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SHORT-TERM VARIABILITY OF CURRENTS AND SEA SURFACE HEIGHT IN THE URAL RIVER PLUME, THE CASPIAN SEA

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This article repots the results of high temporal resolution in-situ measurements of coastal currents and sea level in the Kazakhstan sector of the Northern Caspian. Current velocity data were collected as 1 min averages for 72 hours at 3 moored automatic buoy stations spaced approximately 10 km apart, while those of bottom pressure (i. e., sea surface level) were obtained at one of the stations. The measurements were accompanied by CTD profiling at 18 stations. Wind speed and direction were simultaneously recorded using a portable weather station, with a 1 min temporal resolution. Energetic variability in currents and sea level was detected, manifested as oscillations on time scales centered at 11 and 21 hours. Currents at all stations showed a high simultaneous correlation with each other but no significant correlation with wind stress. Sea level variability was moderately correlated with current velocity, with the maximum correlation observed at a time shift of approximately 2.5 hours. The possible physical origins of the recorded oscillations are discussed, such as the intrinsic oscillations of the river plume due to the internal imbalance of the plume's momentum and mass budgets, and also coastal trapped waves.

Keywords: Caspian Sea, Ural River, river plume, sea currents, sea surface height, short-term variability

1. Introduction

The Ural river, also known as the Jayik, is the third river of Europe by length, after the Volga and the Danube. The long-term average annual discharge from the Ural to the Caspian Sea is estimated as 9.3 km^3 (Ivkina et al., 2020), which represents a modest (compared with that of the Volga) but considerable contribution to the Caspian Sea water budget. The river feeds into very shallow area of the Northern Caspian, the northernmost part of the Caspian Sea, and forms a vast plume often visible in satellite imagery. The Ural river runoff is a significant source of nutrients, and also, potentially, anthropogenic pollutants such as metals and hydrocarbons (Tolosa et al., 2004; Makkaveev et al., 2018; Mityagina et al., 2019). Like the inflows from most other rivers whose catchment basin are densely populated, it can also be a source of microplastics (e.g., Chubarenko et al., 2021). Transport of all these constituents in the coastal zone is largely controlled by river plume dynamics, which is still poorly understood

(e.g., Horner-Devine et al., 2015). In the case of the Ural's plume, the latter may have been strongly affected by the ongoing decline of the Caspian Sea level (e.g., Samant and Prange, 2023). To the best of our knowledge, no direct measurements of currents or sea level variability within the Ural plume have been reported. In this paper, we present the results of a field experiment intended to evaluate the short-period dynamics in the plume area. Furthermore, we discuss plausible physical mechanisms responsible for the observed energetic variability of currents and sea level within the plume.

2. Experimental setup and collected data

The field experiment in the Ural plume area was conducted on April 14–16, 2017. This time interval corresponded to the onset of the spring flood of the Ural river: according to the data available at www.gis.vodinfo.ru, the average runoff of the river at that time is estimated as 1400 m^3/s, which is almost 5-fold the annual mean, and it kept increasing throughout the study period. The study region and the map of stations are shown in Figure 1, the coordinates of stations are specified along with the local depth values in Table 1.

