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

Author's Reply to Anonymous Referee #1

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.

RC1: 'Comment on egusphere-2026-1731', Anonymous Referee #1, 03 May 2026

This paper presents a good and worthy study of sub-hourly sea-level oscillations and currents along channels in Varna Bay. The study implements novel data, measured with novel instruments alongside existing data. Furthermore, it studies the system via analytic and numeric methods proving the characteristics of specific events of interest. It highlights the importance of these sub-hourly oscillations and presents a theoretical framework for future prediction system.

Although the study looks valuable, some issues need to be addressed before the final decision on publication is made. Most are only of technical nature. I attach the pdf file with my in-text comments for various parts of the manuscript. Below I add my general comments which you can find scattered around the pdf as well. Because some comments will likely need a change in Figure, or change in some parts of paragraphs, I propose major revision.

Comment
Before the comments I want to make clear that if you disagree with any comment or my comment is just wrong, just say it and I will accept that. For most of the in-text comments I just need an explanation on why something is done a certain way.

> **Reply**
> All the comments are useful, and we have replied to them all.

Comment
First bigger comment is regarding Figures. I don't know why, but most, if not all, Figures have really low quality. Maybe that is the rendering which is made after your submission and you have uploaded higher quality Figures, I don't know but that should be changed.

> **Reply**
> High-resolution figures have been prepared, and they will be submitted as separate graphic files in the final submission.

Comment
Additionally, a lot of Figures have really small font values and are hard to read, if not impossible.

> **Reply**
> To improve readability, the font sizes have been increased.

Comment
Furthermore, most Figures have titles for subplots which are not needed if the y-axis says the same thing or the caption in good clarity. On top of that, a lot of times x-axis is shared between subplots

which can be the reason to omit ticks on some subplots and leave them only on the bottom ones for creating extra space.

> **Reply**
> The figures have been redrawn following the recommendation and **added at the end of this reply.**

Comment
The spaces between subplots are also large for most Figures. It is better to name subplot as follows: (a) than caption for (a); (b) than caption for (b). Not stating the caption and at the end the letter of the subplot.

> **Reply**
> The figures have been redrawn following the recommendation.

Comment
Link for the data repository is not working. I do not know if that an error from my side or is it wrong.

> **Reply**
> The link works, but in PDF format, the submitted link had a hyphen, which some browsers interpreted as incomplete; only the text before the hyphen was included in the link. Formatting will be checked in the page proof stage. The reformatted working link is https://doi.org/10.48726/86pjq-fpm96

Inline comments in the text, referenced by line numbers

L52-54: Is this more suited for Acknowledgments.

> **Reply:** The sentence “The program was motivated and supported by the ILIAD project (https://iliad-project.eu/) and contributed to the Digital Twins of the Ocean” has been deleted. The new text is:
>
> *Among the applications of these new methods, we note the first presentation of the Varna Port Case Study (Egerer et al., 2025), which used Hydromast observations to study the hydrodynamic patterns in the area.*

L60: Sometimes you write "sea-level" sometimes "sea level". The version "sea level" can be used when it is a noun and "Sea-level" when it is an adjective form.

> **Reply:** We followed the recommendation and checked the spelling.

L91-92: Why is there no Channel 2? Maybe a strange question, but it seems a little bit odd that they are numerated 1 and 3 without the number 2?

> **Reply:** The names of excavated channels and other navigational facilities were assigned during their development. The revised text, to replace the lines 91-93, reads:
>
> *The northern channel (Channel 3, also known as the Old Canal) is older (commenced in 1906) and narrower. It serves multiple terminals in Port Varna - East, including Multipurpose terminal Odesos PBM - Varna, and plays a crucial role in managing large-ship traffic. The southern channel (Channel 1) is newer (1976) and wider, and is the main waterway connection between the Black Sea’s Varna Bay and Lake Varna. The Channel 2 connects Lake*

Varna to Lake Beloslav and forms the primary connection between the Black Sea and the Port of Varna – West connection.

L96-99: This is maybe better suited for the Introduction to give the reader a clearer picture of your interest, but I leave this to the authors to make the final decision.

Reply: The text has been reformulated and moved to the introduction. From line 55, the revised text is:

The purpose of this work is to gain a better understanding of flow dynamics in channels to aid pilots in navigating ships, with a long-term goal of predicting strong flows and promptly informing pilots of changing currents. The study was designed to advance knowledge of water movement patterns, which could support port management and navigation safety and contribute to environmental impact assessments. The study aims to explore events with high current speeds associated with resonant sub-hourly sea-level dynamics in the harbor system comprising a sea bay and narrow channels connecting to the upstream lake and river. The study uses the same data from the Varna Harbor area as analyzed by Egerer et al. (2025).

L102-104 (Figure 1): What does PBM and RK stand for in the subplot (c)? Is the date for last visit the link in the caption needed here?

Reply: The caption of Figure 1 is extended to note that the observations shown in the subplot (c) are presented in Table 1. Regarding the link https://marine.copernicus.eu/ we think it is not necessary to present the date of the last visit, since we do not present any sub-link to the parts of the Copernicus Marine Service, which is a permanent activity.

The revised figure caption is:

Figure 1. (a) Location of the study area, shown on the map of the Black Sea. The western coastal stations where data are shared within the Copernicus Marine Service https://marine.copernicus.eu/ are indicated on the map. (b) Map of the Varna region. (c) Map of the study area displaying the locations of the observation sites. Details of observation points are given in Table 1.

L123-125 (Table 1): How? Didn't you say that Stn. 3 began work on the 6th of March which is later than 18th of February? So, from 18 February until 6 March Stn. 3 was not in function.

Reply: The sentence has been reformulated from “Although the data collection period for different sensors was longer across all three datasets, this paper considers the three months from 18 February to 18 May 2025, as this period coincides with the continuous measurement period across all devices.” to a new formulation:

Among the datasets with different lengths and gaps, the three-month period from 18 February to 18 May 2025 was selected for the data analysis.

L136: It would look better if the eq. is centered.

Reply: The equations were formatted according to the template given by the Copernicus editorial board. We expect that during final typesetting, the editorial team will make arrangements in accordance with the publisher's accepted style guidelines.

L154-156: Although this is a known method, it would benefit the paper if there was an extra sentence or two just explaining a little bit more about coherence since it is talked about and directly presented in Fig. 5. Like, what coherence = 1 means.

Reply: The text has been extended. Revised text starting from line 154 is:

In addition, a comparison between pairs of stations in the frequency domain was performed using coherence analysis. The comparison included coherence calculations between all stations using 5-day segments and a 2-day overlap. Coherence quantifies the strength of the linear relationship between two time series as a function of frequency. Its values range from 0 to 1, where values close to 1 indicate a similar variability at a given frequency, while values close to 0 indicate little or no linear relationship. Hence, high coherence suggests that the stations are responding to the same physical forcing at a given timescale.

L157-158: Is this a bit redundant and maybe wrongly placed.

