

Article

First Long-Term Measurements on Kazakhstan Shelf of the Caspian Sea Reveal Alternating Currents and Energetic Temperature Variability

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Abstract: Moored near-bottom current velocity and water temperature measurements were performed during a period of 194 days (from October 2022 through April 2023) with a 15-min sampling rate at two locations on the shelf of the Kazakhstan sector of the Caspian Sea in its Middle Caspian basin. The area has not been covered by in situ measurements over several decades. The two stations were separated by a distance of 22 km along the coast. The velocity and temperature data collected at 14 m depth were analyzed together with the wind data from the local meteorological station, NCEP/NCAR reanalysis of wind curl data over the Caspian Sea, as well as multi-mission satellite imagery. The analysis revealed that the currents were predominantly along-shore and highly variable in direction, with nearly zero average over the observation period. The along-shore and cross-shore components of velocity exhibited rather high correlation with the along-shore wind stress with the maximum ($r = 0.68$ and $r = 0.53$, respectively) at a time lag of about 9.5 h. The velocity series were not significantly correlated with the wind curl averaged over the entire Caspian Sea at any temporal lag, while there were weak but significant correlations between the along-shore current velocity and the curl of the wind fields over the Middle Caspian and Northern Caspian basins with time lags from one to nine days. The along-shore current velocities at the two stations were highly correlated ($r = 0.78$) with each other at no temporal lag. The temperature at both stations demonstrated nearly identical seasonal march, but a higher frequency variability superimposed on the latter was also evident with amplitudes as high as 2.79 °C. Somewhat surprisingly, the series of these anomalies at the two stations were not correlated either with each other or with surface wind forcing. However, there is evidence pointing to their connection with the cross-shore component of near bottom velocity, i.e., the cross-shore, up or down the bottom slope excursions of water from deeper or shallower depths, retaining a different temperature. During intense winter cooling of the surface layer, this effect is manifested as «warm upwelling» creating strong positive temperature anomalies or the opposite «cold downwelling» and negative anomalies.

Keywords: Caspian Sea; Middle Caspian; Shelf of Kazakhstan; coastal currents; temperature variability; in situ measurements; wind forcing



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1. Introduction

The biggest lake in the world, the Caspian Sea is three times larger by volume than, for example, the Baltic Sea and the White Sea combined. It is obvious that a body of water of such a scale must exercise significant influence on the Earth system, not only at the regional level but also in a global context through teleconnections. In particular, it has been shown that variations in the Caspian Sea level result in changes in precipitation in Central Asia, the temperature regime of the northwestern Pacific during winter, and the sea ice cover in the Pacific, e.g., [1].

The Caspian Sea is subject to various environmental threats. At the present time, the most acute challenge is the decline in sea level that began (or, more precisely, resumed) in 1996 and, after 2018, has acquired an unprecedentedly high rate of 25–30 cm per year [2]. This is almost an order of magnitude faster than was observed during the previous period of sea level drop in 1931–1978, e.g., [3]. Notably, the predictability of the Caspian Sea level changes in numerical climate forecast experiments has been and remains unsatisfactory [1,4–6]. According to some forecasts, the level drop will accelerate in the future, e.g., [7]. The decline in water level leads to the exposure of vast areas of the newly dry bottom, which modulates the sea–atmosphere–land exchanges of momentum, heat, moisture, and gases. The Caspian Sea circulation may have been altered considerably by the ongoing progressive shallowing; however, this issue has not been fully investigated to date.

Almost all known forms of anthropogenic impacts are pronouncedly manifested in the Caspian Sea. The Sea experiences significant anthropogenic pressure in the form of pollution associated with marine sources (oil rigs, pipelines, commercial ships) and land sources (ports, terminals, urban sewage). Some parts of the Sea are considered to be among the most polluted areas of the world's seas and lakes [8–12]. A large volume of pollutants arrive into the Sea with river discharges, particularly those from the Volga, but also from the Ural (Zhayik) and other rivers. These pollutants, along with massive loads of the river-borne nutrients, are then distributed between different parts of the Sea by its circulation. The eutrophication processes have been widespread in the Caspian Sea, frequently leading to blooms of algal flora and phytoplankton, including harmful ones [13]. In addition, rapid changes in the ecosystems of the Caspian Sea have been caused by human-induced introductions of a long list of biological species, including the relatively recent invasion of the ctenophore *Mnemiopsis leidyi* and then of the specialized predator *Beroe ovate*, e.g., [14]. This gelatinous zooplankton colonizes the Caspian Sea traveling passively with sea currents.

Hence, reliable and detailed knowledge of the Caspian Sea's circulation is needed to obtain insights into many key ecological and hydrological issues. Yet, the available information about the currents is rather sparse, and the eastern shelf belonging to the Republic of Kazakhstan (also known as the Mangistau shelf after the name of the riparian region, Figure 1) is, perhaps, the least well covered by in situ data. The eastern continental shelf and slope are known to be the areas of upwelling, particularly in summer, e.g., [15,16], which may interact with the near-shore currents. The classical and widely cited general scheme of the Caspian Sea circulation [17] features a cyclonic basin-scale circulation gyre in the middle part of the Caspian, which would imply a northwestward net flow along the coast of Kazakhstan. However, the published outcomes from existing numerical models diverged significantly in the region, particularly for the cold part of year. For example, a three-dimensional, spherical coordinates primitive equations numerical model by Ibrayev et al. [18] forced by ERA5 reanalysis and realistic river discharge data yielded a well-developed (≈ 10 cm/s) northward flow in winter (December). On the other hand, a Boussinesq approximation, z-coordinate numerical model by Kitazawa and Yang [19] using climatic forcing arrived at the opposite result, and so did a more recently published modeling work by Diansky et al. [20] based on a high resolution σ -coordinate INMOM model forced by the outcome from the WRF atmospheric model—both models predicted southward flow at 10–20 cm/s near the surface.