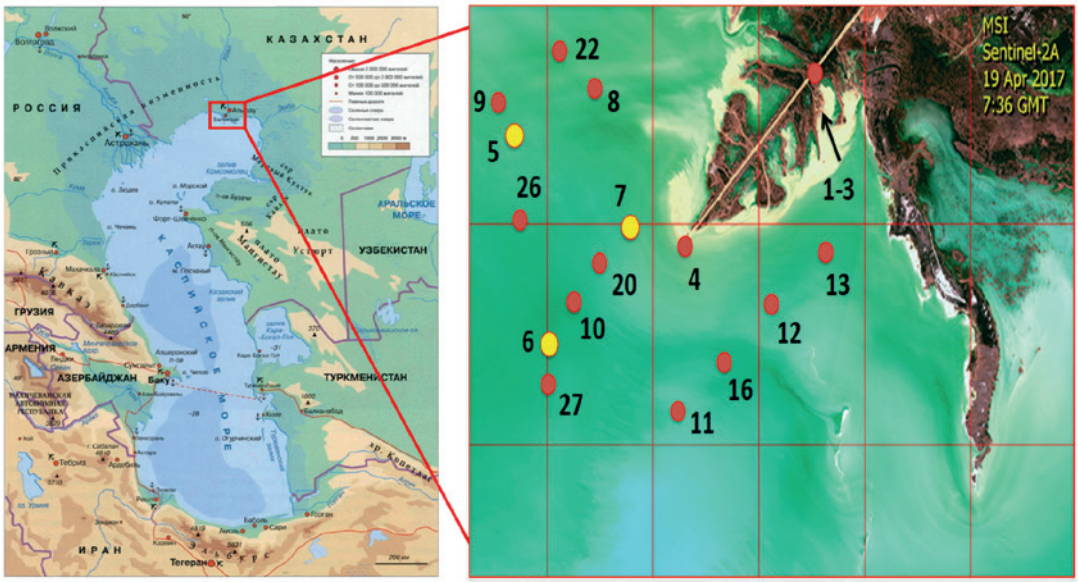


Fig. 1 – Study area. The bullets and numbers indicate CTD stations, the yellow bullets are locations where the moored instruments were deployed. The map on the right panel is superimposed on Sentinel-2A visible band satellite scene of April 19, 2017

As it can be seen from the figure and the table, the study area located directly adjacent to the Ural River delta was extremely shallow, with the depth ranging from less than 1 m to slightly above 4 m. The small, shallow-draft research vessel "Amangaliev Duysekesh" belonging to the Kazakhstan Fisheries Institute was used in the measurements. Vertical temperature and salinity profiling from the surface to the bottom using an *SBE 19plus* instrument was conducted at 18 stations. Moreover, at locations 5, 6, and 7 (see Figure 1), mooring stations

equipped with *SeaHorse* tilt current meters (Ambrosimov et al., 2025) were deployed at the bottom on April 14 and recovered on April 16. Velocity and direction of currents were recorded as 1-min averages during about 72 hours at these three locations. At one of the moorings, namely at the cebtral station 7, a pressure gauge *SeaStar11C8006* was also deployed at the bottom and yielded bottom pressure values (converted to the water column height) as 1-min averages. Finally, a portable weather station *MAXIMET GMX500-5B* onboard the vessel registered wind speed and direction, also at 1-min sampling rate.

Table 1 – Coordinates and depth values at stations. Highlighted in bold are the locations where the moored current meters were deployed.
At station 7, a pressure gauge was also installed at bottom

Station Nr.	Latitude, °N	Longitude, °E	Depth, m
1	47.07523	51.86991	3.8
2	46.96503	51.75700	4.0
3	46.88183	51.61292	4.0
4	46.82586	51.52251	1.8
5	**46.89372**	**51.36779**	**1.7**
6	**46.78257**	**51.38461**	**3.8**
7	**46.83359**	**51.46004**	**2.5**
8	46.9005	51.42405	1.3
9	46.87449	51.34409	1.9
10	46.79968	51.40981	2.2
11	46.74091	51.52894	3.2
12	46.78405	51.57719	2.7
13	46.80055	51.61086	2.0
16	46.76439	51.54787	4.1
20	46.8177	51.43504	3.0
22	46.91731	51.41639	1.5
26	46.8516	51.3814	2.6
27	46.7637	51.3832	3.5

3. Results

The vertical profiles of temperature and salinity at individual stations are shown in Figure 2, and the horizontal distribution of salinity at the sea surface is depicted in Figure 3. Note that the salinity is shown as yielded by the CTD instrument, that is, inferred from electric conductivity under assumption that the ionic composition of dissolved salts in water is equivalent to that in the ocean – which is actually not the case (e. g., Andrulionis et al., 2022). Therefore, the absolute salinity values may be biased, however, the spatial patterns should be captured correctly.

Throughout the study area, the water column was well mixed. Salinity profiles (Figure 2a) were practically uniform vertically, with salinity varying horizontally in the range from 0.5 psu to over 4 psu. The slight vertical inhomogeneities in temperature (Figure 2b) were likely related to the diurnal cycling. The general salinity distribution (Figure 3) reveals a well-developed plume manifested as low salinity area at the horizontal scales of ~20 km.

