Hidden Heat: The case of 2023 Gulf of Trieste Bottom Marine Heatwave

We thank the Editor and the reviewers for their time and constructive comments, which helped us improve the paper. We reduced the number of figures in the main text in line with both reviewers' recommendations and added an Appendix section containing information that was not essential for the general reading of the paper but may be of interest for some readers. We address the reviewers' comments below with our responses written in blue.

Response to Reviewer 1:

Comment on egusphere-2026-2567', Anonymous Referee #1, 29 Jun 2026

This paper presents in situ observations of a bottom marine heatwave (BMHW), based on a 22-year long temperature, salinity and wind record from the Vida buoy in the Gulf of Trieste, complemented by nested high-resolution MITgcm simulations of the 2023 event. The authors show that an extreme summer 2023 BMHW (up to 4.3°C above the long-term average, lasting over three months) developed concomitantly to only moderate surface warming, and attribute this to a salinity increase that weakened the stratification enough to let mixing by wind reach the seafloor. The combination of a rare two-decade in situ bottom record with a high-resolution, non-assimilative regional model, strengthen the interpretation and provides a convincing full picture. The resulting dataset is a valuable contribution and show how such in situ records are crucial. The manuscript is well written, the proposed mechanism is convincing, and the results are presented in a notably didactic and honest way, with the authors transparently flagging the approximations in their own analysis.

We thank the reviewer for these encouraging remarks.

I only have three main suggestions:

> The authors propose a back-of-the-envelope approach to calculating the mixed layer depth that they confront to the observed bottom temperature jumps showing good correspondence. I wonder if this approach could be useful to other studies at sites with sparse CTD coverage? and if so, can you make explicit in the text which parameters are indispensable to the method and which others could be added for improvement or as a sanity check.
>
> As mentioned in the text, our approach to MLD calculation (eq. 7) is too simple to be used for exact MLD estimates. Although it shows surprisingly good performance in this case, we have doubts it could be applied more generally with the same success. The entrainment calculation is based on energy transfer (Cushman-Roisin and Beckers, 2011), however, more exact and consistent methods are based on momentum constraint but are far more complex (Umlauf and Burchard, 2005; Large et al., 1994;

Price, 1979). The buoyancy term from Marshall and Schott (1999) is primarily meant for the calculation of MLD deepening, but we used it for shoaling as well. Overall, MLD dynamics is more complex and this term is only approximate. Our simplistic back-of-the-envelope calculation was primarily used to better identify causes and effects.
As our conceptual MLD model is quite simple, we complement it with simulations of MLD dynamics from a numerical model. Modern ocean models (e.g. MITgcm) adopt more realistic approaches and they also include some mechanisms that were not considered in our calculations (such as wind-driven upwelling mentioned by Reviewer 2).

We provide a table of parameters used in eq. 7 and their sources:

Parameter	**Symbol**	**Source**
Wind speed	u_w	Vida buoy
Brunt-Väisälä frequency	N	CTD
Net heat flux	Q_{net}	ERA5
Evaporation	E	ERA5
Precipitation	P	ERA5
Runoff	R	Hydrological station Solkan (Soča / Isonzo) and Dekani (Rižana).
Salinity	S	Vida buoy

The 5-year (2017–2021) MITgcm run used as a “climatological” reference in Sect. 3.2 is considerably shorter than the 22-year in situ record the authors themselves note falls short of the 30-year recommendation for a climatological mean; some discussion of whether 2017–2021 is itself a representative baseline (i.e. not anomalously warm, cold, or dry) would strengthen the comparisons in Figs. 9, 10 and 12.

We added a figure (current Figure B3) in the Appendix showing data from the Copernicus Marine Service Mediterranean Physics Reanalysis. The first and second plots compare the surface and 20 m temperatures in the Gulf for 2022 as well as the five years, from 2017 to 2021, used in the manuscript as reference, against the average, with 5-95th percentile band, over the 1987-2016 period. The last plot is analogous, but for the cumulative water flux over the Gulf. From these comparisons, the reference years (2017-2021) do not appear to be particularly hotter nor drier than the climatological values. Therefore, we can more safely use this short period as a baseline for the following conclusions regarding the 2023 event. Furthermore, Figure B2 (former Figure 6) in the manuscript, showing buoyancy frequency computed from CTD casts, depicts data from 2008 to 2025, and indicates that 2023 was quite exceptional also in this regard.