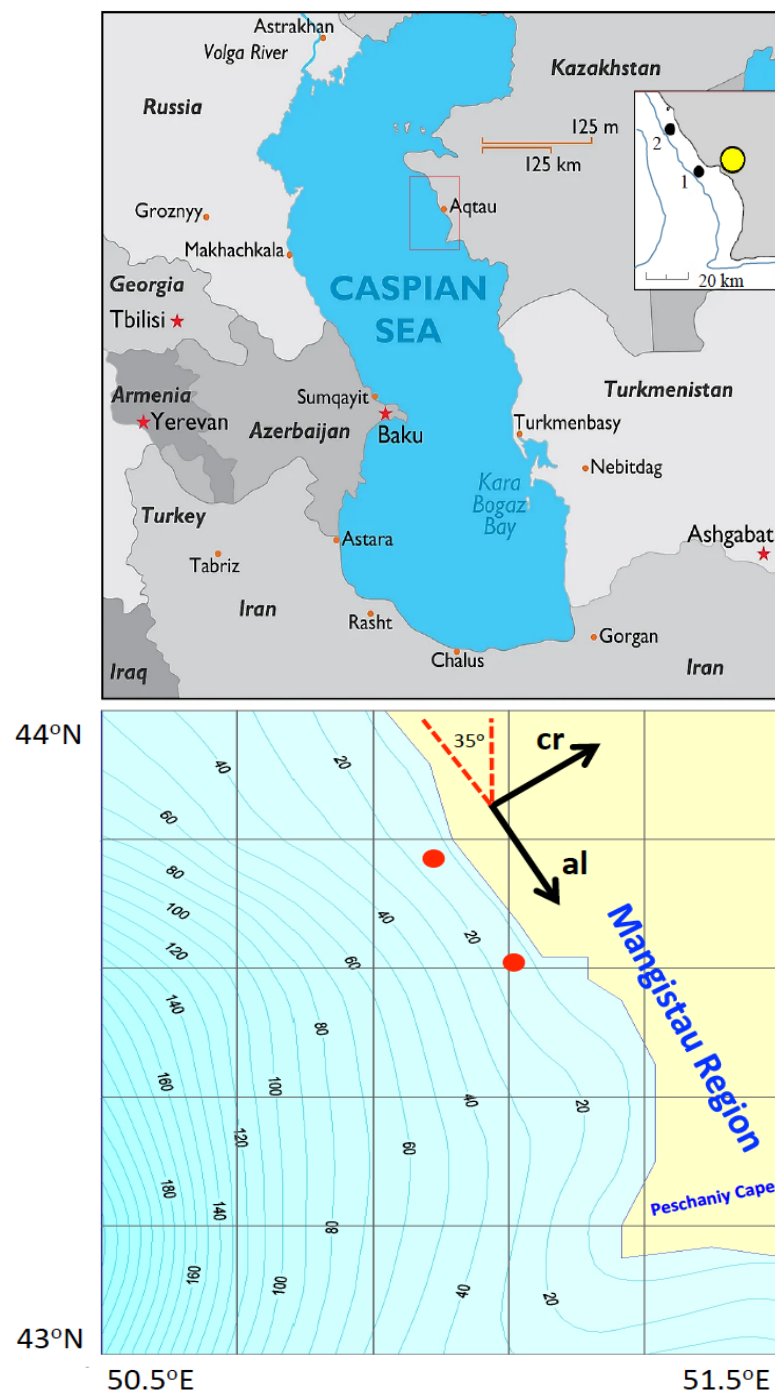


Figure 1. (Upper panel) Study region (red box) and positions of the mooring stations (inset). The yellow circle indicates the City of Aktau where the meteorological station was located. The blue contours in the inset are the 20 m and 100 m isobaths. (Lower panel) Bathymetry map. The depth contours are drawn with an increment of 10 m. Red bullets indicate the positions of mooring stations. The black arrows give the directions of the along-shore (al) and cross-shore (cr) axes used in this study.

Very few direct observations of currents in the region of this study have ever been reported. In 2009–2010, a team from the Shirshov Institute of Oceanology conducted moored current measurements in the Kazakhstan sector of the Middle Caspian [21]. Three Potok-M type mechanical instruments deployed on the continental slope at depths ranging from 120 m to 958 m registered predominantly northwesterly near-bottom currents; however, the shelf itself remained unsampled. In 2021, the authors of the present study carried out nearly 2 months of pilot moored current measurements off the City of Aktau during summer,

which revealed highly variable, bi-directional flow despite the dominance of northeasterly winds [22]. The present article describes the continuation of these measurements for a significantly longer period of time during the cold season. The objective of this study is to quantitatively describe for the first time the flow regime on the Mangistau shelf and attempt to identify the mechanisms controlling it. The instruments were deployed near the bottom at a depth of about 14 m, which is somehow representative of the upper mixed layer, at least during the most part of the year. On the other hand, it should be kept in mind that near-bottom currents may differ significantly from those at the surface. The near-bottom shelf currents are practically important, as, in many cases, they are primarily responsible for sediment fluxes, as well as accumulation and transport of nutrients and pollutants, and, therefore, directly affect benthic ecosystems. While the near-bottom currents represent an intrinsic part of the general basin-scale circulation, they are also controlled by local factors such as bathymetry, e.g., [23], and variable bottom stress, e.g., [24].

In Section 2, we describe the observational campaign and introduce the data used in this study. The results of the measurements are presented in Section 3. In Section 4.1, we discuss the regime of sea currents as inferred from the measurements and their relations with the local and remote wind forcing. The observed variability of water temperature is discussed in Section 4.2. The conclusions are drawn in Section 5.

2. Study Region and Collected Data

The Caspian Sea has a surface area of 371,000 km² and a water volume of 78,200 km³, constituting nearly a half of the planet's lacustrine waters [18,25]. The Sea is almost 1200 km in length and up to 320 km in width and is traditionally subdivided into the shallow Northern Caspian basin (maximum depth of about 20 m), the deep Middle Caspian (788 m) basin, and the deepest Southern Caspian basin (1025 m). The latter two basins are separated by a sill with a maximum depth of about 180 m formed by the submerged extension of the Apsheron Peninsula.

The study area located at the northeastern extremity of the Middle Caspian and the equipment deployment points are shown in Figure 1. Two mooring stations equipped with SeaHorse-type tilt near-bottom current meters [26–28], as well as Star-ODDI DST thermistors measuring water temperature, were installed on 18 October 2022, remained on the sites for 194 days, and were recovered on 30 April 2023. The exact coordinates of Station 1 are 43°37'24" N, 51°08'18" E, and those of Station 2 are 43°46'26" N, 51°00'00" E. The depth at both sites was 14 m (as of October 2022). Each of the stations was located at a distance of about 3.5 km from the nearest point of the coast, while the distance between two stations was 22 km. The instruments measured the current velocity components to the accuracy of 2% [29,30] and temperature to the resolution of 0.03 °C (<https://www.star-oddi.com/media/1/dst-centi-t-1.pdf>, accessed on 4 September 2024). All the data were collected at a temporal sampling rate of 15 min throughout the observation period. The current meter at Station 1 ceased working on 12 March 2023, yielding 13,884 velocity values, i.e., 144.6 days of data. The thermistor at this station kept functioning for another 7 days until 18 March 2023 and recorded a total of 14,500 temperature readings, or 151.0 days of data. At Station 2, both instruments remained active until the recovery of the stations and produced 18,679 valid data points each, representing 194.6 days.

At the beginning of the observation period on 18 October 2022, CTD measurements of the thermohaline structure from the surface to the bottom were performed at both stations using SonTek CastAway CTD probe (YSI Inc., Yellow Springs, OH, USA).

We also use, in this study, the near-surface wind speed and direction data collected at the Aktau airport weather station (international station ID 38111, coordinates 43°51'36" N, 51°05'31" E) and available on the website <https://rp5.ru>. This series, which originally had 30 min temporal resolution with some gaps in the data, was linearly interpolated to 15 min intervals to fill the gaps and match the sampling rate of the sea current meters. The wind speed vectors were then converted to wind stress using standard formulas [31].

For the purposes of this study, we refer to the along-shore and the cross-shore component of both current velocity (U_{al} , U_{cr}) and wind stress (τ_{al} , τ_{cr}), rather than the conventional zonal and meridional components. The procedure of such a conversion is described in [32], for example. In our case, the conversion was made based on the assumption that the coastline in the study region was oriented at an angle of 35° with respect to the meridian (direction SSE-NNW). Hereinafter, the positive sign of the along-shore component corresponds to the SSE direction and that of the cross-shore component to the onshore direction (Figure 1, lower panel).

We also applied NCEP/NCAR reanalysis data [33] to obtain near-surface wind curl over the Caspian Sea and its different parts for the study period. The reanalysis version used had daily temporal and 2.5-degree spatial resolution. The number of the reanalysis grid nodes falling into the Caspian Sea area was 16. The daily wind curl values extracted from the reanalysis were spatially averaged over the entire Caspian Sea and also separately over the Southern Caspian, the Middle Caspian, and the Northern Caspian basins. The NCEP/NCAR reanalysis was successfully used in several recent climatological studies focused on the Caspian Sea winds, e.g., [34–36].

