EGUsphere, https://doi.org/10.5194/egusphere-2026-1731, 2026

Author's Reply to Anonymous Referee #2

The authors appreciate the useful and constructive comments that helped to improve the submitted manuscript:
High current speed events in a harbor channel driven by resonant sub-hourly sea level dynamics: an example from Varna, Black Sea

In the reply, *revised text is given in italics*. The line numbers refer to the initial MS submission.

RC2: 'Comment on egusphere-2026-1731', Anonymous Referee #2, 16 Jun 2026

Comment
The manuscript entitled *"High current speed events in a harbor channel driven by resonant sub-hourly sea level dynamics: an example from Varna, Black Sea"* presents a valuable observational and numerical investigation of high-current-speed events associated with resonant sub-hourly sea-level oscillations in the Varna harbor–channel–lake system. The high-frequency measurements and the combination of spectral, coherence, wavelet, and modeling analyses provide a solid basis for identifying resonant barotropic modes and assessing their hydrodynamic consequences. The manuscript is generally well written and scientifically sound.
However, the study's main objective, practical relevance, and broader applicability are not sufficiently emphasized. Although the authors briefly mention implications for navigation safety, harbor operations, sediment transport, and coastal management, these aspects remain largely generic and are not fully developed. As currently presented, the findings appear somewhat site-specific. I therefore recommend strengthening the Introduction and Conclusions by clearly articulating the study motivation, intended applications, and the extent to which the results may be transferable to other harbor–navigation channel–lagoon/lake systems.

Reply
We have followed the recommendations:
(1) elaborated more on the practical applicability aspects, and
(2) discussed the transferability of the results to other similar basins.

Regarding (2), we added in the discussion text in lines 420-421:

In the Klaipeda Strait of the Baltic Sea, which has geometric dimensions comparable to those of the Varna harbor channels, sub-hourly water-level spectral peaks at 14 and 26 min were observed (Nesteckytė et al., 2024). Our study included current observations that are rare in studies of sub-hourly dynamics, which allowed us to demonstrate the long-wave dependence between maximum water levels and currents. However, the main limitation was the lack of sub-hourly forcing data for the identified high-current-speed events, driven by resonant sub-hourly sea-level dynamics.

Comment
1. Operational relevance of the study area
The operational context of the Varna harbor–channel–lake system should be described in greater detail. Information such as harbor traffic intensity, vessel types and drafts, navigation frequency through the channel, and the extent of traffic between Varna Lake and the harbor would help readers better assess the practical significance of the reported current events.
If available, the authors should also discuss ship-generated waves (typical amplitudes and frequencies) and their possible interaction with the observed water-level oscillations. Even a

qualitative assessment would provide useful context regarding the relative importance of vessel-induced and naturally forced hydrodynamic variability.

Reply

Navigational aspects of the study area are presented in subchapter 2.1 starting from line 70:

Port of Varna, extending from the seaside through the navigational channels to Lake Varna and the upstream Lake Beloslav, is the largest seaport complex in Bulgaria and an important transport hub of the Black Sea. It handles more than 8.4 million tons of cargo annually, specializing in container freight. The East and West Terminals, together with specialized harbors, have a total of 71 berths, with a length that exceeds 100 m (ORDER № Z-160 / VARNA, 2026); they can handle ships up to 50,000 gross tons. It is anticipated that larger vessels, about 200 m in length and 10 m in draft, may cause significant hydrodynamic disturbances in the navigation channels.

// Unfortunately, published results on ship-generated waves are not available.

Reference has been added: ORDER№ Z-160 / VARNA, 06.03.2026, https://www.marad.bg/sites/default/files/upload/documents/2026-04/Order%20160-2026_0.pdf)

Comment

2. Hydraulic structure and forcing mechanisms

The manuscript would benefit from a short subsection, placed after the Study Area section, describing the hydraulic functioning of the channel and the dominant forcing mechanisms (barotropic and/or baroclinic).

Reply

The indicated topics are included in the 2.1 Study area as Reply /1/ and 3.5 as Reply /2/.

Comment

In particular, the authors should clarify:

** Whether the channel flow is generally vertically homogeneous or stratified;

Reply

Based on the estimated flow parameters, the flow is predominantly barotropic, since the pressure difference from the sea-level drop significantly exceeds that from the along-channel density change most of the time. The flow description (Reply /1/) has been added to the study area after line 82.

** The role of density gradients between the lake and the sea;

Reply /1/

(1) The text has been added to the 2.1 study area after line 82.