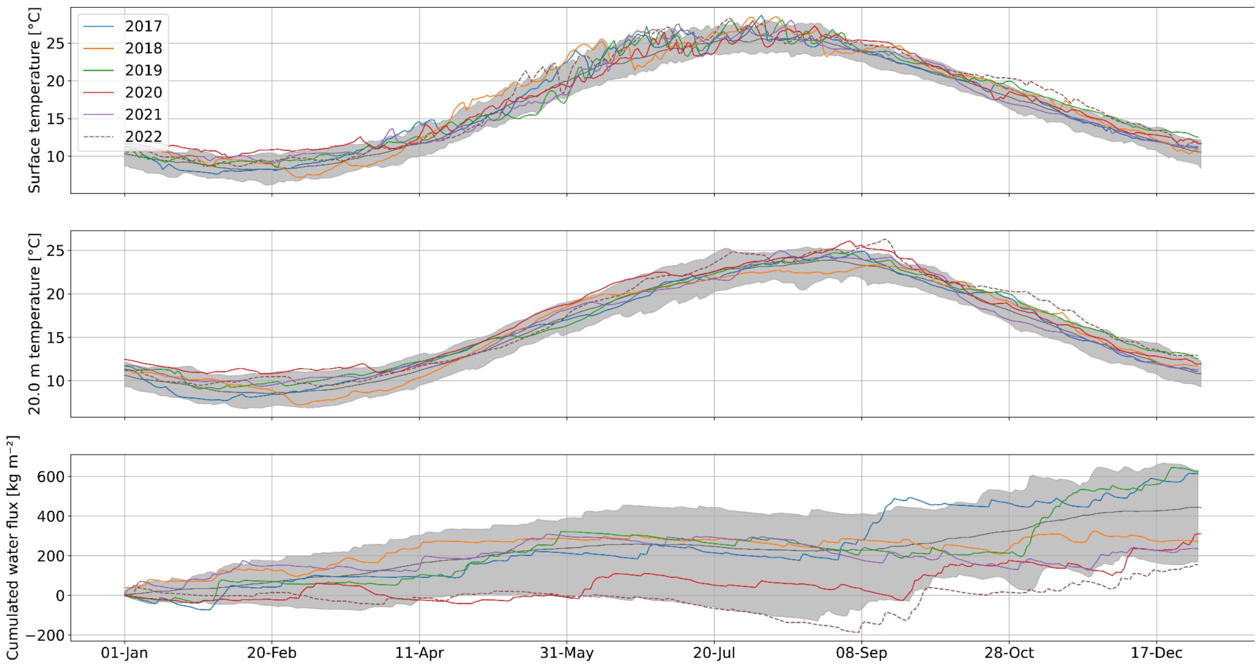


Figure B3: Comparison of surface (top panel) and 20 m deep (middle panel) temperatures and cumulative water flux (bottom panel) from the Copernicus Marine Mediterranean Physics Reanalysis sampled at the model grid cell closest to the Vida buoy location. 5-95th percentile, over the 1987-2016 period, in gray shading; 5-year reference period 2017-2021 (continuous lines) and 2022 (dashed line).

Finally, the explanation of the bottom temperature oscillations between events 2 and 3 in terms of a migrating cyclonic eddy currently rests entirely on the model. If any independent surface signature of this eddy is visible in altimetry (SLA, SST, CHI-A) or HF radar surface currents, even a qualitative comparison would considerably strengthen this part of the argument even though I recognize the Gulf's small scale may be below the resolution of standard gridded SLA products.

Thank you for the suggestion. As the reviewer pointed out, altimetry products (e.g. those provided by the Copernicus Marine Service) usually do not reach resolutions high enough to properly resolve dynamical features in a small basin such as the Gulf of Trieste. However, the HF radar array deployed along the Italian and Slovenian coasts is able to observe sea surface currents at a 1.5 km horizontal resolution. We combined this data with satellite SST to produce a novel figure, reworking former Figure 14. The additional information coming from these observations supports our interpretation, with the eddy footprint visible also at the surface in the HF radar circulation (e.g. first and last frame of the top row of Fig. 11).