Finally, we used as an auxiliary source of information the High Resolution Sea Surface Temperature (GHR SST) Level 4 dataset produced at the Jet Propulsion Laboratory on a global 0.01 degree grid [37]. The version 4 Multiscale Ultrahigh Resolution (MUR) L4 analysis is based on SST observations from several sensors including the NASA Advanced Microwave Scanning Radiometer-EOS (AMSR-E), the JAXA Advanced Microwave Scanning Radiometer 2 on GCOM-W1, the Moderate Resolution Imaging Spectroradiometers (MODIS) on the NASA Aqua and Terra platforms, the microwave WindSat radiometer, the Advanced Very High Resolution Radiometer (AVHRR) on NOAA satellites, as well as in situ SST observations [38]. The data were downloaded from <https://worldview.earthdata.nasa.gov/> (accessed on 25 June 2024).

3. Results of Measurements

The October 2002 CTD profiles at both stations were almost identical, so only those obtained at Station 1 are shown in Figure 2. Although the absolute values of the CTD-derived salinity and density may require correction because of the peculiar ionic composition of the Caspian Sea, e.g., [39,40], this profiling revealed the general vertical structure of the water column, which was well-mixed and practically uniform vertically (except in the lowermost 1 m portion directly adjacent to the bottom), which was expectable, given that the upper mixed layer in the Caspian Sea in the cold season typically extends to greater depths, e.g., [40]. As shown in the latter work based on corrected density estimates, in the Caspian Sea, the contribution to the density gradient from the temperature is typically much larger than that from the salinity.

A summary plot of data collected at the moorings is exhibited in Figure 3. As it can be seen from Figure 3a, throughout the period of observations, the prevailing winds were blowing along the shore, except in some relatively rare events where moderate or strong cross-shore winds occurred, mainly in the spring months. The cross-shore components of the wind stress were generally smaller than the along-shore ones (see also Figure 4a,b). However, the along-shore wind component was highly variable in sign, with northwesterly and southeasterly winds almost equally represented and alternating with each other in a time scale of a few days, and so was the along-shore current at both stations (Figure 3b,c).

The histogram shown in Figure 4c combining both stations demonstrates that the along-shore component of the current velocity was always below 40 cm s^{-1} by module and only in a few exceptional cases exceeded 20 cm s^{-1} . The maximum repetitivity belonged to weak and moderate ($0\text{--}10 \text{ cm/s}$) southeasterly currents as represented by a positive sign of U_{al} , but a northwesterly flow, i.e., negative sign of U_{al} was also frequently observed. Moreover, the periods of northwesterly flow were generally characterized by somewhat higher velocities so that the overall average U_{al} was negative (namely, -2.3 cm s^{-1} for Station 1 and -2.6 cm s^{-1} for Station 2). As for the cross-shore current velocity component

U_{cr} , its variability was represented by a narrower range of velocity values (Figure 4d) spanning around zero from -26 cm s^{-1} to $+19 \text{ cm s}^{-1}$. Expectedly, the overall averaging of U_{cr} over the entire record yielded essentially zero (to be exact, 0.01 cm s^{-1} for Station 1, and 0.12 cm s^{-1} for Station 2).

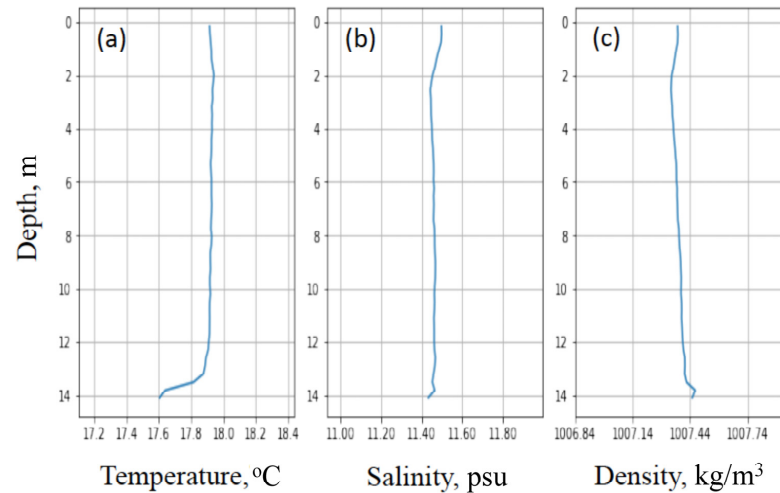


Figure 2. CTD-derived data of profiling at Station 1 on the day of deployment of the mooring stations (18 October 2022). (a) Temperature, °C; (b) Salinity, psu; (c) Density, kg m^{-3} .

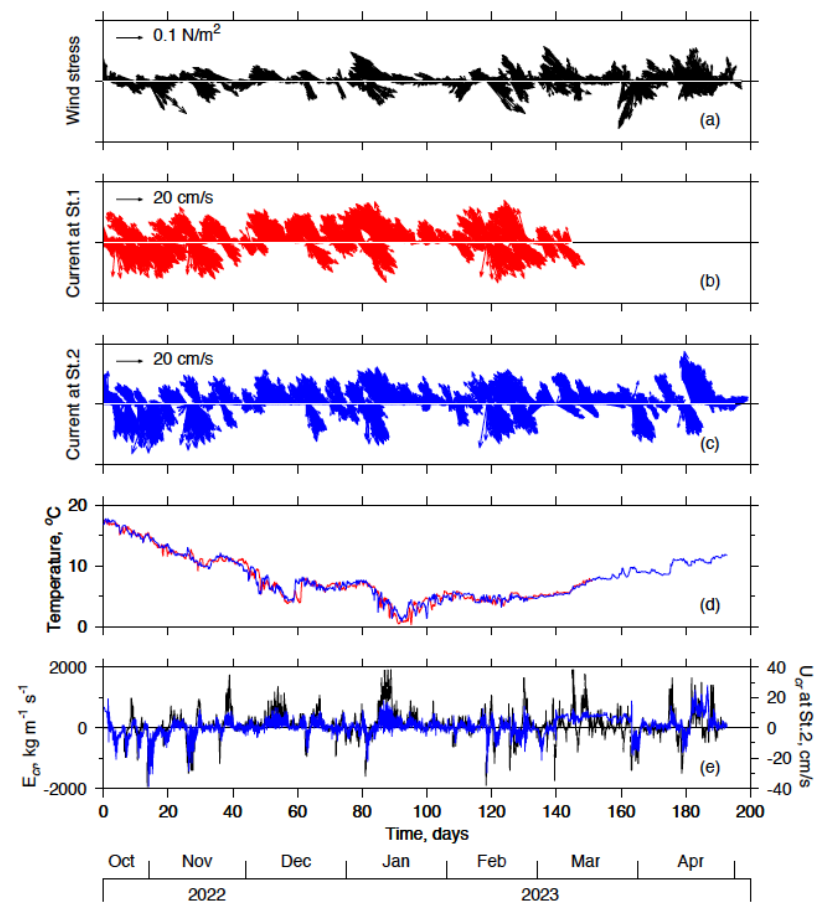


Figure 3. Summary of collected data: (a) Wind stress vectors; (b) Current velocity vectors at Station 1; (c) Current velocity vectors at Station 2; (d) Near-bottom water temperature at Station 1 (red) and Station 2 (blue); (e) Cross-shore component of calculated Ekman transport (black) and cross-shore velocity component at Station 2 (blue).

