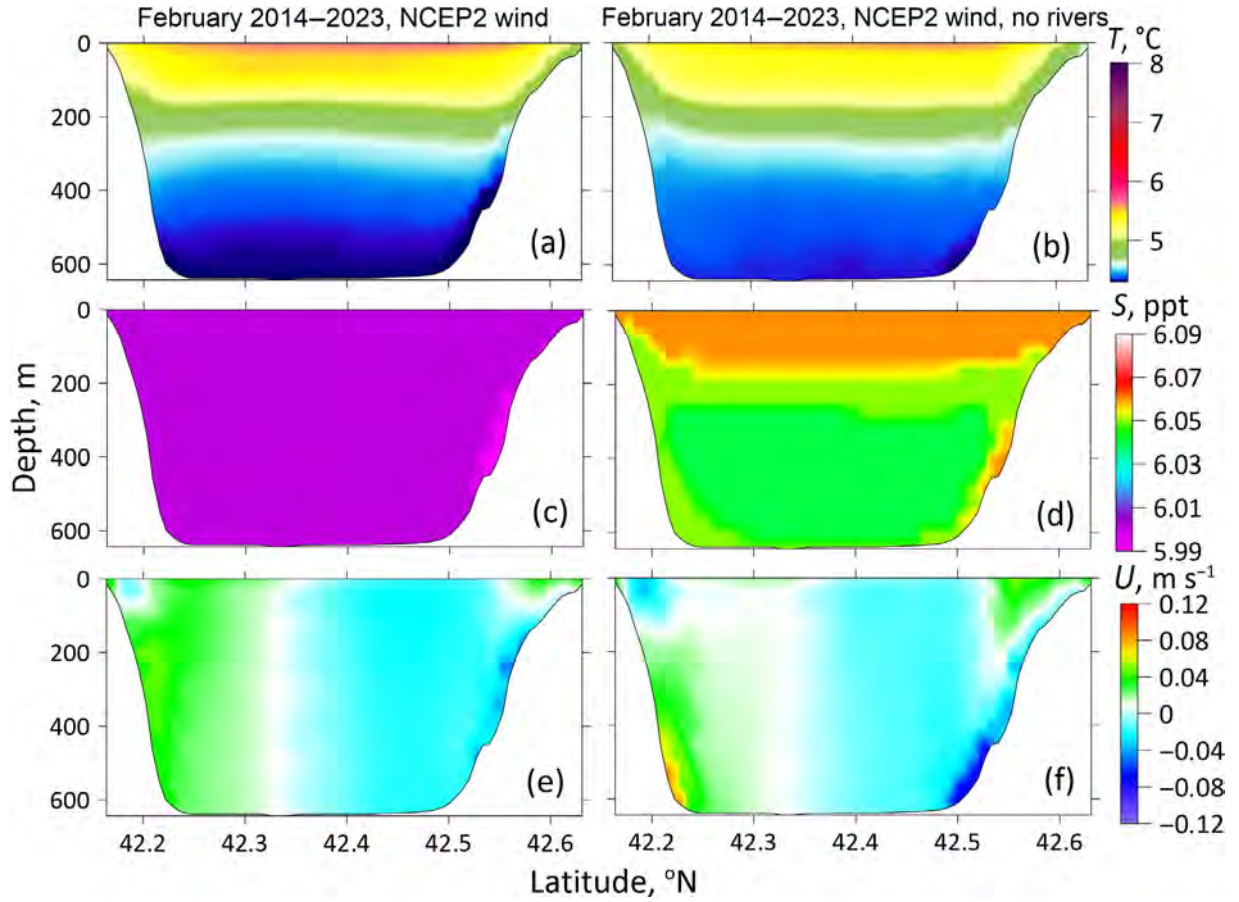


Fig. 9. Same as in Figs. 7 and 8 but for February and the NCEP/DOE AMIP-II Reanalysis (NCEP2) no-rivers run instead of the sin wind, no-rivers (SWNR) run.

averaged over the lake area (Fig. 10e), which is positive throughout the year with maximum in summer, implies some permanent contribution to cyclonic circulation in the lake.