Reply: We understand that this justification is not easily readable, and we have reformulated: from "Consideration of sub-hourly data revealed events of increased variability of currents and water level, which will be identified in sub-section 3.2 and analyzed in 3.4. A monthly spectrogram covering the dominating events was generated" to a new formulation.

Sub-hourly variations were analyzed using a monthly spectrogram over a period that covered the intense sub-hourly events.

L172-173 (Figure 2): From which station are the measurements in pane (a) and (b)? Why are only Stn. 1 and Stn. 3 presented in (d) and not Stn. 2? Also, there is no need to write the x-label at all subplots since they have the same x-axis, this will save some space. Furthermore, I don't know if the figures are of good quality since inserted into the text, they seem a little bit blurry but that can be the result of rendering. This, and also other, Figures have a secondary x-axis, which means in MATLAB, that the year is lower than the ticks. This is not the problem when everything is clear, but since you have 4 subplots here the extra space, that you would save if you turned off the x-axis labels for all but the last subplot is large. Ticks can be switched off because you have the same x-axis for all plots.

Reply: We have redrawn the figure as recommended. Regarding Stn. 2, the data showed similar general current-velocity patterns to Stn. 1 and 3, but it is not included in panel (d) because the current-velocity measurements at times exhibited drift and were considered less representative of the channel flow. This was most likely due to mechanical and/or magnetic disturbances at the sensor location. To avoid over-interpreting measurements with potentially more uncertainty, only the results from Stn 1 and 3 are presented for the velocity. The figure caption was reformulated to:

Figure 2. Time series of meteorological and oceanographic data with 1-hour resolution. (a) Air temperature and air pressure, (b) zonal and meridional components of wind speed, (c) water level and (d) along-channel current speed (positive from lake to sea). Data from RK Varna (a, b), stations from Stn. 0 to Stn. 3 (c), and Stn. 1 and Stn. 3 (d).

L176: Which subplot?

Reply: All the subplots in Fig. 2 used filtered data. Their recording interval was less than 1 hour.

L190: "Water-level" or "water level"? You use both styles.

Reply: We follow the recommendation for “sea level” and check the spelling of “water level” in a similar way.

L202-204: Say that this data is not shown.

Reply: We inserted the proposed correction.

L205: Maybe add some figure, or subplot with the directions so that it is easier to follow.

Reply: We avoided adding more figures or subplots. We have added a sentence in line 204 for easier reading:

Looking from the lake downstream towards the sea (Fig. 1c), Channel 3 is oriented along 130° (geographical direction of currents) near the lake (Stn. 3) and along 110° near the sea (Stn. 1); landward directions are 310° and 290°, respectively.

In lines 206 and 207, mathematical directions 20° and 40° were replaced with the geographical directions 110° and 130°, respectively.

L212-214: I don't know what to make of this statement that looks like a conclusion and does not in any way help the reader. This would be redundant. If you want to specify what each section contains, I propose the end of the Introduction. You already have that paragraph, just, if you feel the need, enlarge it.

Reply: This paragraph has been deleted.

L216: What does this word mean in the context of 1-min data?

Reply: The word “instantaneous 1-minute time series” was replaced by “high-frequency 1-minute time series”

L220: What exactly was the background?

Reply: The sentence “The sub-hourly intensity of scalar current speed and water level had a background of 0.03 m s-1 and 0.03 m, respectively (Fig. 3a).” was reformulated to:

Average of the sub-hourly standard deviations (background) of scalar current speed and water level, calculated over a 1-h interval, had values of 0.03 m s-1 and 0.03 m, respectively (Fig. 3a).

L241 (Figure 3): Same for x-label as before and for the titles of subplots…

Reply: We have redrawn the figure as recommended.

L257-258 (Figure 4): It would be clearer to note (a) than say what is presented in (a), than (b) and than what is presented in (b) not the caption first and letter of the subplot later. Also, the size of the font is really small. The y-label is not readable.

Reply: We have redrawn the figure as recommended and have rewritten the figure caption.

Figure 4. (a) PSD of water level at the four measurement sites of the channel in the range of periods from 2 min to 15 h using a 6-day Welch segment. (b) PSD for periods from 2 min to 1 h, computed using a 1-day Welch segment length to better resolve higher-frequency variability.

L261: Why was specifically Stn. 1 chosen and not any other station?

Reply: Water levels at all stations were well correlated, especially over longer periods (lines 225-228); therefore, we considered it sufficient to present an example from a single station. The revised text is:

Further insight into the time-dependent character of oscillation amplitudes was gained through spectrogram analysis, which used the short-time Fourier transform (STFT) with a 12 h window and 6 h overlap over successive segments. A spectrogram example is given in Fig. 6 based on data from Stn. 1.

L283-284: Why is this of any importance?

Reply: The sentence "A short pulse of strong southerly wind occurred 4 days before the event." was reformulated to:

Regarding possible mechanisms of wind forcing (local, remote, resonant), we note that a short pulse of strong southerly wind occurred 4 days before the event.

L290 (Figure 6): The titles of the subplots seem redundant since everything is explained in the caption - the titles only add more clutter to the plot. Everything else is the same as for most other Figures... small font, etc.

Reply: We have redrawn the figure as recommended.

L320 (Figure 9): Very poor quality of Figure 9. X-axis is very bad, in some instances the ticks overlap - last row of the Figure. There is also a lot of empty space between subplots.

Reply: We have redrawn the figure as recommended.

L341: What does this mean? Were the Channels 1 and 3 simulated via 1 channel with width equal to the sums of widths or just one channel was used in the simulation which whose results can be used in both Channel 1 and Channel 3?

Reply: The sentence "The two channels (Channels 1 and 3), approximately the same length and depth, were merged into a single channel by summing their widths." was reformulated to:

The two channels (Channels 1 and 3), approximately the same length and depth, were modeled as a single channel by summing their widths.

L361: Eq. A4

Reply: Corrected.

L397 (Figure 11): Where is the colorbar?

Reply: The colorbar has been added.

L404: What about the tide gauges that can be seen in Fig. 1a (Igne and Constanta)? Why weren't they used?

Reply: From Igne and Constanta, only hourly data were available; therefore, they were not used for the sub-hourly dynamics. The revised text is:

Sub-hourly forcing data were not available over the larger Varna Bay area, including the adjacent Black Sea stations Igne and Constanta (Fig. 1); therefore, simulation and forecast studies were not conducted.

L414: It is "Teng and Wu, 1992" not Fu.

Reply: The reference has been corrected.

L487: It would be better if the equation was centered. This is a general comment for all of the equations in the Appendix.

Reply: The equations were formatted according to the template given by the Copernicus editorial board. We expect that during final typesetting, the editorial team will make arrangements in accordance with the publisher's accepted style guidelines.

L504: If T0 = 4L/sqrt(gH) and we know that T0 = Lambda0/sqrt(gh), should it be written than, in the earlier equation, Lambda0 = 4L? And not Lambda_n = L/4?