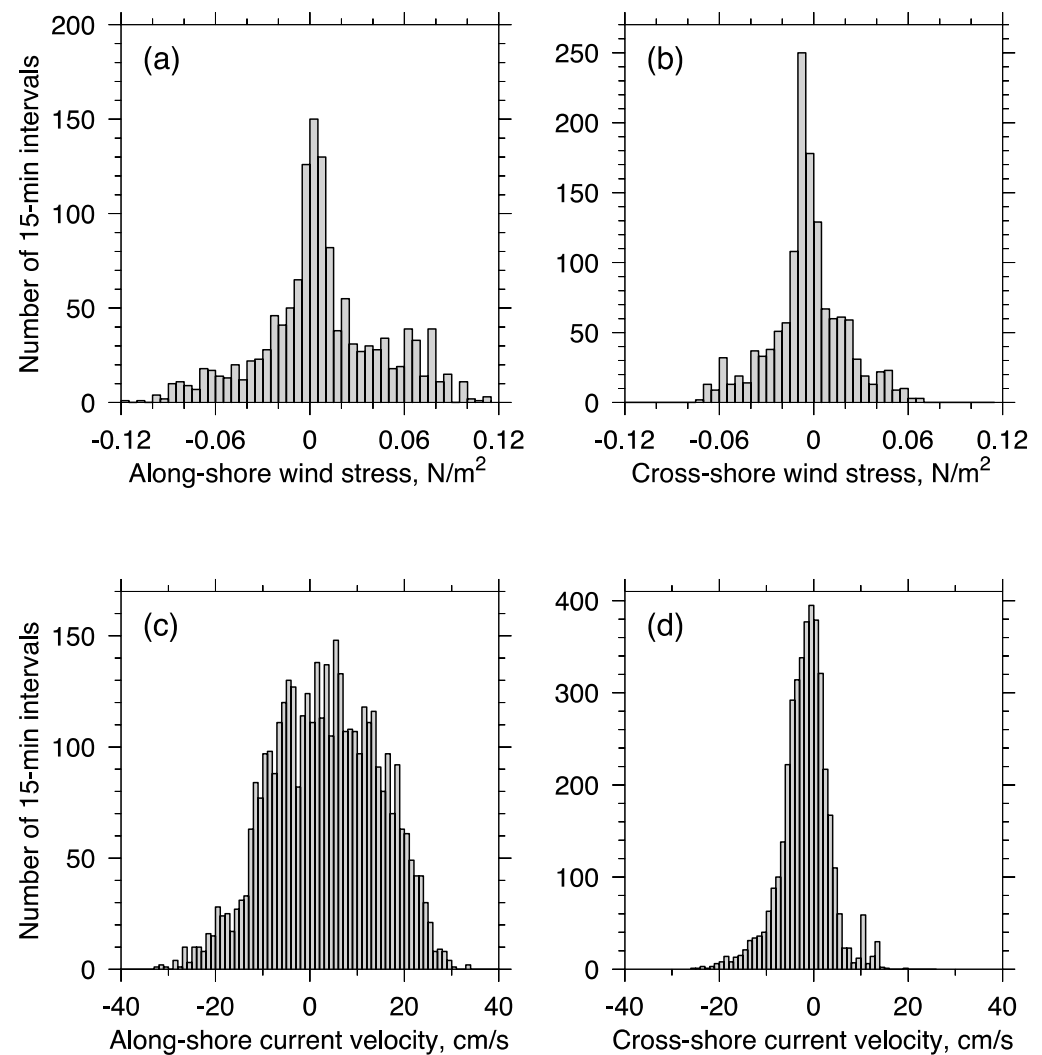


Figure 4. Histograms of the along-shore wind stress (a), cross-shore wind stress (b), along-shore current velocity (c), and cross-shore current velocity (d) for the entire period of observations at both stations. The bin width is 1 cm s^{-1} for velocity and $5 \times 10^{-3} \text{ N m}^{-2}$ for wind stress.

The near-bottom temperature series collected at two stations (Figure 3d) look very similar and represent, first of all, a clear seasonal signal, with temperature gradually decreasing from its maximum registered value of 17.59°C (beginning of measurements, 18 October 2022, Station 1) to the minimum value of 0.48°C (22 January 2022, Station 1) and then increasing again to 12.02°C (the end of measurements, 30 April 2023, Station 2). However, on top of this slow seasonal cycling, there was a considerable variability at smaller temporal scales. This variability is addressed in some detail in Section 4.

Figure 3e exhibits the cross-shore velocity component of the current at Station 2, along with the cross-shore component of the Ekman transport calculated through standard formula from the wind stress and Coriolis parameter. It is discussed below in Section 4.

4. Discussion

In this Section, we first address the variability of current velocity aiming to investigate its connection with the wind forcing and then discuss the observed water temperature variability with special attention to major water temperature anomalies.

4.1. Current Velocity

Some results of correlation analysis applied to the components of the velocity and the wind stress are depicted in Figure 5. To draw the figure, we calculated the Pearson correlation coefficients r between different series as functions of the temporal shift between them. All curves in Figure 5 correspond to the data collected at Station 2 (except the green one calculated based on both stations), where the series was longer. The respective curves for Station 1 are similar and not shown here.

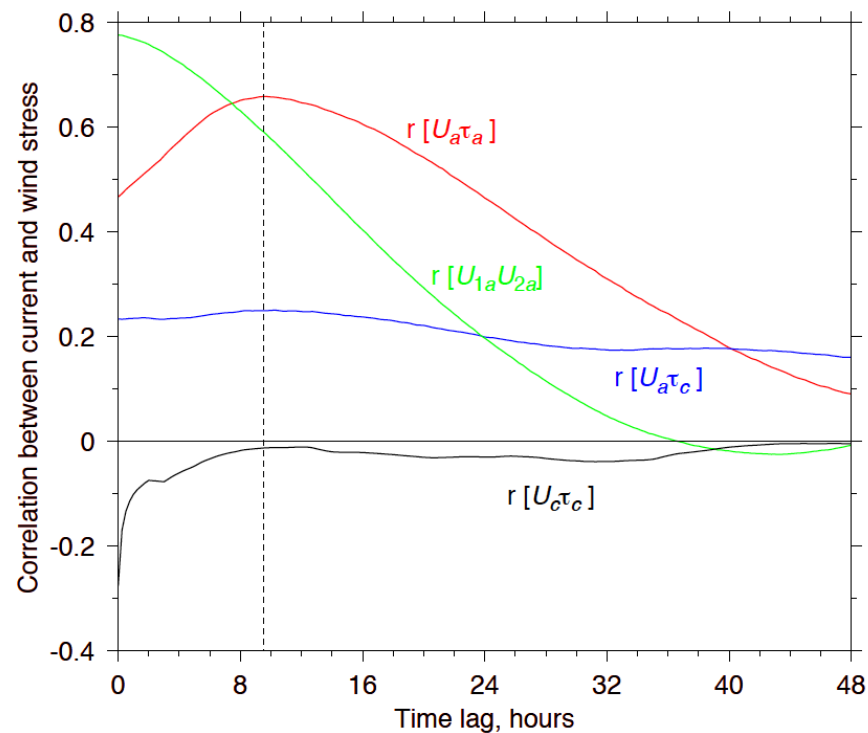


Figure 5. Lagged correlations between the along-shore current velocity series at Stations 1 and 2 (green); along-shore current velocity at Station 1 and along-shore wind stress (red); along-shore current velocity at Station 1 and cross-shore wind stress (blue); cross-shore current velocity at Station 1 and cross-shore wind stress (black).

First of all, we note that the along-shore velocity components at Station 1 and Station 2 were highly correlated with each other ($r = 0.78$) at no temporal lag. The along-shore current velocity and the along-shore wind stress were highly correlated also ($r = 0.68$), which, under assumption of linear relation, would imply a coefficient of determination equal to about 0.47, suggesting that almost one half of the along-shore current variability is controlled by the along-shore wind stress. In this case, the maximum correlation is attained with a temporal lag of the current with respect to the wind equal to 9.5 h.