Discussion and conclusions

This work was aimed at assessing relative effects of atmospheric forcing and river runoff on circulation in Lake Issyk-Kul based on numerical modeling. To achieve this goal, a circulation model of the lake was developed based on Princeton Ocean Model with real bathymetry, atmospheric forcing from NCEP2 reanalysis, and river runoff forcing. Seasonal cycle of the volume rate of 35 principal rivers flowing into the lake was compiled by the authors using data from different sources. To separately assess effects of atmospheric forcing and river runoff on water circulation in Lake Issyk-Kul, the basic model run for the 10-yr period from March 1, 2013 to February 28, 2023 was repeated with no river runoff, and a 2-yr run from March 1, 2013 to February 28, 2015 was performed with no river runoff and the NCEP2 atmospheric forcing except for the wind, which was taken horizontally uniform and sinusoidal in time.

To avoid discrepancies between model results and observations resulting in unrealistic deep-layer temperature trends on interannual timescales, a procedure was implemented to force the exponential tendency of deep-layer temperature to a prescribed, not necessarily constant climatic value (see Eqs. 1, 2). This procedure can be considered as a kind of data assimilation without which the long-term prognostic run of any operational circulation model would inevitably diverge from the reality. As a result, the basic model run reproduced well the recurrent seasonal cycle of temperature in the lake, while the water circulation remained almost unaffected (see Supporting Information Figs. S3, S4, S6–S9). It could have been expected that a similar procedure would have to be introduced for adjusting salinity to climate. But it turned out that evaporation (calculated from the bulk parameterization formulas using NCEP2 reanalysis data and the modeled temperature of the lake surface), precipitation (taken from NCEP2 reanalysis data) and river runoff (which was meticulously compiled from various sources) are balanced so well that the temporal trend of deep-layer salinity did not exceed $-0.001 \text{ ppt yr}^{-1}$ (see Supporting Information Fig. S5) and therefore can be neglected at the decadal time scale.