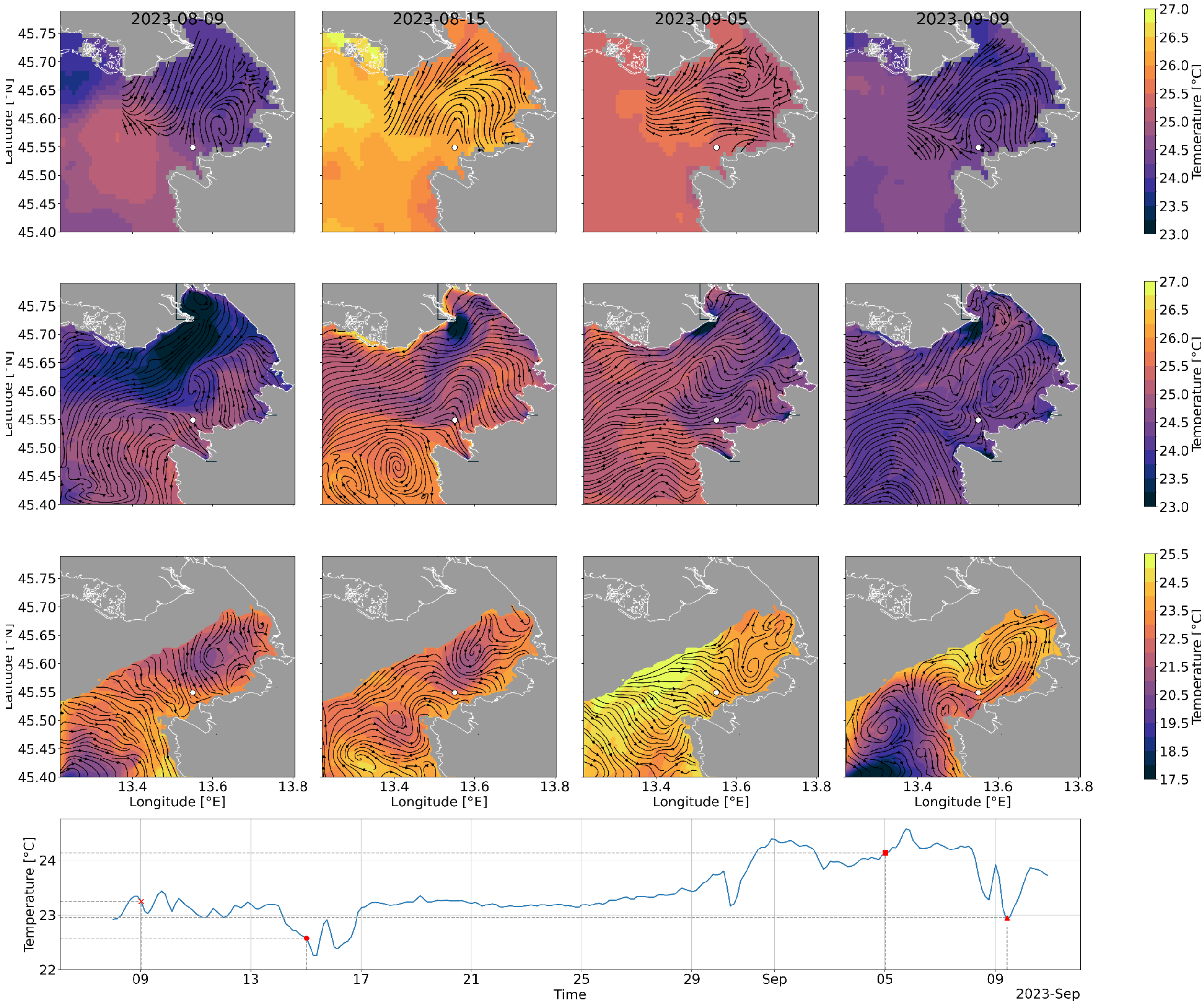


Figure 11: **first row**: satellite surface temperature and HF radar circulation streamlines; **second row:** MITgcm simulation surface temperature and circulation; **third row**: 20 m depth temperature and circulation streamlines from the MITgcm simulation (note that the temperature colorscale is different); **fourth row:** 20 m depth model temperature time series at the Vida buoy location, marked with a white dot.

A list of more specific minor comments is provided below.

- The manuscript would benefit from some consolidation of the figures, of which there are currently fourteen, several of which somehow overlap. Figure 7 (bottom panel) repeats Figure 3 almost exactly and could be removed (the MLD-event ellipses could go on figure 3). In Figure 14, the left-hand size time series panels are duplicates of one another with only the highlighted date changing and could be combined into a single panel, freeing up space to enlarge the corresponding maps. None of this is essential, but given the density of material already in the paper, a more compact set of main-text figures would improve readability. Regarding the figures, captions are not always self-contained, I would suggest the authors to revise captions so that each figure can be understood without reference to the main text.

As suggested by the reviewer, the bottom panel in former Figure 7 (now Figure 5) has been removed and Figure 3 has been modified to include the ellipses. Former Figure 14 (Figure 11 in the revised manuscript) has been changed. The time series panels have been merged into a single panel. The modelled MLD time series from former Figure 11 has been moved to current Figures 7 and 8 (formerly Figures 8 and 9), overlaid with the Hovmöller diagrams, to reduce the load of images in the text. The captions of all figures have been carefully revised to make sure they contain all the necessary information.

- 21–22 and reference list: Gómez-Gras et al. 2021 is cited twice here but appear to only refer to one reference.

Accidentally the LaTeX typesetting system treated Gómez-Gras from both papers as two different persons due to confusion regarding the apostrophe. In fact these are two different papers by the same author, both published in 2021. We overlooked this mistake and thank the reviewer for pointing this out. The error has been corrected in the revised manuscript. The sentence now reads:

“These anomalies are most often referred to with a generic broad term of marine heatwaves (MHWs), and lead to a series of dramatic undesired effects in the ocean, from mass mortality events to shifts in ecosystemic community structures (Garrabou et al., 2022; Gómez-Gras et al., 2021a, b), but can also impact dominant climate modes (Holbrook et al., 2019) and contribute to compound extreme events (Rodrigues et al., 2025; Gruber et al., 2021), such as atmospheric heatwaves and heavy precipitation events, boosting risks of regional flooding and coastal region wildfires.”