Reply: There was a typing error in the quarter-wavelength. Thank you for finding that. Correct formula in line 503 is Lambda_0/4 = L.

L540: The link is not working for me. I do not know if the problem is at my end or you have written a bad link?

Reply: The link works, but in PDF format, the submitted link had a hyphen, which some browsers interpreted as incomplete; only the text before the hyphen was included in the link. Formatting will be checked in the final submission.

L588-589: The references for Egerer show be switched since the first needs to be the one from 2024 if I'm not mistaken.

Reply: The sequence of references has been corrected. Other similar sequence cases were corrected as well.

L628: This reference is not cited in the text.

Reply: The reference was cited in the earlier version of the text, in the part that is now omitted. Since it is no longer cited, the reference is deleted.

L630: This reference is not cited in the paper? Or am I overseeing it?

Reply: The reference was cited in an earlier version of the text, in the part now omitted. Since it is no longer cited, the reference is deleted.

Jüri Elken 10 July 2026

Updated figures

Fig01

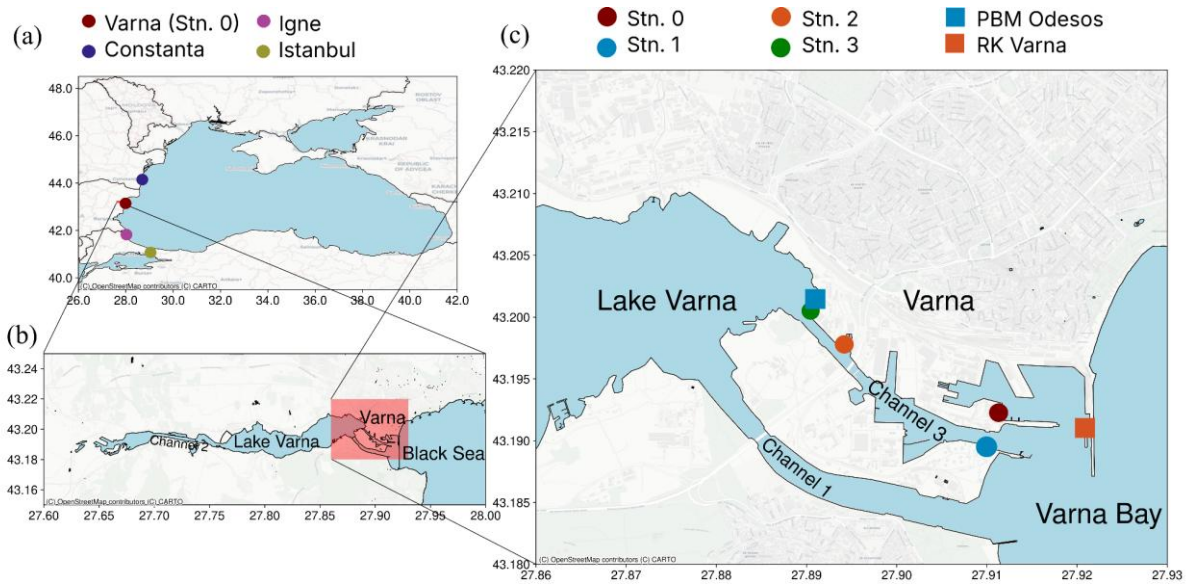


Fig02

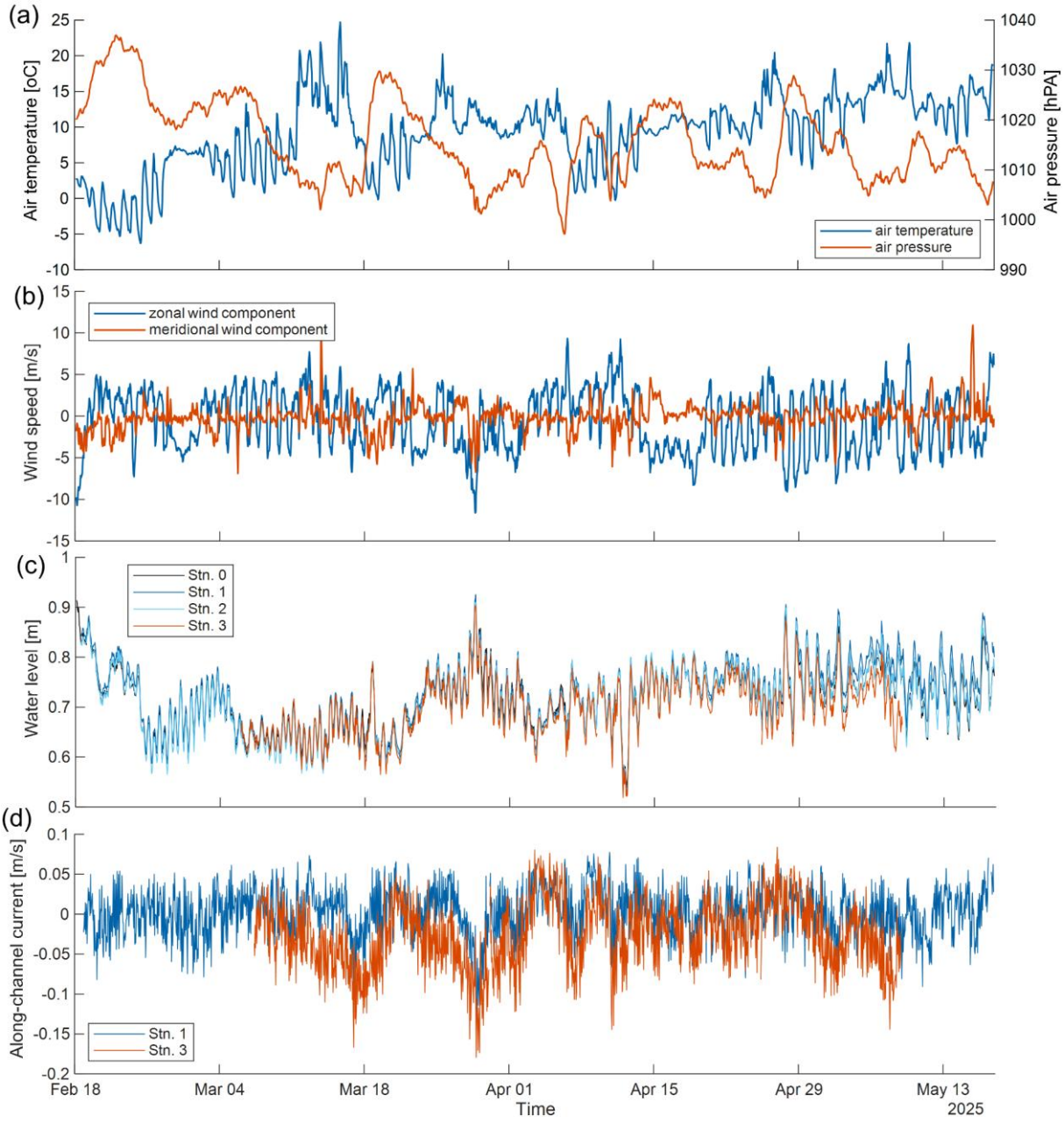

(a)
Air temperature [oC]
Air pressure [hPA]
air temperature
air pressure
(b)
Wind speed [m/s]
zonal wind component
meridional wind component
(c)
Water level [m]
Stn. 0
Stn. 1
Stn. 2
Stn. 3
(d)
Along-channel current [m/s]
Stn. 1
Stn. 3
Feb 18
Mar 04
Mar 18
Apr 01
Apr 15
Apr 29
May 13
Time
2025