The Varna Lake-Varna Bay system facilitates freshwater inflow into Black Sea and saline seawater flow into Varna Lake (Yakushev et al., 2026). Typical salinity at the lakeside is 12 g kg^{-1}, and on the adjacent Black Sea side is 17 g kg^{-1}. The average river discharge to the lake area is 3 m^3 s^{-1}. Using the Knudsen salt and water budget for stationary flows, this freshwater input is balanced by a seawater inflow of 5.5 m^3 s^{-1} and a lake water outflow of 8.5 m^3 s^{-1}. Therefore, long-term freshwater-induced currents are well below 0.01 m s^{-1}, and they should not interfere with current oscillations. A salinity difference of 5 g kg^{-1} creates a density difference of about 4 kg m^{-3}, which, at a depth of 10 m, is balanced by a sea level difference of

0.04 m. This sea-level threshold is easily exceeded by diurnal and semidiurnal oscillations and storm surges, indicating a dominant barotropic flow regime in the channels.

** Under which conditions stratification breaks down, if relevant;

Reply

This question has been addressed in reply to the earlier comment on the role of density gradients between the lake and the sea (Reply /1/), noting the dominance of a barotropic flow regime in the channels. It is assumed that a two-layer flow regime exists under calm sea-level conditions, when the sea-level difference does not exceed 0.04 m. Such calm situations are rather rare, since semidiurnal oscillations typically have amplitudes above 0.04 m.

If the two-layer flow occurs, the reduced gravity is about 0.04 m s^{-2}, and the phase speed of the long internal wave is about 0.1 m s^{-1}, which can be easily exceeded by the speed of water motion, creating a supercritical flow regime with the Froude number above unity. Barotropic flows can effectively exchange salt between connected basins, as in the Danish Straits connecting the Baltic Sea. However, we set aside these details, which are important for the water and salt exchange problem, as they are a bit outside the focus of the present study.

** The relationship between water-level gradients and current velocities.

Reply

Regarding the amplitudes, within the shallow water theory, $\omega u_0 = gk\eta_0$, where u_0 and η_0 are the amplitudes of current velocity and sea level, ω and k are the frequency and wavenumber of long barotropic wave, and g is the gravity acceleration. Bearing in mind the dispersion relation $\omega = \sqrt{gH}k$ (H is the depth), the current speed amplitude is $u_0 = \eta_0\sqrt{g/H}$. In case of H = 7 m and η_0 = 0.34 (Fig. 3), u_0 = 0.4 m s^{-1} that agrees with the observations. For water-level gradients, see the next reply.

A shorter text has been included in **Reply /2/**.

Comparison of the "amplitudes" of current speed and water level revealed a ratio consistent with that of long linear barotropic waves, thereby independently justifying the use of a 1D shallow-water approach.

** Since the water-level difference between the two ends of the channel appears to be the primary driving mechanism, it would be useful to present this parameter together with the measured currents. For example, the water-level difference (Stn3–Stn1) could be included as an additional axis in Figure 2 to facilitate interpretation of the current response.

Reply

In the hourly data as shown in Fig. 2, the water level difference Stn3-Stn1 (the curves shown in Fig. 2c) was small and not directly related to the along-channel currents shown in Fig. 2d. By linear theory, the wave period T and wavelength λ are related as $\lambda = cT$. Adopting phase speed c= 10 m s-1 and period T = 10^4 s = 2.77 h, the wavelength λ = 10^5 m = 100 km is much larger than the length of the channel. Therefore, in the low-frequency band, the channel flows were driven by the seaside water level, without significant local wave effects.

The intensity of sub-hourly variations in water-level differences was highly similar to that of water levels and current speeds (Fig. 3a). We have also prepared the new figure given below, but instead of overloading the figure, we preferred to keep the previous version of Fig. 3 and add a new text after line 221:

The intensities of along-channel currents and water level (Fig. 3a), as well as the along-channel water-level difference (not shown), were highly correlated (r > 0.85).