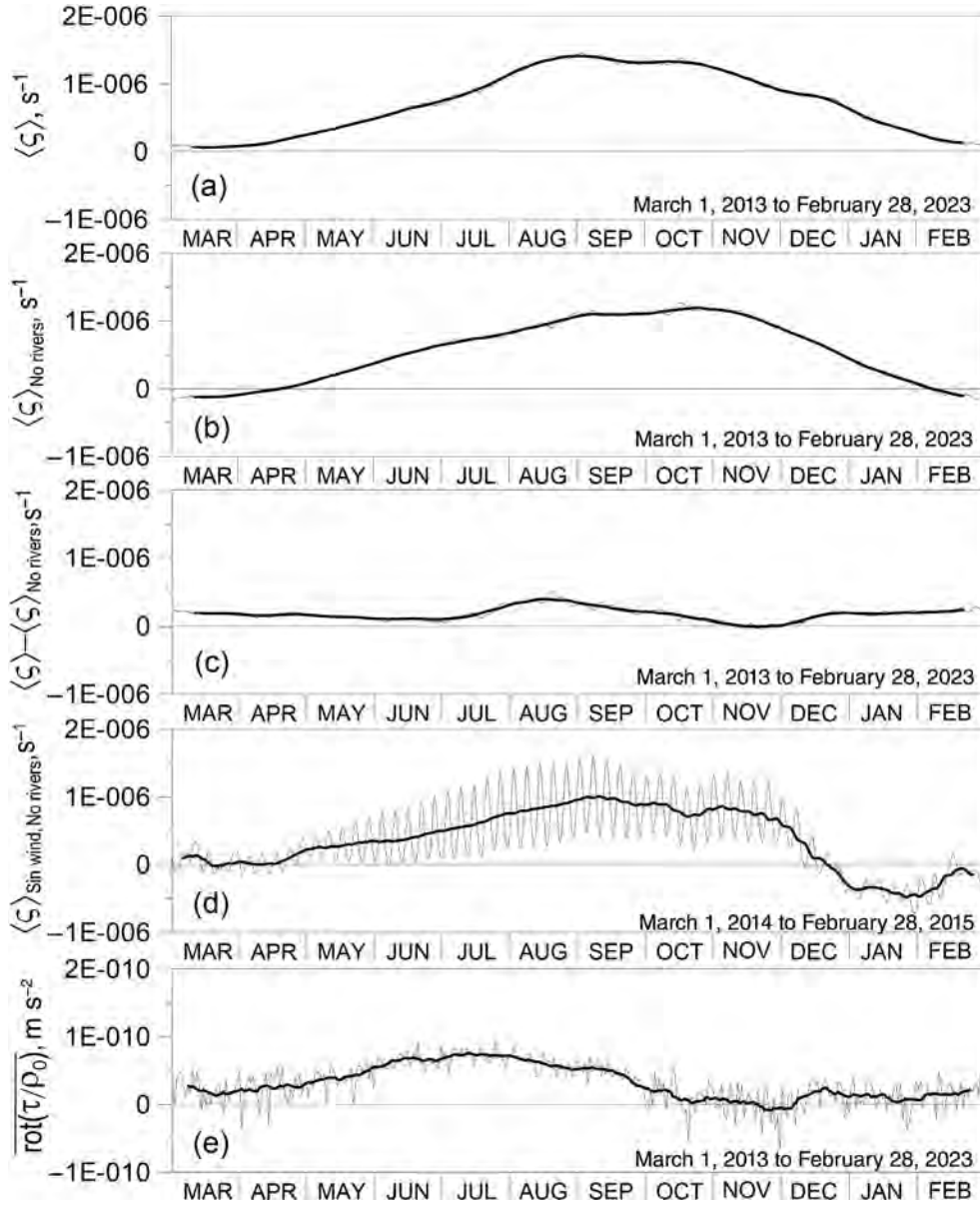


Fig. 10. (a) Seasonal cycle of the circulation parameter $\langle \zeta \rangle$ averaged over the 10-yr basic run; (b) and (d) are same as (a) but for the no river run, $\langle \zeta \rangle_{no\ rivers}$, and the sin wind, no-rivers (SWNR) run, $\langle \zeta \rangle_{sin\ wind, no\ rivers}$, respectively; (c) is the difference of (a) and (b), $\langle \zeta \rangle - \langle \zeta \rangle_{no\ rivers}$; (e) is the seasonal cycle of the wind stress curl averaged over the lake area, $rot(\tau/\rho_0)$, according to NCEP/DOE AMIP-II Reanalysis (NCEP2) for March 1, 2013 to February 28, 2023. The thin curves present the time series with 6-h step and the thick curves are the running mean at a 12-d window.

At least two mechanisms can be considered by which atmospheric forcing could potentially create gyre circulation of water in Lake Issyk-Kul. The first and most common mechanism is related to the wind stress curl applied to the lake surface, $rot(\tau/\rho_0)$. If $rot(\tau/\rho_0) > 0$, the cyclonic circulation is generated, and if $rot(\tau/\rho_0) < 0$, the anticyclonic circulation is generated (e.g., Kochergin, Klimok, and Bokovikov 1990; Ezer and Mellor 1994; Schwab and Beletsky 2003; Kubryakov et al. 2016; Lips et al. 2016). The model results did not confirm a primary role of the wind stress curl mechanism in gyre

circulation in Lake Issyk-Kul, because the seasonal cycle of $rot(\tau/\rho_0)$ assessed from NCEP2 reanalysis did not fit the seasonal cycle of the circulation parameter $\langle \zeta \rangle$ (cf. Fig. 10a,e).