Fig03

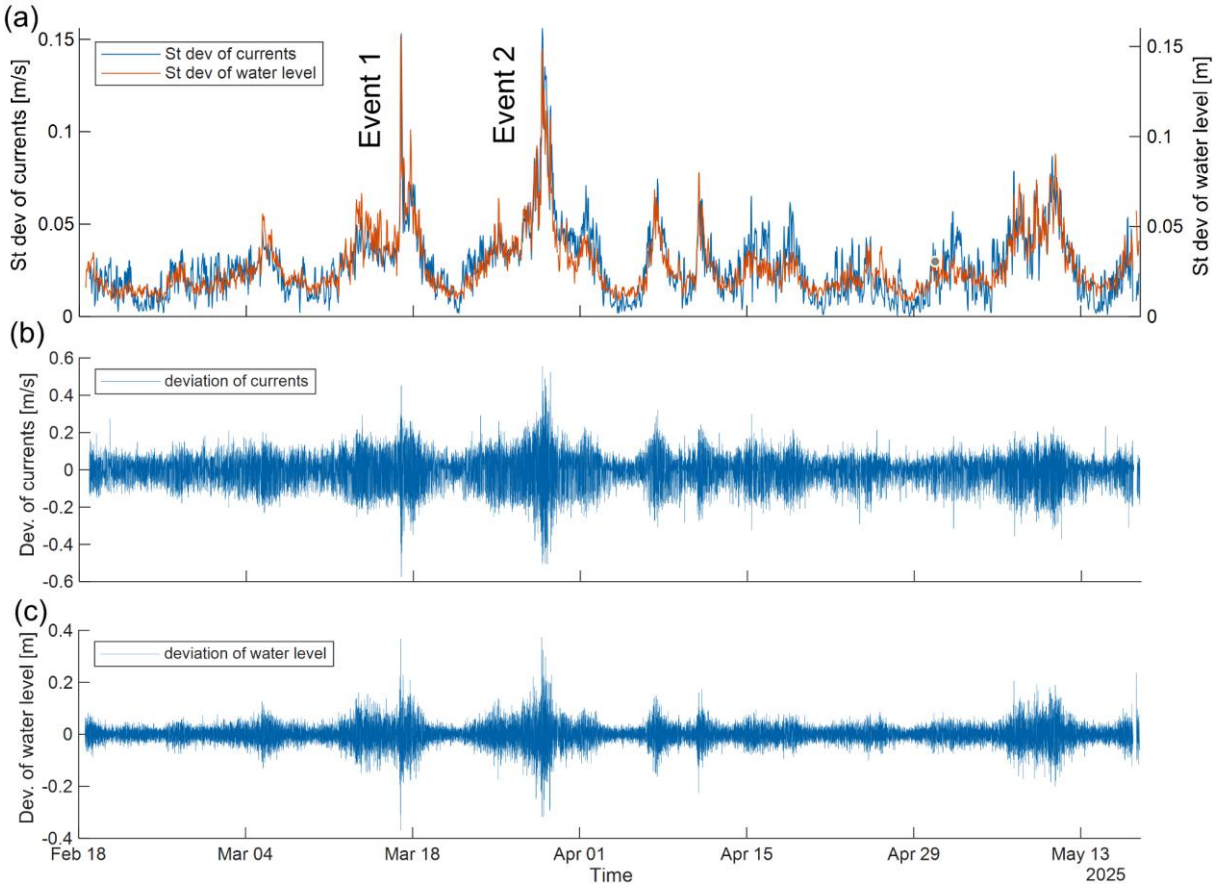

(a)
St dev of currents
St dev of water level
Event 1
Event 2
St dev of currents [m/s]
St dev of water level [m]
0.15
0.1
0.05
0
(b)
deviation of currents
Dev. of currents [m/s]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
(c)
deviation of water level
Dev. of water level [m]
0.4
0.2
0
-0.2
-0.4
Feb 18
Mar 04
Mar 18
Apr 01
Apr 15
Apr 29
May 13
2025
Time