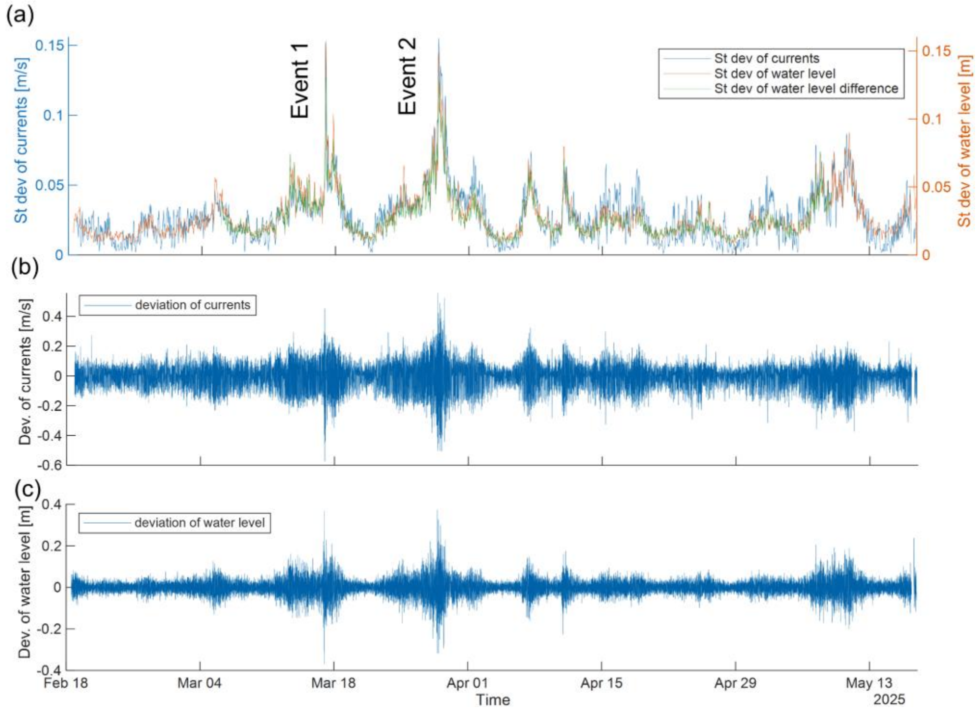

Figure 3 alternative version, not included in the MS.

Comment
3. Numerical modeling

Several aspects of the numerical model require further clarification:

Reply

The study focuses on the analysis and interpretation of observational results. In lines 63-64 it is written:

The observed variability is subject to interpretation using a 1D shallow-water model outlined in the Appendix.

We revised the text in lines 330-341 to address the comments. The revised text is:

Reply /2/

The basic question is which hydrodynamic processes cause the observed high-current-speed events. The dynamics of channels and their networks are frequently treated using shallow-water theory, which considers along-channel flow variations averaged over depth and width and employs conservation laws for mass, momentum, and energy expressed as differential equations. A broad spectrum of problems includes flooding and flow routing, long-wave dynamics for transient waves, their reflection, transition, and damping depending on the degree of nonlinearity (e.g., Lighthill and Whitham, 1955). In narrow, elongated basins, where the width is much less than the length, the transverse flow component is damped, thereby decreasing also the influence of Earth's rotation. This results in a 1D model.

In the case of small disturbances of motion from rest (water-level deviations are much smaller than the depth), the flow follows the linear shallow-water equations. Consider that the basin geometries: the navigation channels 3 and 1 were approximated with length L = 2,400 m, depth H = 7 m, and a total width B = 300 m; the lake was approximated with length L = 11,000 m, depth H = 10 m, and width B = 1,900 m. Consequently, the conditions for the 1D model are met in the first-order approach both for the channels and the lake. Regarding the assumption of linearity, the observed water-level amplitude up to 0.4 m and current-velocity amplitude up to 0.4 m s^{-1} over a half-period of

10 min suggest that in the momentum equation the non-linear advection is less than 10% of the acceleration term. The linear barotropic (with density variations considered small) shallow-water equations (Eq. A1) and related oscillation modes are outlined in Appendix A. Comparison of the "amplitudes" of current speed and water level revealed a ratio consistent with that of long linear barotropic waves, thereby independently justifying the use of a 1D shallow-water approach.

The first interpretations based on quarter-wave resonance used a channel of constant depth, with prescribed water-level oscillations at one end and a closed boundary at the other. Further refinement of the interpretations included a larger study area, idealized as a network of connected 1D channels with small but distinct widths. rectangular-basin approach, assuming constant depth and width within each basin. The two parallel navigation channels (Channels 1 and 3), approximately the same length and depth, were modeled in the lake-channel-sea system as a single channel by summing their widths. Note that for a 1D channel, the results are independent of the channel width; width comes into play when channels are connected sequentially.

Seiche (standing wave) periods were studied using analytical and numerical experiments, labeled Exp. 1 to Exp. 7 (Table 4). Already, the simplest model approaches in Exp. 1 and 2 revealed an approximate match to the observed oscillation periods in the range of a few tens of minutes (Table 2). Subsequent refinements from Exp. 3 to Exp. 7 included different configurations of the connected sea, channels, and lake, using analytical and numerical methods. In this interpretation study, detailed consideration of topography and coastline, which could create multiple hydrodynamic effects, was deferred to future studies.

* The justification for representing the two channels as a single equivalent channel by summing their widths should be explained in greater detail. Potential impacts on frictional losses, local hydraulic effects, and resonance characteristics should be discussed.

Reply

This comment has been addressed in Reply /2/ as:

Note that for a 1D channel, the results are independent of the channel width; width comes into play when channels are connected sequentially.

* The rationale for examining the alternative geometries listed in Table 4 should be clarified. Why was the realistic geometry not used as the primary reference configuration?