It has been well established that the velocity of non-stationary wind-driven sea currents generally demonstrates a certain temporal delay with respect to wind stress, e.g., [32,41,42], because it takes time for the current to gain momentum and fully develop. If we look at the currents in subsurface layers, e.g., at a 14 m depth as in the case of this study, additional time is needed for the momentum to reach to this depth through turbulent friction, so the temporal lag further increases. The value of this delay depends on the morphometric and hydrological settings of the scene and may vary significantly. The finding that on the Mangistau shelf of the Caspian Sea, it takes the flow (as manifested at 14 m depth) 9 to 10 h to adjust to wind variability is a noteworthy result of this study. We note that ADCP measurements by Ghaffari and Chegini [32] on the Iranian shelf of the Caspian Sea yielded comparable results, where time lags of up to 10 h were documented.

The correlation between the along-shore component of the current velocity and the cross-shore component of the wind stress is weak (around 0.2 in a wide range of temporal lags, blue curve in Figure 5), and so is that between the along-shore component of the current velocity and the cross-shore component of the wind stress (-0.28 at no temporal lag, black curve in Figure 5). However, with the length of the series being over 18,000 members, even these small values of correlation are significant. The negative sign of the correlation coefficient between the cross-shore components probably indicates that the on-shore wind producing the on-shore flow at the surface also generates compensating off-shore flow in the near-bottom layer, and vice-versa, which is quite expectable. In contrast with the energetic response to along-shore wind forcing, which takes 9 to 10 h to fully develop, the current reacts to cross-shore wind weaker but nearly instantaneously.

As it is seen from Figure 3 (bottom panel), the cross-shore velocity component that shows only weak correlation with the cross-shore wind stress responds rather energetically to wind forcing expressed as the cross-shore component of the Ekman transport determined by the along-shore component of wind stress. The maximum correlation coefficient between the two variables equals to 0.53 and is attained with the temporal lag nearly the same as that found for the along-shore velocity component, i.e., about 9 h.

The frequency spectra for wind stress and current look alike, which highlights the predominantly wind-driven nature of the shelf circulation. In the high frequency domain, there are no significant diurnal (24 h) and inertial (17.6) peaks. The absence of the inertial signal was reported by Masoud et al. [43], although they identified a significant diurnal peak associated with breeze winds. This, however, was not the case for the region and the period of our study, where breeze is not manifested in the wind record. The most energetic variability lies in the synoptic range of periods between 4 and 16 days, which is consistent with the findings for the Southern Caspian shelf by Masoud et al. [43], which these authors attribute mainly to coastally trapped waves.

In order to investigate the influence of not only the local winds but also the remote wind field, we performed a similar correlation analysis with the wind curl series obtained from NCEP/NCAR reanalysis and averaged over the entire Caspian Sea, as well as separately over the Northern Caspian, the Middle Caspian, and the Southern Caspian basins, as explained in Section 2. Because the reanalysis data had daily temporal resolution, for the purposes of this analysis, the current velocity data were also converted to a 24 h averages, thus yielding series of 194 daily values (Figure 6).

The analysis of lagged correlations between the along-shore current on the Mangistau shelf and the curl of wind fields in different parts of the Sea (Figure 7) revealed weak correlations. For the length of the series used, the Student's *t*-test gives about 0.18 as the minimum correlation coefficient significant at a 95% confidence level. Hence, only the correlations with the Northern Caspian winds and, perhaps, marginally, with the Middle Caspian winds were likely significant. In both cases, the best correlation was attained at temporal lags of 9 to 10 days. The maximum correlation by module (-0.35 , implying the coefficient of determination equal to 0.12) corresponds to the Northern Caspian rather than the Middle Caspian, situated next to the study area. Interestingly, the signs of correlation for the Northern Caspian and the Middle Caspian were opposite to each other. This could be hypothetically explained by the fact that while the wind curl in the Middle Caspian would affect the study area directly, in the Northern Caspian, it would rather modulate the Northern Caspian gyre, which may exercise negative feedback on the adjacent Middle Caspian gyre through velocity shear and lateral friction at the interface between the two gyres. Of course, this is merely a hypothesis that needs further analysis and verification, in particular, by means of numerical modeling. Overall, the influence of the large-scale wind fields over the Caspian Sea upon currents on the Mangistau shelf appears to be slim and, according to the obtained coefficients of determination, is only responsible for one tenth or so of the observed variability.

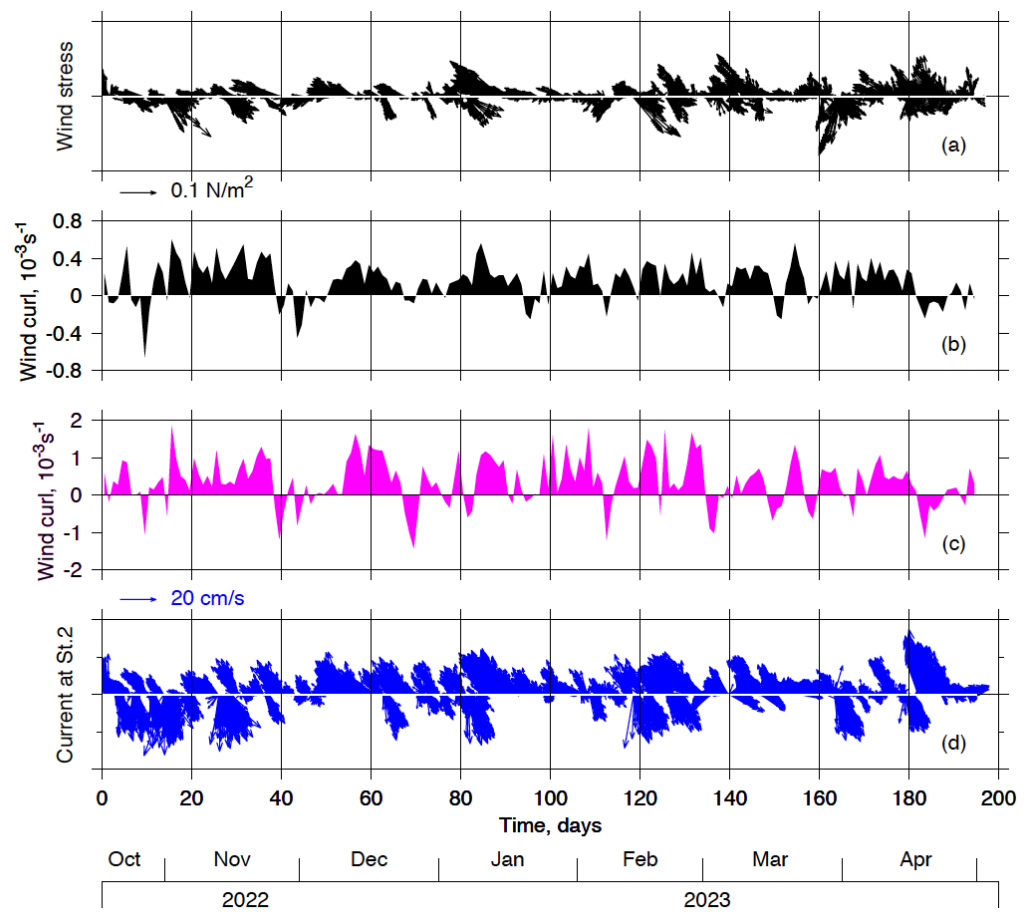


Figure 6. (a) Wind stress vectors (scale is given by black arrow under the panel); (b) Wind speed curl averaged over the entire Caspian Sea area; (c) Wind speed curl averaged over the Northern Caspian area; (d) Current velocity vectors at Station 2 (scale is given by blue arrow above the panel).