The second mechanism is associated with differential warming/cooling of the water column. If the horizontal dimension of the lake is much larger than the baroclinic radius of deformation, then wind-driven longshore currents associated with coastal upwelling/downwelling and internal Kelvin waves are generated at the lateral periphery of the lake over the sloping bottom (Csanady 1975) which provide

enhanced vertical mixing through shear instabilities. Due to enhanced vertical mixing and reduced bottom depth, the entire water column warms up faster and cools down faster at the lateral periphery of the lake than in the center. This, in view of geostrophic balance, causes cyclonic circulation in the lake in the period from late spring to early winter and the anticyclonic circulation during the rest of the year. A convincing argument in favor of the second mechanism is the results of a model run with the replacement of the NCEP2 reanalysis wind by a spatially uniform sinusoidal in time wind (see Figs. 6–8, 10d).

Baroclinic radius of deformation can be expressed as

$$L_{bc} = \frac{1}{f} \sqrt{g \frac{\delta \rho}{\rho_0} \frac{h(H-h)}{H}} \quad (4)$$

where $\frac{\delta \rho}{\rho_0}$ and h are the non-dimensional density jump and depth of the pycnocline, respectively, H is the full depth of the water column, g is the gravity acceleration, and f is the Coriolis parameter (Csanady 1975). Taking the numbers inherent to Lake Issyk-Kul in summer, $h = 50$ m, $H = 600$ m, $\frac{\delta \rho}{\rho_0} = 0.001$, $g = 9.8 \text{ m s}^{-2}$, $f = 0.98 \cdot 10^{-4} \text{ s}^{-1}$, we obtain $L_{bc} = 6.8$ km which is an order of magnitude smaller than the horizontal size of Lake Issyk-Kul.

According to the model results, river runoff does not play a primary role and only moderately contributes to the cyclonic circulation in the lake. In summer when the river runoff is maximum, it can increase the cyclonic rotation by 24% due to geostrophic adjustment of buoyant coastal discharges (Yankovsky and Chapman 1997). Despite the fact that in winter the river runoff is minimal, it is able to maintain a weak hydrostatically stable density stratification in the coastal zone and slow down ventilation of deep layers by cascading processes. As a consequence, the dome of cold water formed in the summer in the central part of the lake does not collapse completely and the weak cyclonic circulation associated with it remains.

Model experiments showed that the cyclonic circulation prevailing in Lake Issyk-Kul could actually develop even without positive wind stress curl attributed to the local winds, such as the westerly Ulan and the easterly Santash. The major finding of this work is that the gyre circulation in Lake Issyk-Kul can be generated by atmospheric forcing through differential warming and cooling regardless of the wind stress curl. In our opinion, similar process may occur in other large lakes but could be more specific. In large freshwater lakes with ice cover in winter differential warming in spring to early summer typically leads to a thermal bar (e.g., Lake Ontario, Lake Ladoga, Lake Onega, Lake Baikal). The process described here probably can only become relevant after the thermal bar period, that is, when the surface water is above 4°C in the entire lake including the open water. This is different in lakes that never freeze or have sufficiently large salinity that water density decreases

monotonously with increasing temperature (e.g., Issyk-Kul, East African lakes).

The results presented in this paper reflect model simulations and further comparative analysis based on in situ data on currents or satellite imagery would be needed for validation.

Author Contributions

Maria Golenko: Data curation; formal analysis; investigation; software; validation; project administration; visualization; writing – original draft preparation; writing – review and editing. **Victor Zhurbas:** Conceptualization; formal analysis; investigation; methodology; supervision; validation; writing – original draft preparation; writing – review and editing. **Peter Zavialov:** Conceptualization; formal analysis; investigation; supervision; validation; writing – original draft preparation; writing – review and editing.

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Conflict of Interest

None declared.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

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