Corrected references:

Gómez-Gras, D., Linares, C., Dornelas, M., Madin, J. S., Brambilla, V., Ledoux, J.-B., López-Sendino, P., Bensoussan, N., and Garrabou, J.: Climate change transforms the functional identity of Mediterranean coralligenous assemblages, Ecology Letters, 24, 1038–1051, https://doi.org/https://doi.org/10.1111/ele.13718, 2021a.

Gómez-Gras, D., Linares, C., López-Sanz, À., Amate, R., Ledoux, J.-B., Bensoussan, N., Drap, P., Bianchimani, O., Marschal, C., Torrents, O., Zuberer, F., Cebrian, E., Teixidó, N., Zabala, M., Kipson, S., Kersting, D. K., Montero-Serra, I., Pagès-Escolà, M., Medrano, A., Milani, A., Frleta-Vali´c, M., Dimarchopoulou, D., López-Sendino, P. C., and Garrabou, J.: Population collapse of habitat-forming species in the Mediterranean: A long-term study of gorgonian populations affected by recurrent marine heatwaves, Proceedings of the Royal Society B: Biological Sciences, 288, 20212 384, https://doi.org/10.1098/rspb.2021.2384, 2021b.

- 142: “Ponetalgoscuro” likely a typo for “Pontelagoscuro”.

Corrected.

- Fig. 4 caption: “Blue w lines” appears to be a typographical error.

Corrected.

Response to Reviewer 2:

RC2: 'Comment on egusphere-2026-2567', Anonymous Referee #2, 08 Jul 2026
This manuscript investigates a rare bottom marine heatwave observed in situ at a mooring buoy in 22 m of water in the Gulf of Trieste in 2023. The authors show that the event lasted for more than three months, with bottom temperatures reaching 4.3°C above the 20-year average, and that it was not detectable from satellite or surface observations.
By estimating the mixed layer depth and analysing in situ salinity, precipitation, and runoff, the authors link the bottom marine heatwaves (MHW) to prolonged drought, elevated salinity, weakened stratification, and unusually deep mixing. They also use a model to present spatial maps of the bottom heat anomaly and its spatial extent, and to rule out ocean advection as the primary cause of the bottom MHW.
This study is one of the first to show the role of salinity in stratification and the trapping of bottom heat, and is therefore very valuable. The availability of this long-term dataset is invaluable, and the mechanism identified here is likely important in many coastal areas. The authors provide an interesting estimate of the mixed layer depth from atmospheric forcing and background stratification, which appears to work well despite the limitations, which are clearly stated. The modelling study used to further investigate the generation of the event is also well motivated. However, the manuscript remains very qualitative and descriptive, and misses opportunities to synthesise and complete the story in a more robust way. I therefore recommend major revisions.

We thank the reviewer for appreciating our efforts, recognizing the importance of the presented work, and for the constructive criticism that allowed us to improve the manuscript.

My main concerns are as follows:

1. **The relative roles of the atmospheric forcing terms should be quantified more clearly.** The manuscript argues that drought, evaporation, reduced freshwater input,

elevated salinity, and weakened stratification were central to the development of the bottom MHW. However, the relative contributions of these processes remain mostly qualitative. The authors should quantify, at least approximately, the influence of net heat flux, evaporation, river run-off and precipitation on the mixed layer depth evolution. This should be possible from Equation 7 and would make the proposed mechanism much more convincing. The mixed layer depth estimate is one of the strengths of the manuscript, and it performs surprisingly well when compared with CTD estimates in Figure 7, so I would really like to see it used for a decomposition of terms, which would substantially strengthen the paper. Moreover, you seem to have discarded the potential effect of wind-driven downwelling, can you explain why?

It is true that wind-driven downwelling was not included in the MLD estimate. As mentioned in the manuscript, the eq. 7 is an approximate back-of-the-envelope calculation and the implementation of wind-driven downwelling would be less straightforward. However, the equation performs surprisingly well as is, and therefore we decided that the addition of wind-driven downwelling is not necessary. Indeed, the Gulf of Trieste is an area of very weak winds in the summer (mainly light land-sea breeze), interrupted only by occasional short-lasting wind events.

The question of how much each of the terms contributes to the change in mixed layer depth (MLD) is an interesting one. However, after we started exploring this topic, it turned out that the answer is more complex than it may seem. A plot of all three terms (wind term, heat term and freshwater term) for the year 2023 shows large variability (Figure R1). Furthermore, the MLD is limited by the surface and by the bottom at 22 m depth, so,often, when MLD is close to the limit, change is not possible and the terms (although sometimes large) have no effect.