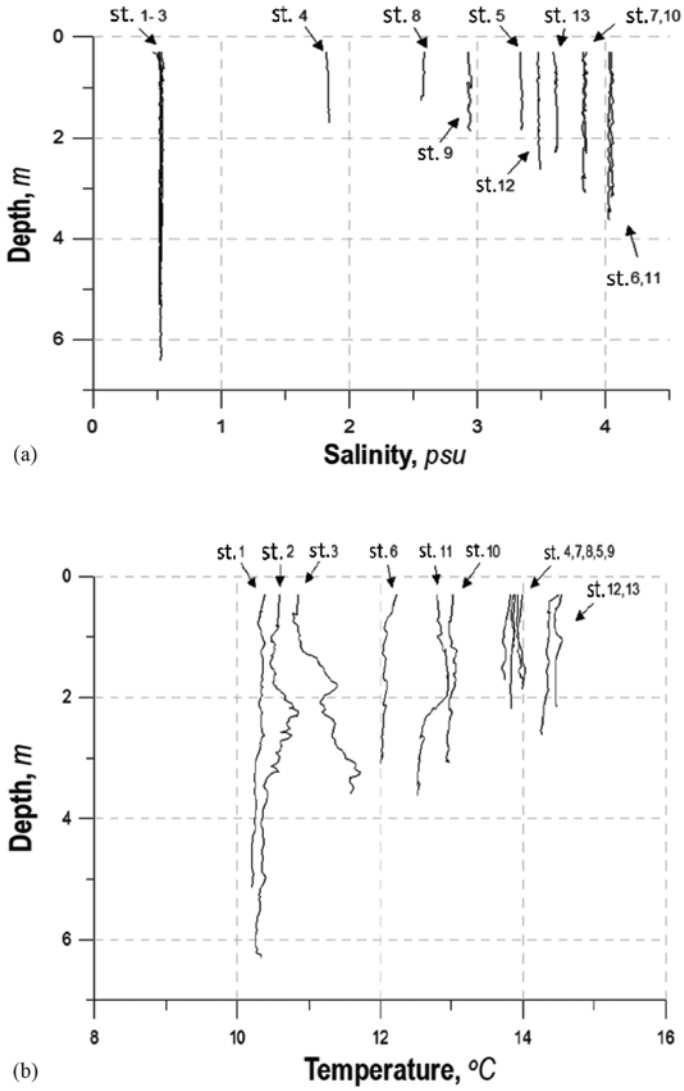


Fig. 2 – Salinity (**a**) and temperature (**b**) profiles collected during the field campaign. The numbers correspond to the stations as depicted in Fig. 1