Another topic that needs to be discussed here is the potential contribution from tidal currents. Most of the previous publications considered tides and tidal currents in the Caspian Sea insignificant (see, for example, the summarizing book [3]), as it may have been expected for an inland water body. This is also supported by some specific observational and modeling studies. For instance, Ghaffari and Chegini [32], who collected long-term time series of moored ADCP measurements on the Iranian shelf, explicitly mention upon analyzing the data that tidal currents were weak and negligible. Similar statements were made by Korotenko et al. [44] as an outcome from POM modeling and by Ghaffari et al. [23] in the context of their semi-analytical modeling and observations. A recent paper by Masoud and Pawlowitz [45] reported a diurnal “tide-like” component with an amplitude of up to about 2 cm s^{-1} in current velocity on the shelf of Southern Caspian, but they established by means of data analyses and modeling that the origin of this variability was not tide but rather breeze winds. On the other hand, Medvedev et al. [46–48] put forward the notion that tides in the Caspian Sea may be significant, and supported it by some observational evidence and model results. They estimated the maximum tidal range for the Caspian Sea level as 21 cm and for the velocity of tidal currents up to 22 cm s^{-1} , which, of course, would have been quite significant. However, these figures refer to the maximum in 100 years, and only at specific locations. Generally, the tides and tidal currents in the Caspian Sea are smaller by at least an order of magnitude.

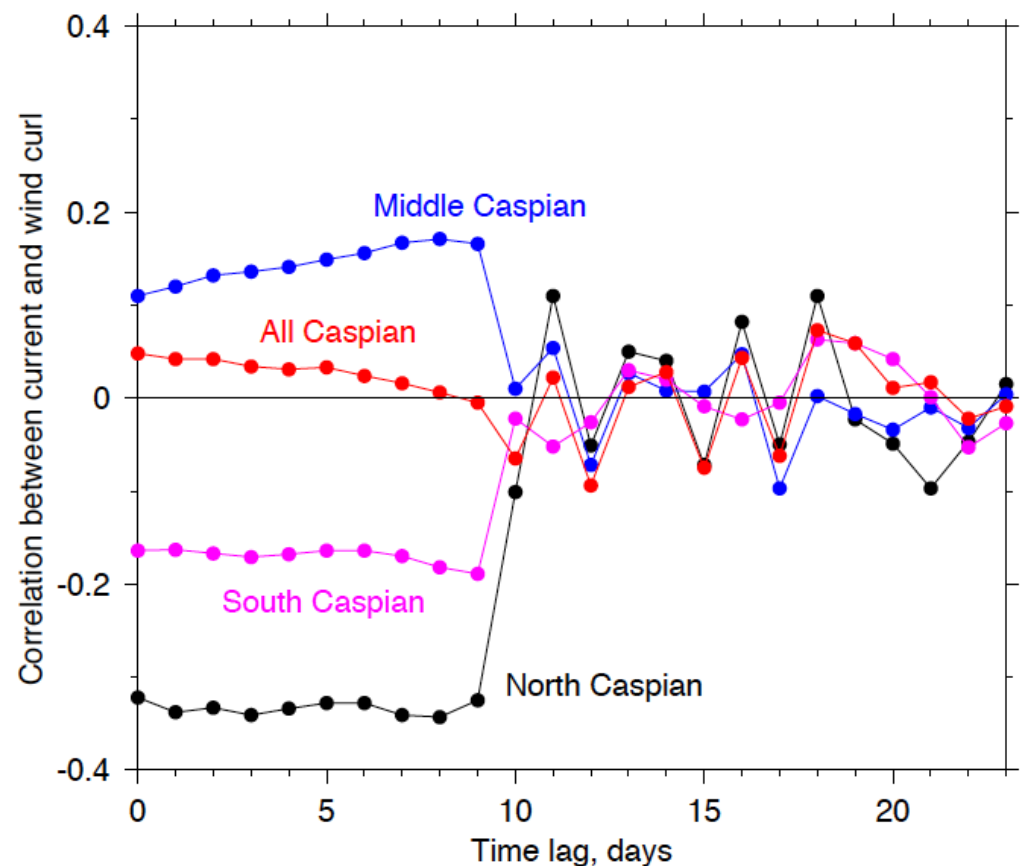


Figure 7. Lagged correlations between wind speed curl averaged over the entire Caspian Sea (red), Southern Caspian (magenta), Middle Caspian (blue), and Northern Caspian (black) on the one hand, and the along-shore current velocity at Station 2 on the other.

The currents registered in our measurements have demonstrated the “back-and-forth” nature somewhat reminiscent of tides, but the characteristic periods at which they change sign are of a few days—and not diurnal or semi-diurnal, as could have been observed if the currents were tidal. This is clearly seen in Figure 3. Nevertheless, we quantitatively estimated the magnitudes of the diurnal and semi-diurnal harmonics in the velocity records. This was carried out by finding numerically the best fits of these harmonics to the data enclosed in an 8-day-wide window moving along the data series, yielding, therefore, the best fitting amplitudes and initial phases for over 18,000 data subsets. This procedure arrived at the following outcome: for the diurnal signal, the mean amplitude was 0.9 cm/s at Station 1 and 1.3 cm/s at Station 2. For the semi-diurnal harmonics, the mean amplitude was 0.3 cm/s at Station 1 and 0.4 cm/s at Station 2. The respective overall maximum amplitudes were 2.9 cm/s for the diurnal and 1.4 cm/s for the semi-diurnal components. Hence, although marginally detectable at their maxima, the tidal components of the current are essentially negligible compared with the wind-driven currents we focused on in this study.

4.2. Temperature Variability

As already mentioned in Section 3, the curves depicting the changes in water temperature at the two stations over the entire period of measurements look very much alike, if not identical (Figure 3d,e). This high visual correlation, however, is only due to the presence of a relatively long-period seasonal trend in both series. Superimposed on this correlated seasonal signal is a higher frequency «noise» with considerable amplitudes whose structure and possible origins need to be discussed.

To extract the high frequency water temperature variability to focus on, we filtered the data low-pass with an 8-day-wide moving window and then subtracted the resulting series

from the original one, thus obtaining the high frequency «anomalies». The window width of 8 days, which is a typical synoptic time scale, was chosen based on published reports that the maximum of spectral energy in relatively long-term variability of the Caspian Sea currents corresponds to the periods between 3 and 14 days, e.g., [43].

The strongest 14 of the observed anomaly events, namely, those that had amplitudes exceeding 1.5 °C by module (hereinafter referred to as «the major anomalies»), both negative and positive, at both stations, are summarized in Table 1, together with the simultaneous values of the wind stress and velocity components. They are also graphically shown in Figure 8. For the velocity and wind stress components, we show in Table 1 both the instantaneous values and the anomalies calculated through the same procedure as that used to obtain the temperature anomalies. Use of the anomalies along with the absolute values indicates deviations from longer-term conditions and helps to make comparative analysis more illustrative.

Table 1. Major near-bottom water temperature anomalies (exceeding 1.5 °C by module) at both stations and respective values of the cross-shore wind stress, along-shore wind stress, cross-shore current velocity, and along-shore current velocity. For the latter variables, both absolute values (highlighted in bold) and high-pass filtered anomalies are given, separated by slash (see text for explanation). The values correspond to the time of maximum water temperature anomaly.