Reply

This comment has been addressed in Reply /2/ as:

In this interpretation study, detailed consideration of topography and coastline, which could create multiple hydrodynamic effects, was deferred to future studies.

* The assumption of a linear barotropic system should be supported with information on typical salinity conditions in both the lake and the sea.

Reply

The text has been added to the presentation between water-level gradients and current velocities.

* The choice of grid resolutions (12 m in the channel and 30 m in the lake) should be justified, preferably with reference to a grid-sensitivity analysis.

Reply

The text in lines 367-368 has been extended:

The spatial grid step was set to 12 m in the channel and 30 m in the lake, based on sensitivity experiments with different grid sizes. Both basins used a linear friction coefficient of $R = 10^{-4}$ s^{-1} that ensured reasonable amplification coefficients (mostly less than 10) at resonant periods.

* The manuscript does not clearly indicate whether the model was calibrated and/or validated against observations. Additional information is needed to assess the reliability of the numerical results.

Reply

We did not intend to conduct a channel dynamics simulation, which would be an interesting but labor-intensive study in its own right. Instead, our aim was to interpret interesting observational findings using simple theoretical approaches. The comment has been addressed in Reply /2/ as:

In this interpretation study, detailed consideration of topography and coastline, which could create multiple hydrodynamic effects, was deferred to future studies.

* The statement that oscillations did not propagate significantly into the lake requires further explanation. The authors should clarify whether this behavior reflects physical processes or numerical limitations.

Reply

In lines 359-362, the text has been modified as:

For the oscillation periods of the forcing at 66 min (peak P7 in Table 2) and 24 min (peak P11), the water-level signal was initially confined within the channel. It did not propagate significantly into the lake from initial (Figs. 11a and 11b) to the saturated phase (Figs. 11c and 11d). The numerical setup was adopted from Exp. 7; these periods were found to be peaks in the observations but were not resonant in the model (Fig. 10) within the limits of the selected setup, due to limitations of the model.

Minor Comments:

1. Instrumentation: Please provide additional technical specifications of the Hydromast instruments, including sampling frequency, blanking distance, number of measurement cells, and other relevant parameters.

Reply

The Hydromast working principle has been described in detail by Egerer et al. (2024). We have added some details to clarify the main technical aspects. The blanking distance and number of measurement cells are specific to acoustic measurement devices and not relevant here. The sampling frequency is specified in line 129.

The text has been extended starting from line 107:

The Hydromast is a flow-monitoring device that uses a 3D Hall-effect sensor to measure direction and velocity at a fixed point. The Hydromast operates via a positively buoyant mast connected to a flexible membrane, allowing it to respond freely to the surrounding flow. The instantaneous mast deflection is measured using a 3D Hall-effect sensor, from which current velocity and direction are determined. In addition, it is equipped with absolute pressure and temperature sensors. These devices have been shown to provide accurate measurements across various marine applications (Egerer et al., 2025; Eelsalu et al., 2025).

2. Velocity measurement range: The statement that the instruments provide reliable velocity estimates in the range of 0.06–0.6 m s^{-1} appears inconsistent with reported current velocities reaching 0.8 m s^{-1}. Please clarify the instrument limitations and the uncertainty associated with measurements exceeding the nominal range.

Reply

The Hydromast devices with a mast length of 500 mm were used at all three sites, providing validated velocity estimates ranging from 0.06 m s^{-1} to 0.6 m s^{-1}. In this study, occasional current velocities reached approximately 0.8 m s^{-1}, which are within the Hydromast's operating range but exceed the range covered by the published validation in (Egerer et al., 2025).

3. Current direction convention: The sign convention for current velocity should be explicitly defined in both the text and the figure captions (e.g., positive and negative flow directions).

Reply

Explanations have been added.

4. River inflows: Please indicate whether significant river inflows enter Varna Lake and discuss their potential influence on the lake–channel system. Although likely negligible at sub-hourly timescales, river discharge may contribute to seasonal water-level gradients and extreme conditions.

Reply

We have included a note on river discharge, salinity, and Knudsen budget in Reply /1/

5. Operational thresholds: The discussion of current velocities reaching 0.8 m s^{-1} would benefit from comparison with existing navigation or harbor-operation criteria, if such standards or guidelines exist. This would help quantify the practical significance of the reported events.

Reply

The explanation has been added to the discussion after line 446:

High-speed current events may be harmful for shipping and harbor operations, but so far no published operational limits have been identified for the Port of Varna. Navigation restrictions at the port are primarily based on vessel characteristics and environmental conditions, such as wind and visibility, with maneuvering decisions made by the Harbor Master and Traffic Control based on prevailing conditions. Therefore, the observed peak current velocities are reported as hydrodynamic observations rather than compared with fixed operational thresholds.

Jüri Elken, 10 July 2026