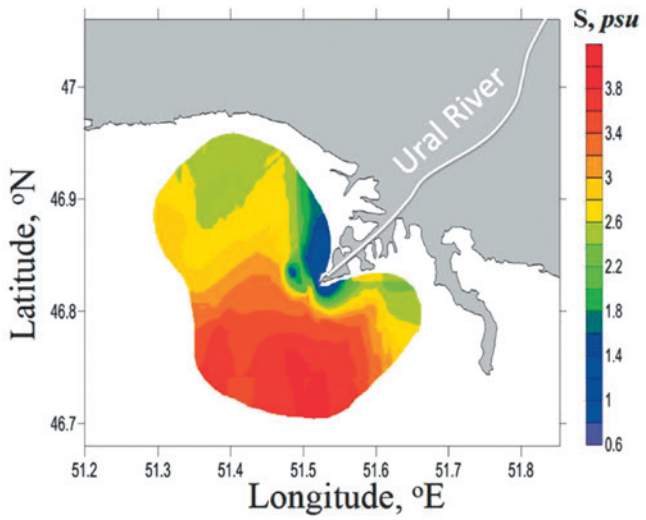


Fig. 3 – CTD derived surface salinity distribution

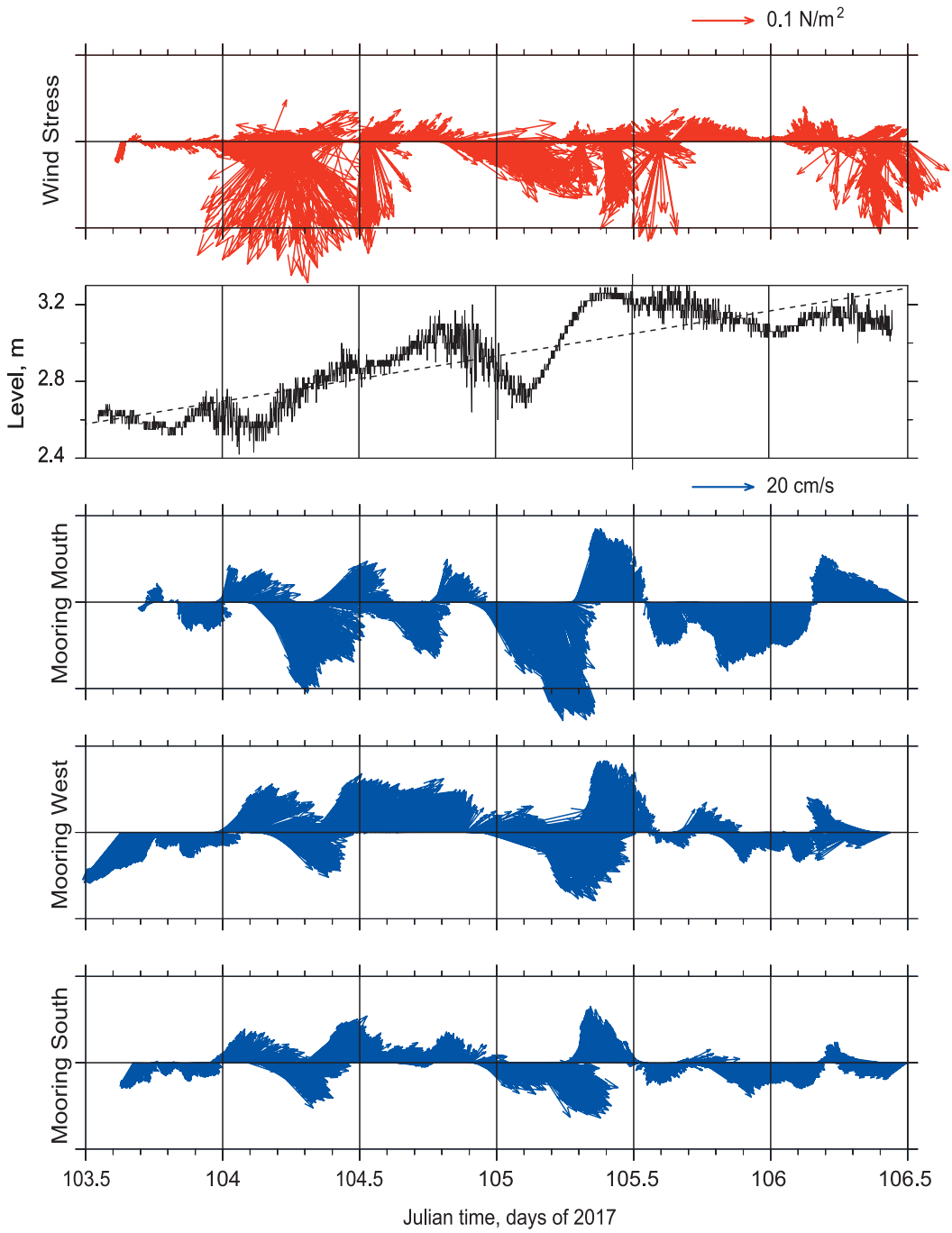


Fig. 4 – Plot of all moorings-based data as functions of time, from top to bottom: wind stress vectors; water column height at station 7; current velocity vectors at station 7; current velocity vectors at station 5; current velocity vectors at station 6

Figure 4 exhibits the near-bottom current velocity vectors at the mooring stations along with the sea surface height (expressed as the water column height above the pressure sensor deployed at the bottom at station 7), and wind stress vectors. As it can be seen from the figure, throughout the experiment, the winds were predominantly northerly. At the same time, the sea level height exhibited general growing trend at about 20 cm per day, which is consistent

with intensifying spring flood and increasing river runoff on the days of the survey (information taken from web site gis.vodinfo.ru, not shown here). Superimposed on this positive trend are oscillations with the amplitudes up to 20–30 cm and the periods of 10–20 hours. Similar oscillations are also seen in the plots of the velocity vectors at all three stations, showing high current speeds up to 40 cm s^{-1} and energetic variability. The structure of these dynamical features will be addressed in more details in the following section.