	Date and Time (Local)	Anomaly ΔT , °C	τ_{cr} , Nm ⁻²	τ_{al} , Nm ⁻²	U_{cr} , cms ⁻¹	U_{al} , cms ⁻¹	Station
1	16 November 2022, 17:41	−1.79	−0.035/−0.032	−0.062/−0.088	−6.6/−4.2	−6.0/−8.1	1
2	5 December 2022, 13:58	−2.42	−0.003/0.025	−0.003/0.015	−0.2/−1.2	−1.9/1.4	2
3	6 December 2022, 03:00	−2.35	−0.014/0.013	−0.014/0.006	−1.9/−1.9	−3.6/0.4	1
4	8 December 2022, 03:00	+1.61	−0.029/−0.003	−0.029/0.005	2.7/0.5	−9.3/−1.4	2
5	16 December 2022, 22:55	+1.65	−0.008/−0.008	−0.002/0.010	0.2/−1.1	−5.7/−2.9	2
6	17 December 2022, 23:36	−1.77	−0.027/−0.013	−0.013/−0.005	−1.3/−1.1	−4.5/0.0	1
7	18 December 2022, 22:55	+1.78	−0.012/−0.001	−0.047/−0.037	5.3/5.4	−21.5/13.6	1
8	11 January 2023, 09:00	−2.79	−0.051/−0.023	−0.073/−0.031	0.5/−0.2	−6.0/−0.7	2
9	12 January 2023, 11:39	−1.61	−0.010/0.018	−0.120/−0.058	3.6/1.9	−26.4/−14.9	1
10	21 January 2023, 12:33	−1.62	−0.018/0.002	−0.040/−0.020	−12.1/−0.7	−1.6/−6.3	1
11	21 January 2023, 14:45	+1.68	−0.036/−0.016	−0.051/−0.032	1.5/−0.2	−9.3/−3.0	2
12	22 January 2023, 11:12	+1.57	−0.003/−0.007	−0.057/−0.040	0.3/0.4	−6.2/−1.9	1
13	26 January 2023, 11:45	−2.42	−0.010/0.007	−0.012/0.002	−1.8/4.3	−0.1/−3.0	2
14	28 January 2023, 01:33	−1.50	−0.027/−0.012	−0.02/−0.013	−3.4/−3.8	−9.8/−5.2	1

By analyzing the data shown in Table 1 and Figure 8, we arrive at the following findings.

All 14 registered major near-bottom water temperature anomalies occurred between 16 November 2022, and 28 January 2023, i.e., during 74 days of the measurements, characterized by intense surface cooling. No comparable temperature anomalies were registered during either the first 29 days of measurements when the temperature, although decreasing, was still above 10 °C, or the last 93 days of the measurements when the general cooling trend switched to warming (see Figure 3d,e).

Major temperature anomalies at Station 1 and Station 2 were not correlated with each other—most of the registered anomalies were observed at one station only, and the two stations may even have demonstrated major anomalies of opposite signs on the same day, as on 21 January 2023.

All of the registered major temperature anomalies with no exception occurred when both the along-shore and the cross-shore wind stress components were negative, i.e., directed to NW and offshore. All of the registered major positive temperature anomalies with no exception occurred when the along-shore component of the current velocity was negative, i.e., directed to NW. All of the registered major positive temperature anomalies with no exception occurred when the cross-shore component of the current velocity was positive, i.e., directed onshore. Most of the registered major negative temperature anomalies (7 out of 9) occurred when the cross-shore component of the current velocity was negative, i.e., directed offshore.

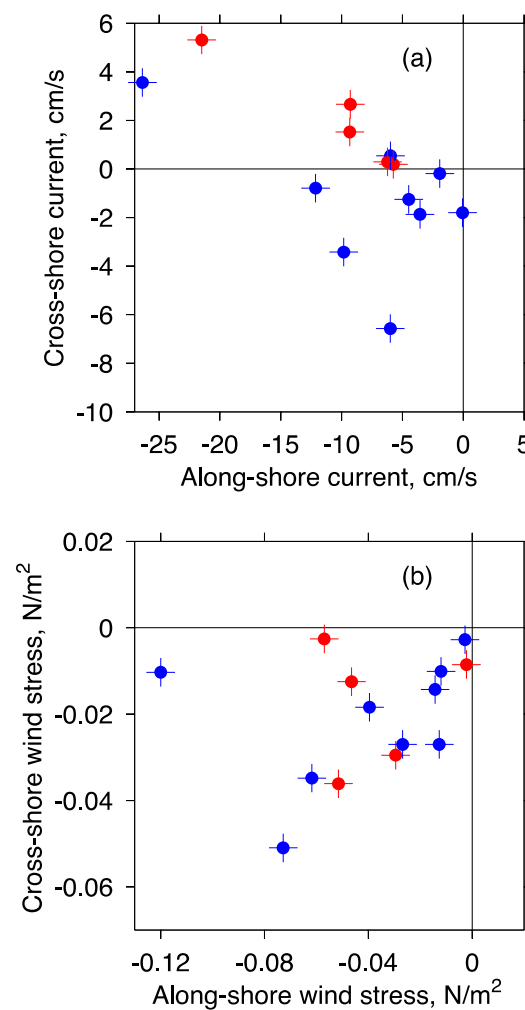


Figure 8. (a) Positive (red) and negative (blue) major temperature anomalies vs. the cross-shore current velocity and along-shore current velocity; (b) Positive (red) and negative (blue) major temperature anomalies vs. the cross-shore wind stress and along-shore wind stress.

The abovementioned properties taken in consideration together might be indicative of the local, submesoscale near-bottom advection as the principal origin of temperature variability. Indeed, all major positive temperature anomalies took place when the cross-shore component of the current velocity was directed onshore spanning from 0.2 to 5.3 cm s^{-1} (Table 1). We note also that if we examine the entire temperature anomaly data set and not only the major anomalies, we find that the majority of events where the cross-shore velocity was directed on-shore were accompanied by positive temperature anomalies (7015 out of 11,690). Because we refer here to the near-bottom velocity, such events represented local upwelling. Despite the common notion that upwellings usually result in cold anomalies (which is indeed the case in the vast majority of cases), they can also have opposite thermal signatures in winter time, particularly in shallow environments prone to intense cooling from the surface. In such situations, waters from deeper layers maintaining higher temperature climb up the bottom slope and, while mixing convectively with colder surface water, may produce a significant warming effect. This phenomenon of «warm upwelling» has been reported for the Gulf of Finland [49], the Atlantic shelf of Spain [50], and the southern Baltic Sea [51]. In a synthesized multi-sensor satellite-derived sea surface temperature (SST) field taken on the day of the strongest recorder positive anomaly (18 December 2002), there are features that could be interpreted as an indirect supportive evidence of such a warm upwelling event, manifested as a stripe and several individual spots of relatively

warm water near the shelf break surrounded from either side by colder ambient waters, see Figure 9.