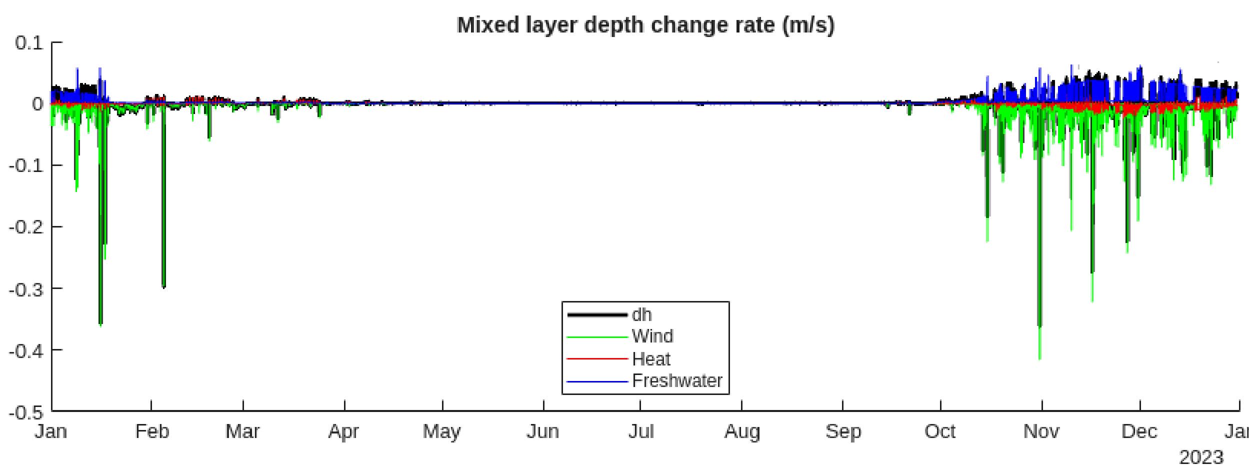


Figure R1. MLD change rate (black) and the contribution of each of the terms in eq. 7 (green - wind, red - heat, blue - freshwater). The z axis is oriented upwards, therefore negative values entail deepening of the MLD.

Due to the low stratification (low N^2), the terms have much larger values in autumn and winter. The wind and freshwater terms dominate in periods of high wind and high freshwater input. We present separate plots for two periods of MLD deepening: beginning of August - start of the BMHW (Figure A1) and beginning of September - time when the bottom temperature matches the surface temperature (Figure A2).

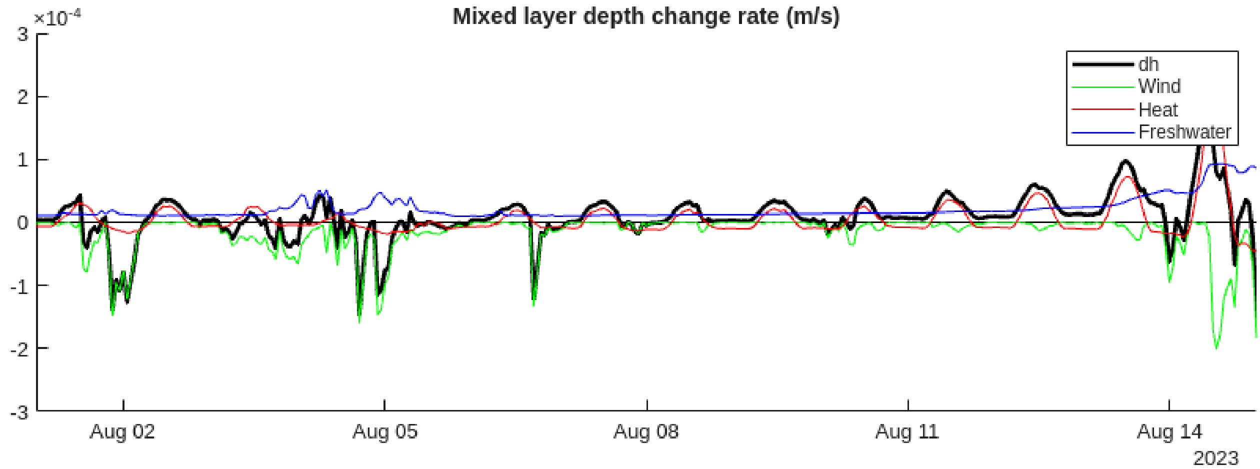


Figure A1. MLD change rate at the beginning of August. The BMHW starts on the 5th of August. MLD change rate (black) and the contribution of each of the terms in eq. 7 (green - wind, red - heat, blue - freshwater). The z axis is upwards,therefore negative values entail deepening of the MLD.