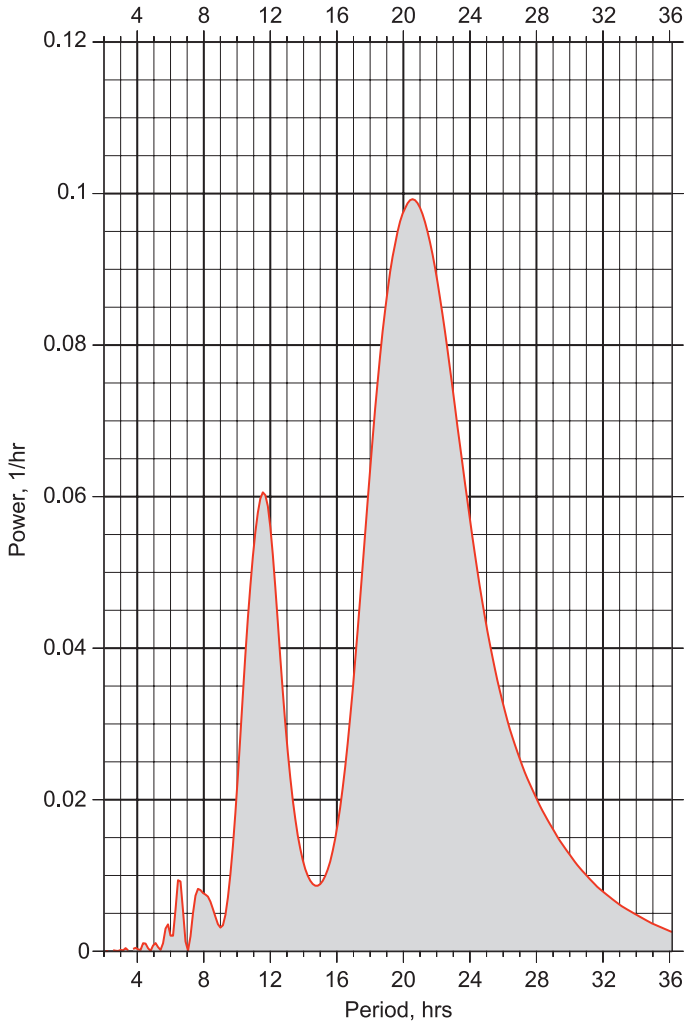


Fig. 5 – Periodogram for meridional velocity at station 7 (the nearest to the mouth)

4. Discussion

The periodogram for the meridional (i. e., essentially, the cross-shore) component of current velocity at station 7 is exhibited in Figure 5. The periodograms for the neighboring mooring stations 5 and 6 not shown here were very similar. The shown periodogram was obtained as follows: for every period value, the best fitting sinusoidal curve was found by varying the amplitude and minimizung the root mean square deviation (rms) from the demeaned and detrended observational data. The spectral power was then determined as the

ratio of variability correctly captured by the best fitting harmonics of a certain period, i. e., the total rms variability in the observational data minus the rms deviation between the data and the harmonics, to the total rms variability in the observational data. The ratio is normalized to the unit interval of periods, i. e., 1 hour. The periodogram shows two distinct peaks, one centered at 21 hours, and the other one at 11 hours.

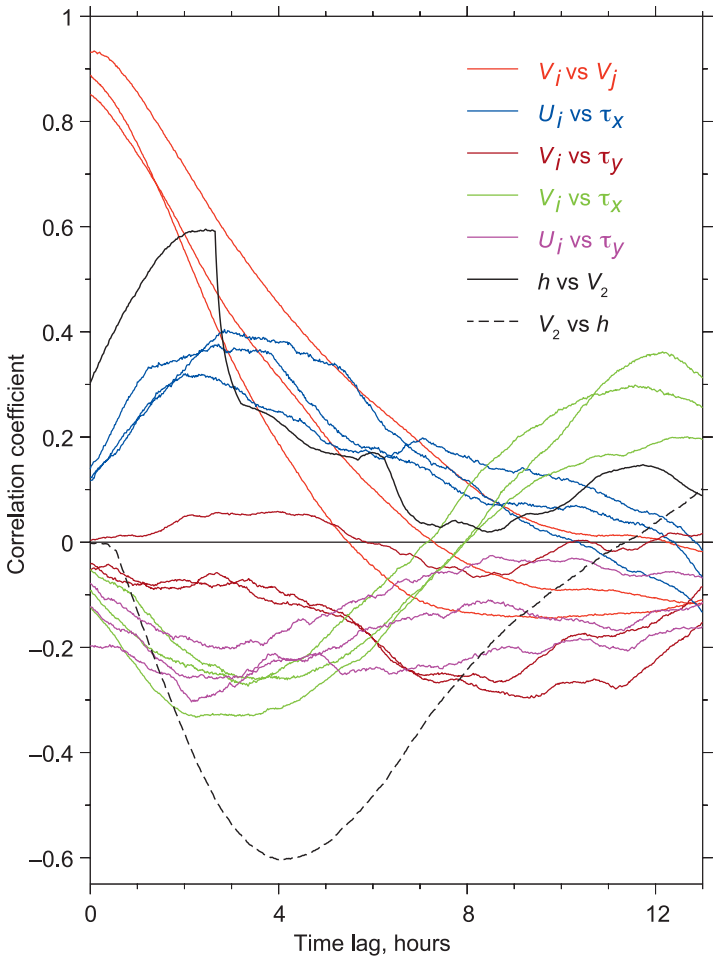


Fig. 6 – Lagged correlations between the measured variables as functions of the time lag: correlation between meridional velocity components at different stations (red); zonal velocity at different stations versus zonal wind stress (blue); meridional velocity at different stations versus meridional wind stress (brown); meridional velocity at different stations versus zonal wind stress (green); zonal velocity at different stations versus meridional wind stress (magenta); sea surface height (SSH) versus meridional velocity at station 7 – velocity leads (black, solid); meridional velocity versus SSH at station 7 – SSH leads (black, dashed)

The lagged correlations between different variables are shown in Figure 6. Somewhat surprisingly, there is no substantial correlation between the currents and the wind stress at any time lag. These correlation coefficients do not exceed 0.3. Although, given that the length of the data series is 4238 members, this correlation value is formally significant, such values of the correlation coefficient indicate that the action of winds only accounts for less than 10 % of the observed variability of currents. At the same time, current velocities at the three

moorings demonstrated high (about 0.9) correlations with each other. Notably, the maximum correlation is simultaneous with no temporal shifts, hence, the velocity oscillations at different locations were generally aligned in phase.