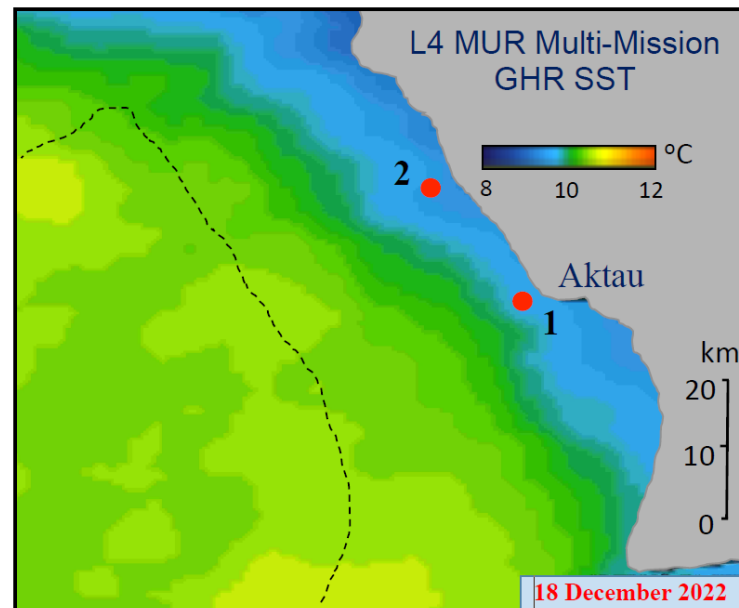


Figure 9. Satellite-derived sea surface temperature distribution on 18 December 2022. Note the manifestations of meandering of near-shore current and possible upwelling. SST data extracted from the GHR SST Level4 MUR global sea surface temperature analysis product [37] were downloaded from <https://worldview.earthdata.nasa.gov/>. The dashed line indicates approximate position of the shelf break.

Hence, hypothetically, the observed major positive anomalies of the near-bottom temperature could have been associated with such warm upwelling events, while the major anomalies of the negative sign mainly associated with the cross-shore velocity component directed offshore represent cold downwellings generated by the opposite mechanism, i.e., near-bottom offshore advection of very cold waters of surface origin. Again, if we analyze the complete data set rather than the major anomalies only, we find that out of the total of 15,617 negative anomalies observed at both stations, 10,942 were associated with the cross-shore bottom current directed off-shore. This is also graphically demonstrated in Figure 10, despite significant scatter. Both mechanisms can only be effective if the part of the water column adjacent to the surface becomes colder than waters in the adjacent deeper areas.

However, the anomaly-generating near-bottom cross-shore motions considered here were apparently not solely wind-driven, as there is no significant correlation between the sign or the magnitude of the temperature anomalies and wind stress. Hypothetically, they can be attributed to the coastal current meandering, whose traces in the SST field can be seen in Figure 9. Meandering is largely random, and, therefore, the cross-shore components of the velocity at two stations situated at the same isobath 22 km apart from each other are not correlated. This is clearly seen in Figure 10 where, while the along-shore velocity components at two stations were correlated (Figure 10a, see also Figure 5), the temperature anomalies (Figure 10c) were not. In Figure 10c, we exhibit all temperature anomalies with the magnitude below 1 °C obtained as explained at the beginning of this subsection, which represent the vast majority of all anomalies.

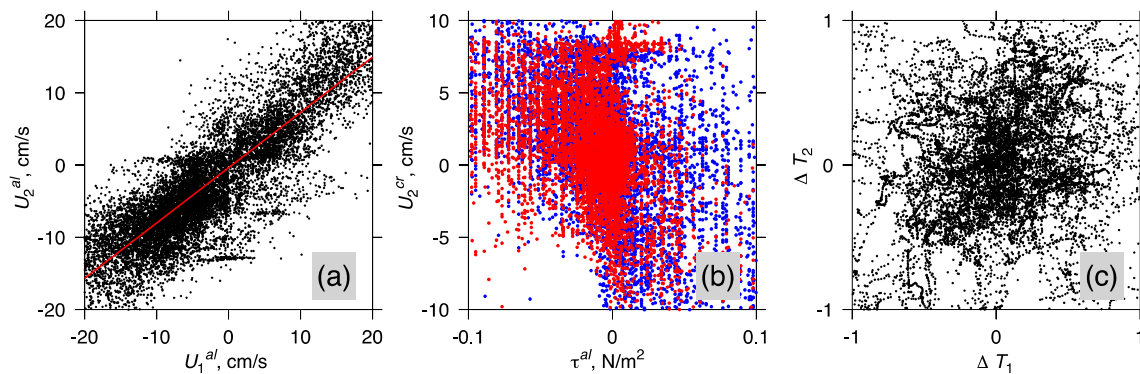


Figure 10. (a) Along-shore velocity at Station 1 vs. along-shore velocity at Station 2. The red line is the regression line; (b) Positive (red) and negative (blue) temperature anomaly occurrences depicted vs. respective values of along-shore wind stress and cross-shore current at Station 2 within the shown intervals; (c) Temperature anomalies at Station 1 vs. temperature anomalies at Station 2.

5. Conclusions

The first in the region relatively long-term, high temporal resolution measurements of currents and water temperature variability at two mooring stations, deployed at a distance of 22 km from each other on the Kazakhstan shelf of the Middle Caspian, both at the depth of 14 m, were conducted during 194 days in the cold half of year. The measurements revealed that there were no dominant directions in the flow; that is, the occurrences of northwestward and the southeastward along-shore current were almost equally represented, alternating each other on a temporal scale of 4–16 days. Such a regime is not favoring the rapid flushing of pollutants from the area, and the practically important question as to where the pollutants from multiple anthropogenic sources in the region are advected to has no unambiguous answer. However, the overall averaging for the entire period of measurements yields a weak ($\approx 2 \text{ cm s}^{-1}$) northwesterly net flow, in formal agreement with the traditional concept of the cyclonic circulation gyre in the Middle Caspian basin. The currents of either direction were predominantly along-shore, with maximum velocity values up to 35 cm s^{-1} .

The principal factor controlling the flow is the action of the local wind stress responsible for about half of the observed variability of the along-shore current velocity. The delay in the fully developed current's response to the changes in wind stress is found to be 9 to 10 h (as of the depth 14 m where the data were collected). Additionally evident are slim but significant teleconnections with vorticity of larger scale wind fields over the Middle Caspian and especially the Northern Caspian basins, best developed at a temporal lag of about 8 days.

The observed variability of near-bottom temperature at the mooring sites was largely dominated by seasonal signal with the amplitude of over 17°C for the period of the measurements from mid-October to late April. This seasonal cycling was nearly identical at both moorings. Nonetheless, the removal of the seasonal signal through high-pass filtering revealed an energetic variability of temperature at synoptic temporal scales of a few days and shorter and yielded series of temperature anomalies, including several major events of both signs with magnitudes as high as up to 2.79°C . Somewhat surprisingly, the series of these anomalies at the two stations were not correlated either with each other or with surface wind forcing. However, there is evidence pointing to their connection with the cross-shore component of near bottom velocity, i.e., the cross-shore, up (or down) the bottom slope excursions of water from deeper (or shallower) depths retaining different temperatures. During intense winter cooling of the surface layer, this effect is manifested as «warm upwellings», creating positive temperature anomalies, or the opposite, «cold downwellings» and negative anomalies. Apart from the local wind forcing, there might be other dynamical mechanisms involved in shaping the cross-shore exchanges, including

coastal trapped waves or continental shelf waves, as suggested in [43,52]. This, however, is a subject of future research.

Information about shelf circulation in the region of this study is needed for many scientific and practical applications, considering that many sources of ecological risks, including the major city and port of Aktau, several industries, petroleum extraction sites, and even radioactive waste deposits, are concentrated in this area, e.g., [53–55]. It is still unclear whether the Kazakhstan shelf is a source exporting pollutants to the neighboring areas or, inversely, a sink for pollutants arriving from elsewhere, particularly from the Northern Caspian.

The data presented in this paper were limited to the cold half of the year and a fixed depth level. Moored ADCP measurements that will provide velocity profiles and cover a year or a longer period are highly desirable. Hence, although the regional measurements reported in this paper have provided some long-awaited observational insights into, and quantitative information on, the dynamical regime of the Kazakhstan shelf, the body of collected data is far from being sufficient, and significant expansion of the measurements in space and time is in planning.

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