Fig04

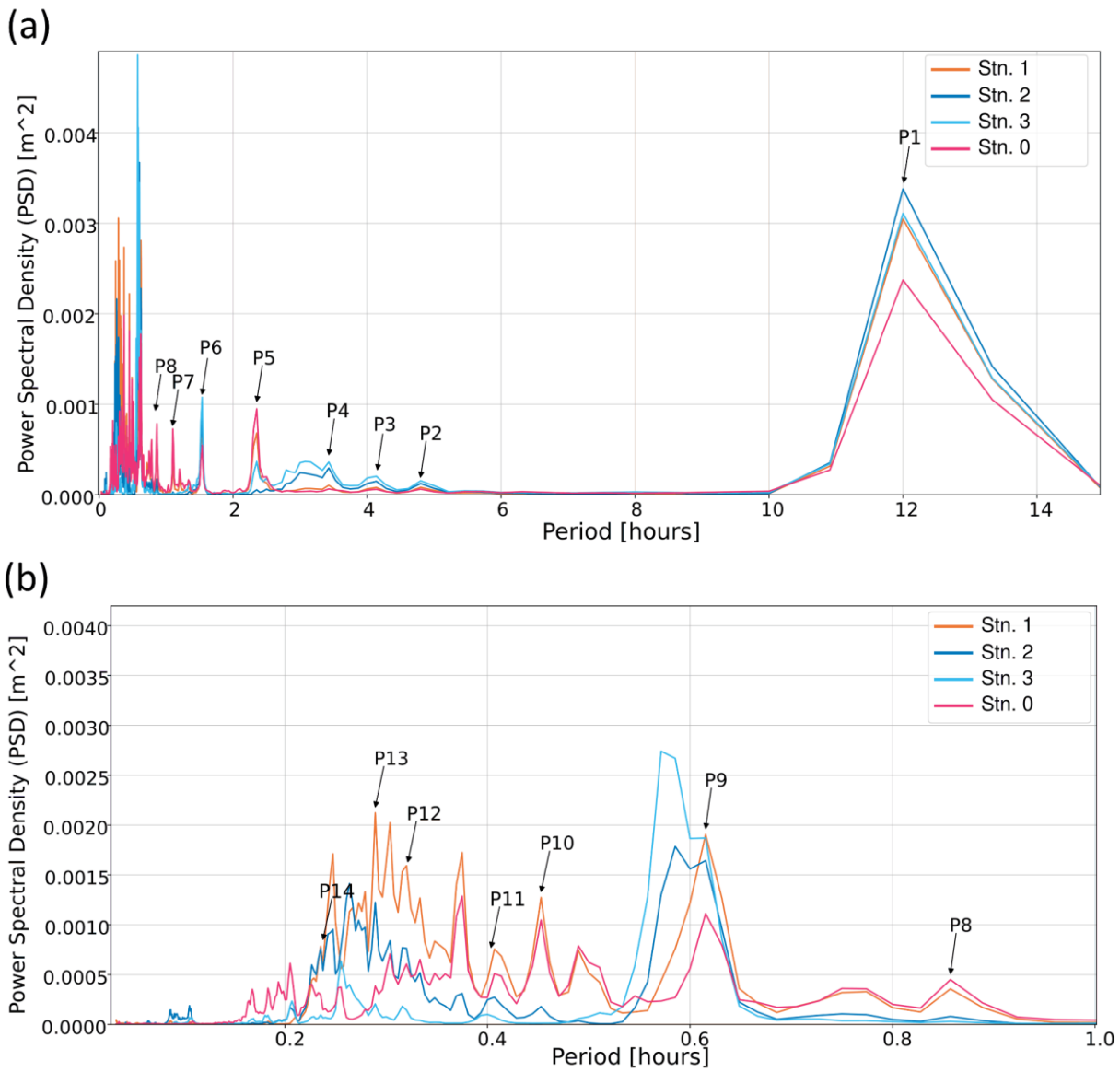

(a)
Power Spectral Density (PSD) [m^2]
Period [hours]
Stn. 1
Stn. 2
Stn. 3
Stn. 0
P1
P2
P3
P4
P5
P6
P7
P8
(b)
Power Spectral Density (PSD) [m^2]
Period [hours]
Stn. 1
Stn. 2
Stn. 3
Stn. 0
P8
P9
P10
P11
P12
P13
P14

Fig05

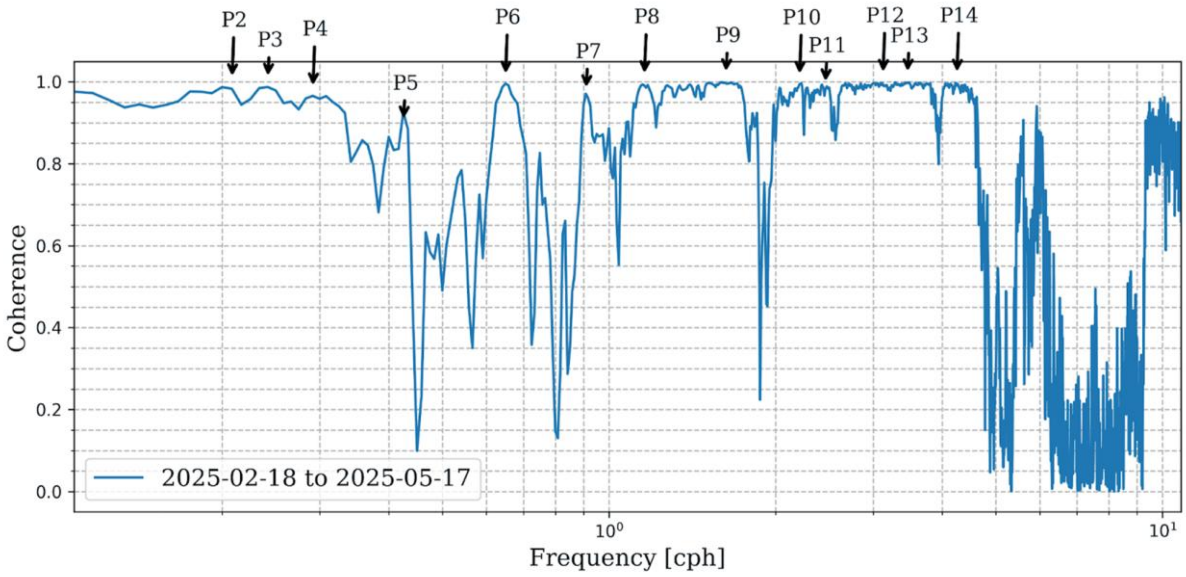

P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
Coherence
1.0
0.8
0.6
0.4
0.2
0.0
2025-02-18 to 2025-05-17
10^0
10^1
Frequency [cph]