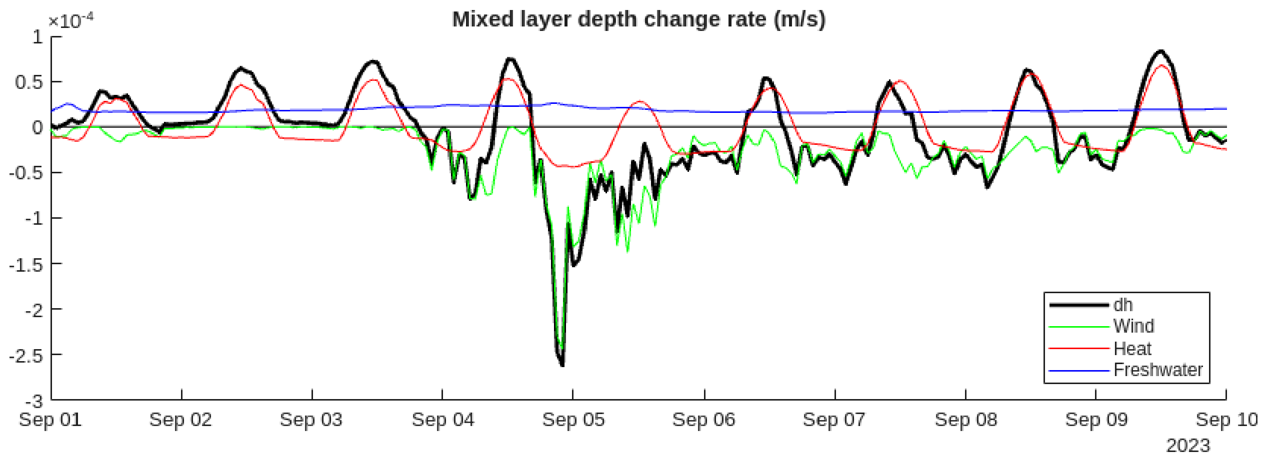


Figure A2. MLD change rate at the beginning of September. The bottom temperature matched the surface temperature on the 6th of September, indicating a fully mixed water column. MLD change rate (black) and the contribution of each of the terms in eq. 7 (green - wind, red - heat, blue - freshwater). The z axis is upwards,therefore negative values entail deepening of the MLD.

In both events we can see that the wind term fully dominated the MLD change in the period prior to the event. On the other hand, the freshwater term is slightly positive all the time, indicating that the freshwater inflow was slightly dominating over evaporation (the Gulf of Trieste is a ROFI region) and constantly shoaling the MLD. The heat budget term oscillates on a daily basis, following heat loss during the night and heat gain during the day. As Figure 7 in the manuscript shows, in the absence of, at least, moderate wind, the sum of the terms is generally positive from May to September 2023. However, during wind events, the wind term dominates and causes deepening of MLD.

Some of this information is already contained in Figure 7 ("Estimated mixed layer depth" - Figure 5 in the revised manuscript). The deepening of MLD coincides with the vertical lines marking the wind events, which shows that the wind is driving the deepening. The difference between the thick red line (calculated MLD) and the thin red line (calculated MLD with increased N^2) confirms that the reduced stratification was the cause for deeper mixing. However, we agree that the question about the contribution of each term is an interesting one and we added the Figures A1 and A2 to the Appendix, accompanied with the following text:

"The eq.7 which was used for MLD estimation consists of three terms: MLD deepening due to wind forcing (u_w), change of MLD due to heat flux (Q_{net}) and change of MLD due to freshwater flux (evaporation E, precipitation P and river runoff R). We present the contribution of each of these terms during two MLD deepening events. Figure A1 shows the MLD change rate at the beginning of August, when the BMHW started (5th of August) and Figure A2 shows the MLD change rate at the beginning of September when the bottom temperature matched the surface temperature (6th of September), indicating a fully mixed water column. The z axis is negative and negative change rates mean deepening of MLD. It can be seen in both figures that the wind-related term (green curve) dominates prior to both events. This supports the claim that the wind caused the deepening of the MLD which resulted in the BMHW. On the other hand, the freshwater term (blue curve) is slightly positive all the time in both plots. The Gulf of Trieste is strongly influenced by substantial river runoff and the freshwater input was dominant over evaporation and was constantly shoaling the MLD. The heat term (red curve) shows negative values during the night (cooling - MLD deepening) and positive values during the day (heating - MLD shoaling). "

2. **The model validation should be quantified.** The model is used to support key conclusions about the spatial extent of the bottom heat anomaly and the processes responsible for its generation. However, the validation currently appears too descriptive. The authors should provide quantitative skill metrics comparing the model with available observations, such as temperature, salinity, and mixed layer depth. Even simple metrics

such as bias, root-mean-square error, correlation, or variance explained would help assess how much confidence can be placed in the model results. This is particularly important because the model is used not only for illustration, but also to support mechanistic interpretation.

The simulation in the reference period (2017-2021), was also used in another work (https://doi.org/10.1016/j.ocemod.2026.102748) which reported a validation of the same model setup against observations of temperature (both from satellite and in situ) and salinity (in situ), showing overall good performances, if compared to, for example, Copernicus modelling products skill.
We added a reference to this work to the main text, and we also reported a table summarising error metrics (bias and root mean square difference); this same table is copied here as well.

Table 1. Summary of the validation for temperature and salinity, compared to different observational sources, for the 2017-2021 northern Adriatic Sea reference run; from Giordano et al. (2026).

	Bias	**RMSD**
Satellite sea surface temperature [°C]	-0.177	0.927
In situ temperature profiles [°C]	0.277	1.654
In situ salinity profiles [ ]	0.965	1.755

3. **A heat budget is ideal to assess the relative roles of advection and air-sea heat fluxes.** The authors argue that ocean advection was not the primary cause of the bottom MHW, but this conclusion is not yet demonstrated robustly. The current descriptive figures are useful but insufficient to separate the effects of local air-sea forcing, vertical mixing, lateral advection, and storage. One of the main advantage of the model in the marine heatwave space is that ability to perform a heat budget. It would allow the authors to properly quantify the mechanisms responsible for the onset, persistence, and decay of the event. Without such analysis, the added value of the model remains limited and the conclusion regarding the role of advection is not fully supported.