The sea surface height and meridional velocity are significantly inter-related. Firstly, it takes about 2.5 hours for the velocity variability to be reflected in respective sea level changes (solid black curve in Figure 6). This correlation shows the maximum value of about 0.6 and is positive, which is logical: an increase of the northward velocity component should lead to additional "pumping" of sea water into the plume and, hence, the increase of SSH therein. Secondly, following these changes, the SSH and the meridional velocity, as the former leads the latter, start to exhibit negative correlation attaining the maximum value of –0.6 at the time lag of 4 hours (dashed black curve in Figure 6). This is also consistent with the concept of the exchanges between the plume and the surrounding sea waters controlled by pressure gradient. Indeed, as the SSH grows near the coast, a compensating pressure gradient develops pushing water offshore outwards of the plume, thus leading to the negative changes of the meridional velocity component.

The observed pattern of spatial and temporal variability of velocity and SSH is rather unusual. Indeed, normally, the near-shore currents in the Caspian Sea tend to be directed along the coast and be largely controlled by winds (e. g., Zavialov et al., 2024). In this case study, however, the currents have major cross-shore component, and lack significant correlation with the local wind forcing which was essentially unidirectional. Instead, the currents and the SSH exhibited their own oscillatory variability, with the dominating periods of 11 and 21 hours. What mechanism(s) could be responsible for such a pattern? The inertial frequency oscillations are not an option, given that the inertial period, equal to 16.5 hours at the latitude of our interest (namely, 46.8 °N), actually exhibited minimum of the spectral energy. Tidal oscillations are also ruled out, because the Caspian Sea as an enclosed water body is considered practically non-tidal. Although some authors have identified small but observable manifestations of tides (Medvedev et al., 2016; Medvedev et al., 2017; Medvedev at al., 2020), this rudimentary tidal signal is much smaller than the observed oscillations. Another plausible possibility is a coastal trapped wave (CTW). The CTWs have been previously documented for the South Caspian Sea basin (Ghaffari et al., 2010; Masoud et al., 2019). These topography-controlled waves tend to populate the sub-inertial frequency range, which is consistent with one of the observed leading periods around 21 hours. The CTWs are running waves, so they must demonstrate phase shifts between stations at different locations – which apparently is not the case, given that the maximum correlation between the velocity records at the 3 stations is achieved simultaneously with no temporal lag (Figure 6, red curves). However, a more focused look at this issue is presented in Figure 7. Again, the depicted curves were calculated as the harmonics at the 11-hours and 21-hours periods best fitting the observational data. Figure 7 reveals that while the high frequency leading harmonics (11-hours period) are indeed almost simultaneous at all stations, the low frequency ones (21-hours period) are organized differently. They do exhibit phase shifts of about 1 hour between the neighbouring moorings, which, given the distance between the moorings, implies the wave propagation speed of about 3 m/s, agreeing with the speed expected for the CTWs in such a shallow environment and

consistent with previous observations of CTWs in the Caspian Sea (Masoud et al., 2019). Because the phase shifts apply only to the "long-period" harmonics and are relatively small compare with these long periods, they do not affect much the general correlation functions shown in Figure 6. Thus, it is not unreasonable to hypothesize that the long-period part of the observed variability at periods around 21 hours were associated with a coastal trapped wave. However, the high frequency variability centered at periods about 11 hours and showing no phase shifts between the stations must be attributed to a different mechanism.