Fig06

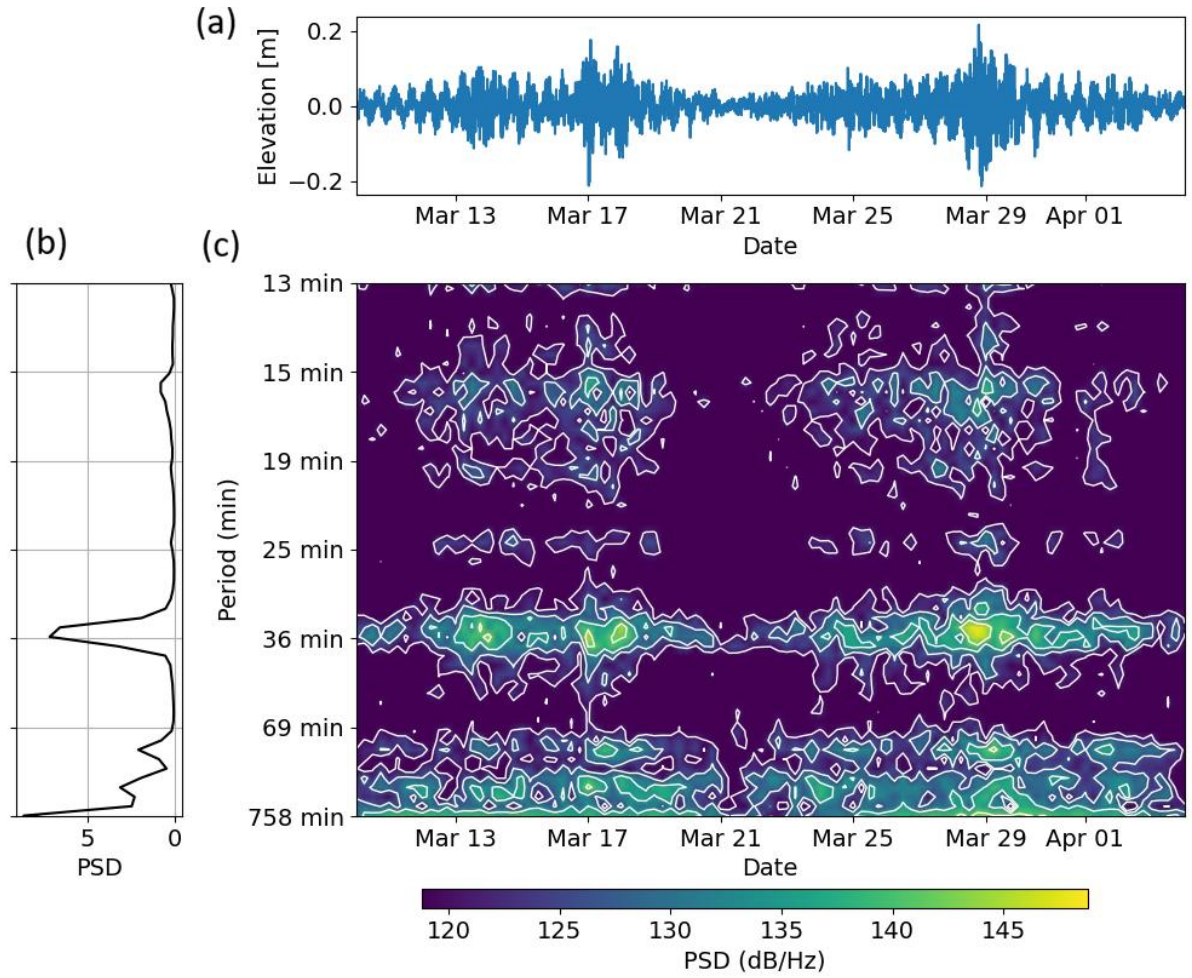

(a)
Elevation [m]
0.2
0.0
−0.2
Mar 13
Mar 17
Mar 21
Mar 25
Mar 29
Apr 01
Date
(b)
5
0
PSD
(c)
13 min
15 min
19 min
25 min
36 min
69 min
758 min
Period (min)
Mar 13
Mar 17
Mar 21
Mar 25
Mar 29
Apr 01
Date
120
125
130
135
140
145
PSD (dB/Hz)

Fig07

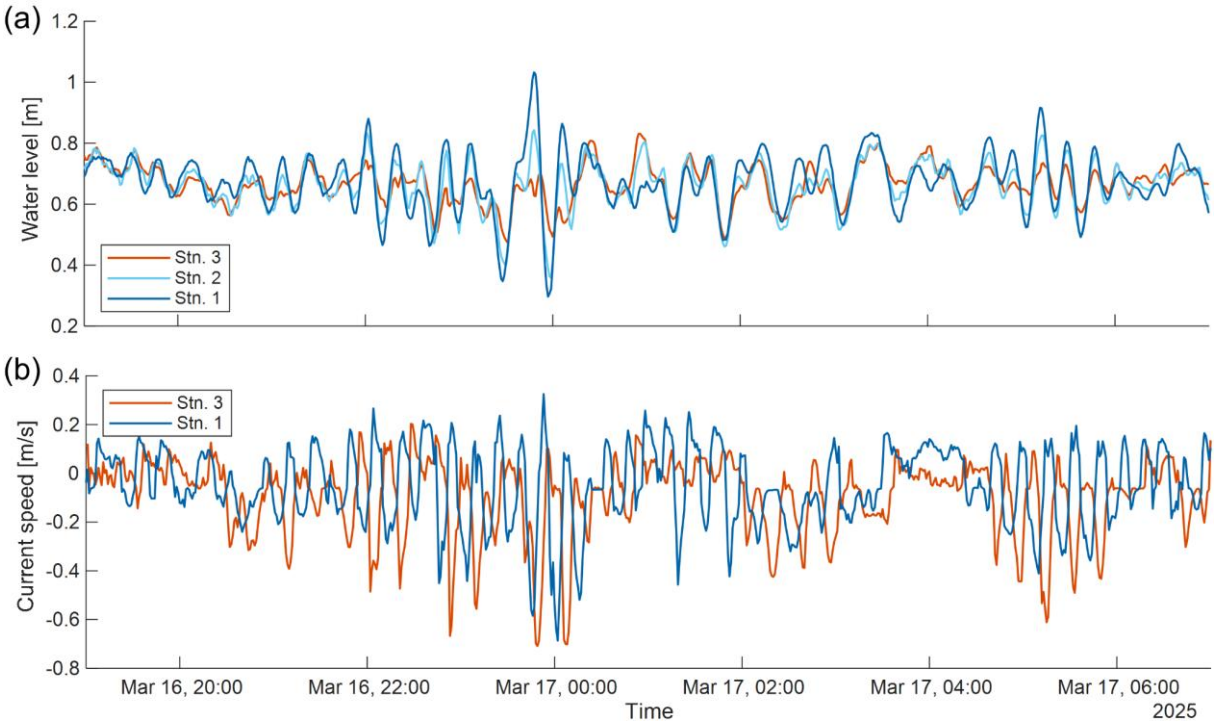

(a)
Water level [m]
1.2
1
0.8
0.6
0.4
0.2
Stn. 3
Stn. 2
Stn. 1
(b)
Current speed [m/s]
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Stn. 3
Stn. 1
Mar 16, 20:00
Mar 16, 22:00
Mar 17, 00:00
Mar 17, 02:00
Mar 17, 04:00
Mar 17, 06:00
Time
2025

Fig08

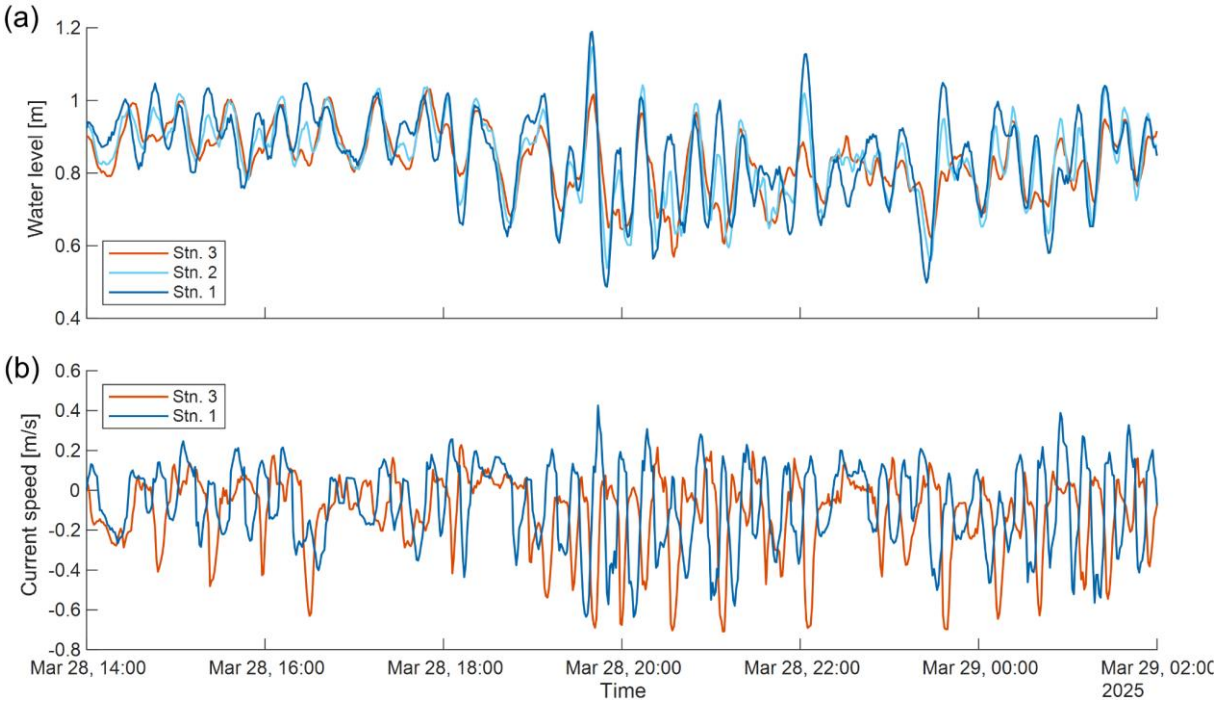

(a)
Water level [m]
1.2
1
0.8
0.6
0.4
Stn. 3
Stn. 2
Stn. 1
(b)
Current speed [m/s]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Stn. 3
Stn. 1
Mar 28, 14:00
Mar 28, 16:00
Mar 28, 18:00
Mar 28, 20:00
Mar 28, 22:00
Mar 29, 00:00
Mar 29, 02:00
Time
2025

Fig09

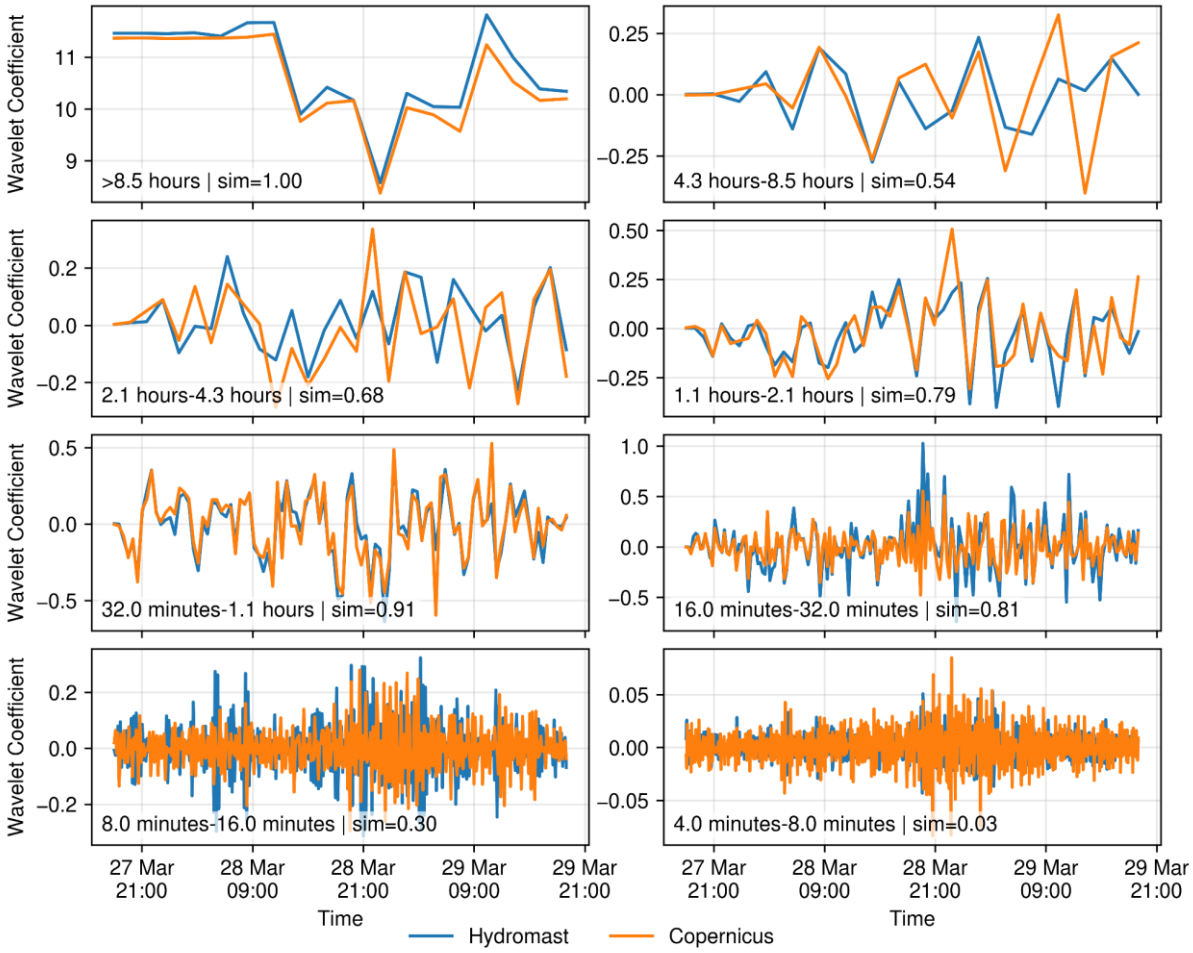

Wavelet Coefficient
>8.5 hours | sim=1.00
4.3 hours-8.5 hours | sim=0.54
2.1 hours-4.3 hours | sim=0.68
1.1 hours-2.1 hours | sim=0.79
32.0 minutes-1.1 hours | sim=0.91
16.0 minutes-32.0 minutes | sim=0.81
8.0 minutes-16.0 minutes | sim=0.30
4.0 minutes-8.0 minutes | sim=0.03
27 Mar 21:00
28 Mar 09:00
28 Mar 21:00
29 Mar 09:00
29 Mar 21:00
Time
Hydromast
Copernicus