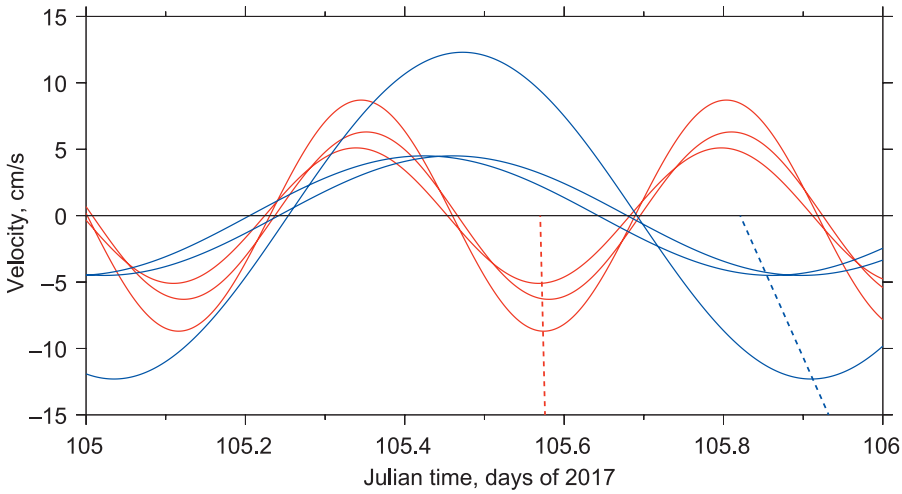


Fig. 7 – The principal harmonics of meridional velocity with 21-hours (blue) and 11-hours (red) periods at the 3 mooring stations. The dashed lines are intended to highlight that while the phase shift between the 11-hours harmonics is nearly zero, this is not so for the 21-hours harmonics

As previously substantiated by Zavialov (Zavialov, 2021), river plumes may exhibit intrinsic velocity and SST oscillations of their own, due to the fact that the equilibria of the plume's mass and momentum budgets, generally, do not coincide with each other. In a simplified model (Zavialov, 2021), the equations expressing these respective budgets read

$$b^2 \frac{dH}{dt} = Q - Ubh; \tag{1}$$

$$\frac{dU}{dt} = -\frac{1}{\rho}\frac{dP}{dx} \approx g\frac{H}{b}; \tag{2}$$

and the solutions are

$$H(t) = H_0 \cos(\omega t + \varphi_H); \omega = \frac{\sqrt{gh}}{b}; \tag{3}$$

$$U(t) = \frac{Q}{bh} + H_0\sqrt{\frac{g}{h}} \sin\left(\omega t + \varphi_H\right); \tag{4}$$

$$T = \frac{2\pi b}{\sqrt{gh}}, \tag{5}$$

where t is time, $H(t)$ and $U(t)$ are the SSH and the velocity of the outflow from the plume, respectively; g is gravity acceleration; H_0 and φ_H are the amplitude and the initial phase of

SSH oscillations; b is the horizontal size of the plume; h is the characteristic depth at the external border of the plume; Q is the volumetric river discharge rate; T is the period of the oscillations.

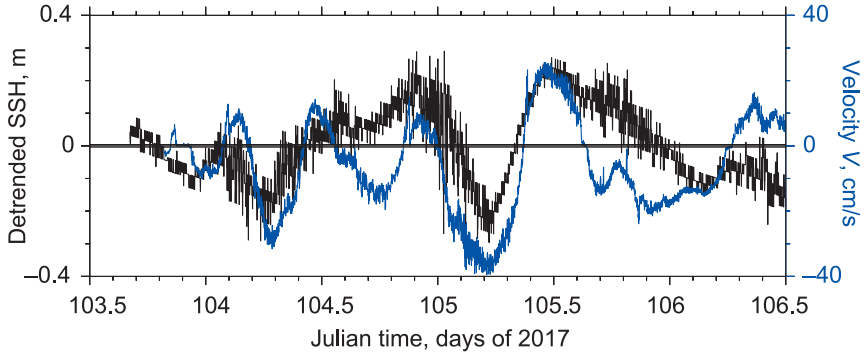


Fig. 8 – Demeaned and detrended sea surface height (black) and meridional velocity at station 7, shifted by 2.5 hours forward (blue)

The high frequency pattern recorded in the observations we report here is generally consistent with the model described above. Indeed, for the characteristic plume size $b \approx 30$ km and mean depth $h \approx 2$ m, Eq. (5) yields for the period $T \approx 10$ hours, which is close to that observed. Also, as it follows from Eqs. (3–4), the SSH and velocity variations are shifted by a quarter of the period with respect to each other. The phase relation revealed by the actual observations was rather close to this model prescription. In Figure 8, the detrended SSH at the central mooring is plotted together with the meridional velocity shifted forward by 2.5 hours, which is roughly the quarter of the leading harmonics of 11 hours. The two variables exhibit visible correlation with the maximum $r = 0.59$ attained at this temporal lag.