Fig10

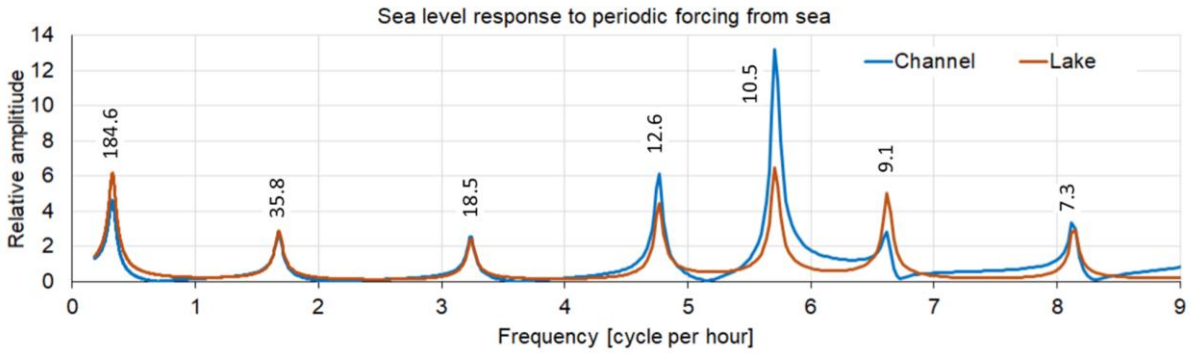
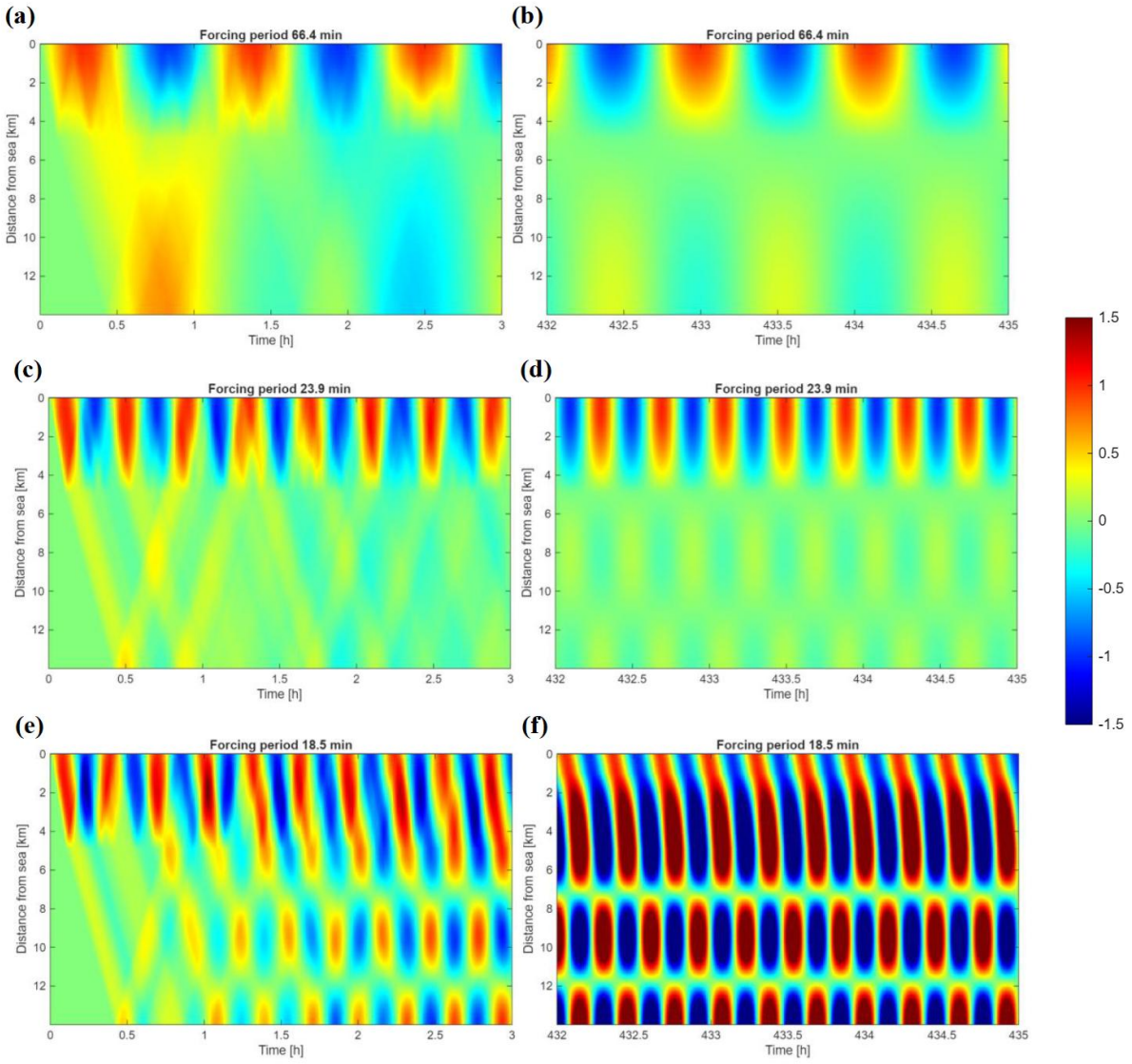

Sea level response to periodic forcing from sea
Channel
Lake
Relative amplitiude
Frequency [cycle per hour]
184.6
35.8
18.5
12.6
10.5
9.1
7.3
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6
7
8
9

Fig11


(a)
Forcing period 66.4 min
(b)
Forcing period 66.4 min
(c)
Forcing period 23.9 min
(d)
Forcing period 23.9 min
(e)
Forcing period 18.5 min
(f)
Forcing period 18.5 min
Distance from sea [km]
Time [h]
1.5
1
0.5
0
-0.5
-1
-1.5

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: ORDERNº 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).

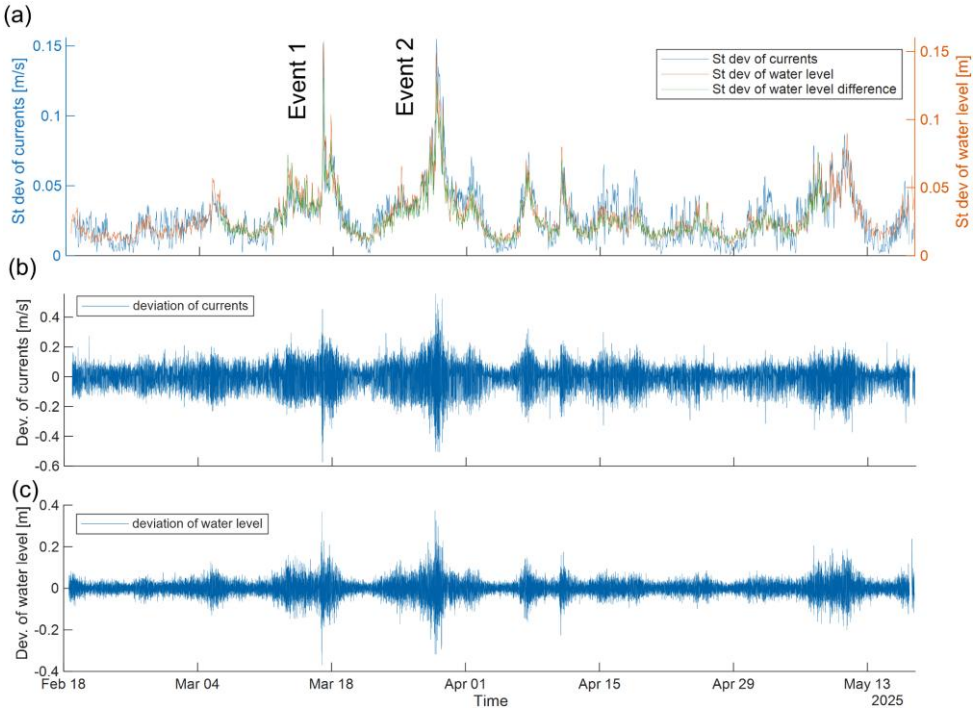


Figure 3 alternative version, not included in the MS.

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