5. Conclusions

The case study reported in this article was aimed at examining the short-term variability of currents and SSH in a shallow coastal area within the Ural River plume at temporal scales ranging from a few minutes to 1–2 days. Although, regrettably, the field experiment was restricted to a relatively small period of time, the collected data revealed rich dynamics, apparently not directly linked with the local wind forcing. The currents and the sea surface level exhibited strong variability in an oscillatory pattern showing a superposition of two dominant spectral components, the "low frequency" one centered at 21 hours period and the "high frequency" one at 11 hours. Neithher component was significantly correlated with the wind stress. We showed that the high frequency variability is likely to have been generated by the intrinsic plume's oscillations, being consistent with the properties of the latter (as expected from previously published modeling results), whilest the low frequency domain was likely represented by coastal trapped waves. Because of the limited temporal span of the available data, both mechanisms are merely hypothetical, but what the measurements reported here demonstrated for sure is very energetic (up to 50 cm/s) coastal currents with significant cross-shore component alternating the on-shore

and the offshore directions of the flow, as well as the associated SSH variability of up to 60 cm magnitude at sub-diurnal scales. These dynamical features may have important implications for functioning of the local marine, deltaic, and coastal systems, including transport of river-borne dissolved and suspended matter, nutrients, and pollutants.

It must be kept in mind that the data reported in the paper had been collected in 2017, i. e., nearly 10 years prior to this publication. Since then, the average Northern Caspian Sea level dropped by about 80 cm (e. g., Safarov et al., 2025), which must have resulted in considerable bathymetric and morphological changes in the study area. This, in turn, may have triggered alterations of the velocity fields. Regular additional measurements are needed to elucidate the relations between the sea level variability and the dynamical regime in the study area.

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КОРОТКОПЕРИОДНАЯ ИЗМЕНЧИВОСТЬ ТЕЧЕНИЙ И УРОВНЯ КАСПИЙСКОГО МОРЯ В ПЛЮМЕ РЕКИ УРАЛ

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В статье представлены результаты высокоразрешающих натурных измерений прибрежных течений и уровня моря вблизи устья реки Урал в казахстанском секторе Северного Каспия. Ежеминутные измерения скорости выполнялись в течение 72 часов на трех заякоренных автоматических буйковых станциях, разнесенных на расстояния около 10 км друг от друга, а измерения придонного давления, т. е. уровня поверхности моря – только на одной из станций. Были выполнены также CTD-зондирования на 18 станциях. Одновременно с помощью портативной метеостанции регистрировались скорость и направление ветра, также с временным разрешением 1 мин. Обнаружена энергичная изменчивость течений и уровня в виде осцил-

ляций на временных масштабах порядка нескольких часов, причем отчетливо выделяются высокочастотная составляющая с периодами вокруг 11 час и низкочастотная с периодами около 21 час. Течения на всех станциях показали высокую одновременную корреляцию между собой, но никакой существеннной корреляции с напряжением трения ветра. Изменчивость уровня моря была коррелирована на умеренном уровне значимости со скоростью течений, причем максимальная корреляция отмечена при временном сдвиге около 2.5 час. Обсуждается возможная физическая природа наблюдавшихся осцилляций. Показано, что высокочастотная составляющая может быть связана с собственными колебаниями речного плюма, возникающими вследствие внутренней взаимной несогласованности балансов импульса и массы в области влияния пресноводного стока, а низкочастотная – с захваченными прибрежными волнами.

Ключевые слова: Каспийское море, река Урал, речной шлейф, прибрежные течения, речной плюм, краткосрочная изменчивость

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乌拉尔河羽流中里海海流与海面高度的短周期变化

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本文报道了在北里海哈萨克斯坦海域乌拉尔河河口附近进行的沿岸海流和海面高度高分辨率现场测量结果。流速以每分钟测量一次的方式在三个相距约10公里的锚系自动浮标站上连续采集72小时，而底压（即海面高度）的测量仅在其中一个站点进行。此外还在18个站点进行了CTD剖面观测。同时使用便携式气象站记录风速和风向，时间分辨率同样为1分钟。观测发现了海流和海面高度的强烈变化，表现为时间尺度为数小时的振荡，其中清晰地分离出周期约11小时的高频分量和周期约21小时的低频分量。所有站点的海流彼此之间具有高度同步相关性，但与风应力摩擦无任何显著相关性。海面高度变化与流速呈中等显著性相关，最大相关性出现在约2.5小时的时间滞后处。本文讨论了所观测到振荡的可能物理成因。研究表明，高频分量可能与河流羽流因淡水入流影响区域内动量与质量收支的内部相互不协调而产生的固有振荡有关，而低频分量则与沿岸陷波有关。

关键词： 里海，乌拉尔河，河流羽流，沿岸海流，河流羽流，短期变化

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