   We thank the reviewer for this comment, which gave us the opportunity to provide more robust arguments to explain the observed dynamics. As suggested, we performed a heat budget analysis. Looking at the cumulative temperature increments, the largest contributions were due to advective fluxes, but the horizontal and vertical components almost completely cancelled out. Horizontal diffusion was instead very small, while atmospheric heat fluxes (radiative, sensible and latent) were confined mostly at the surface. Thus, the leading term was due to vertical diffusive fluxes, in agreement with the idea of heat penetrating downwards following a deeper mixed layer. We included a figure (current Figure 10) showing the results of this heat budget analysis, and moved the more qualitative former Figure 13 to the Appendix (current Figure C2).

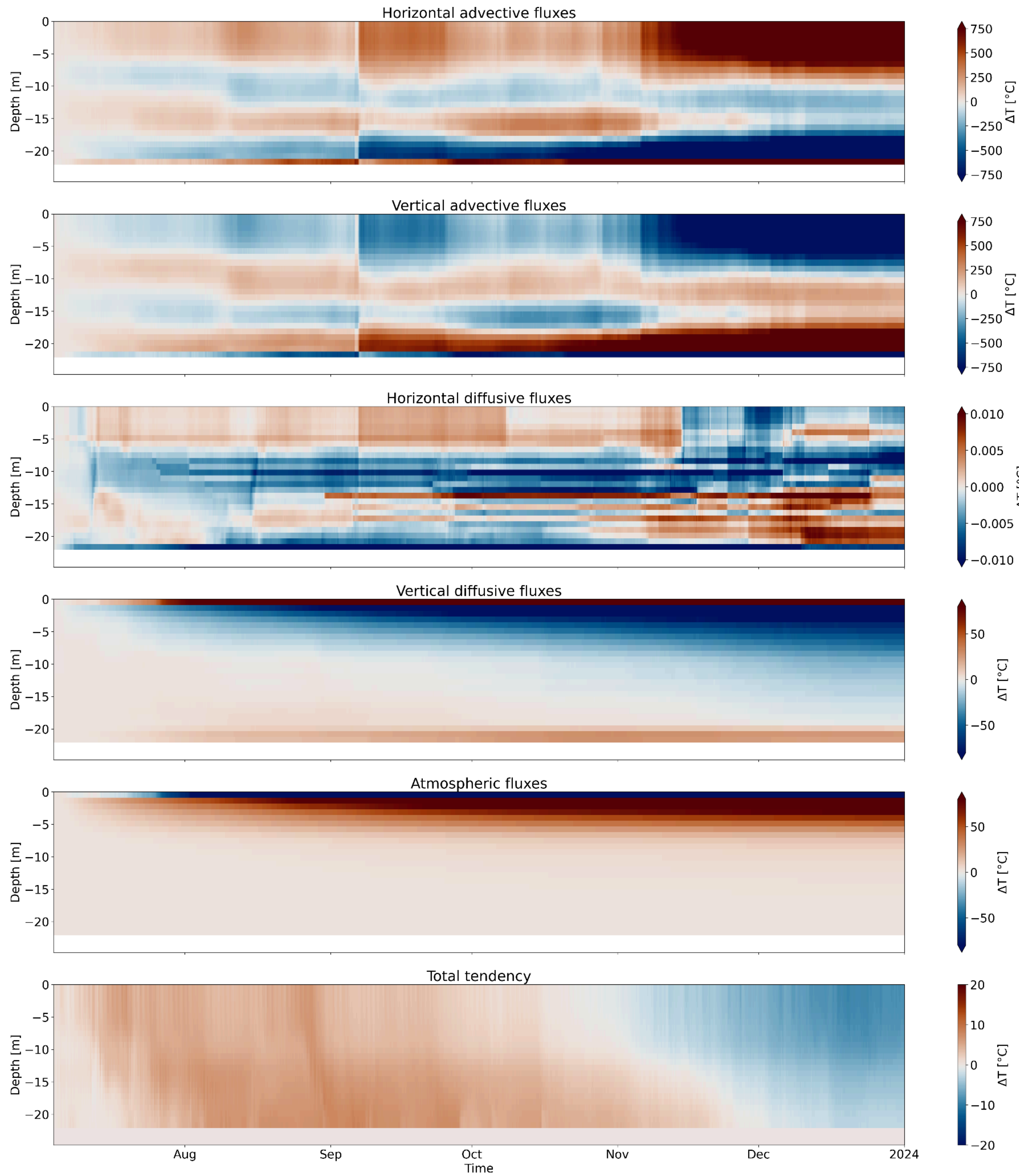
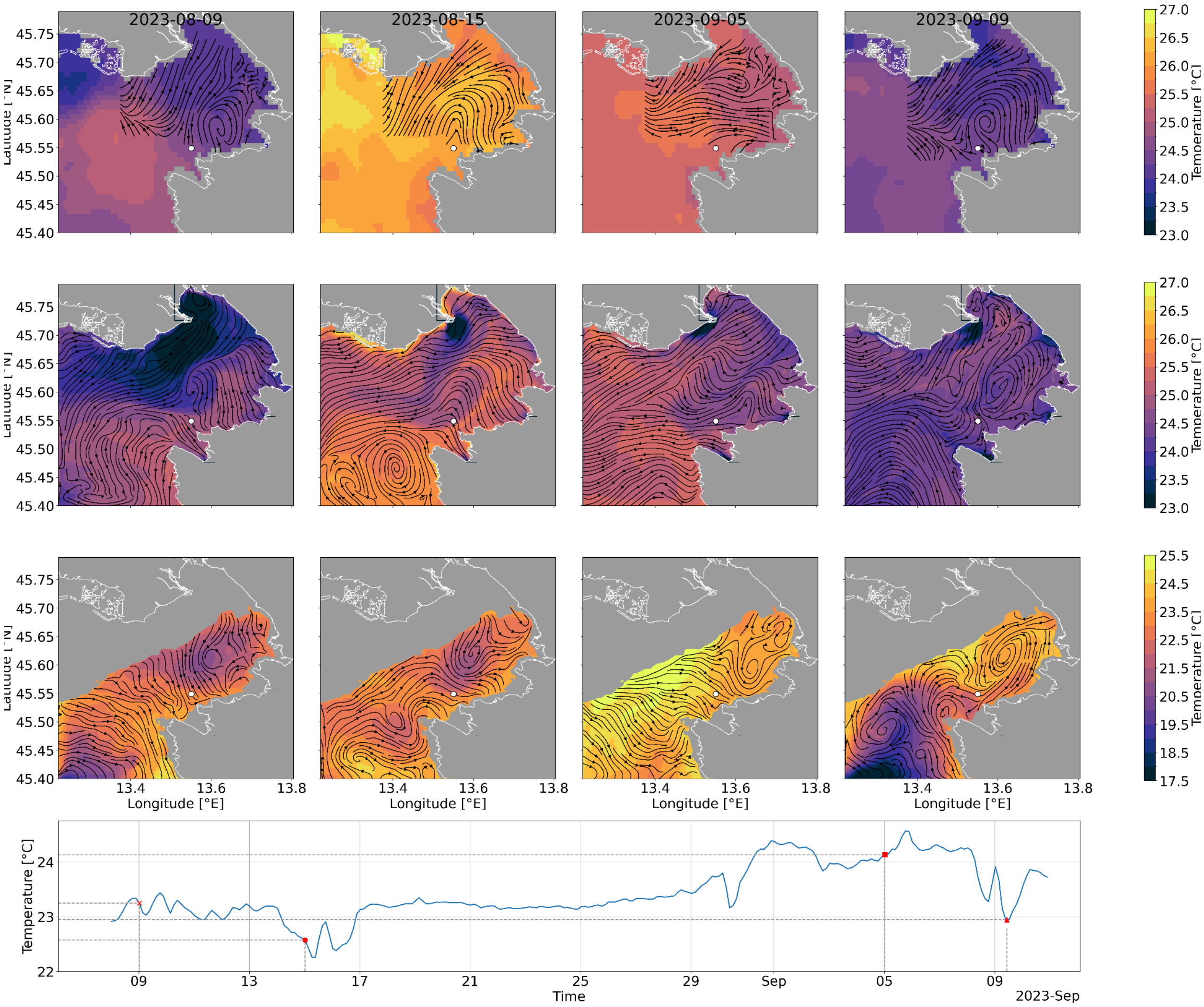


Figure 10: cumulative heat flux contributions and total temperature tendency computed at the Vida buoy location, from July to December 2023. From top to bottom: horizontal and vertical advection, horizontal and vertical diffusion, atmospheric fluxes and total temperature tendency.

4. **The presentation of the figures should be streamlined.** The manuscript contains too many simple figures, with 14 figures in total. The authors should reconsider how the results are presented and merge several figures where possible. For example, Figure 11, showing the modelled MLD, could be overlaid on Figures 9 and 10. Figure 14 presents the same line in four panels, and Figures 3 and 7 are essentially the same. These examples are not exhaustive. Reducing repetition and combining related diagnostics would make the paper clearer and would help the reader focus on the main mechanism. Also, please revise the captions which need to contain all information (rather than in the text).

The modelled MLD has been overlaid on Hovmöller diagrams (previously Figures 9 and 10 and marked as Figures 7 and 8 in the revised manuscript) as suggested by the reviewer and the model MLD figure has been removed (previously marked as Figure 11). As previously commented, former Figure 13 has been moved to the Appendix, while former Figure 14 has been reworked (now Figure 12) to avoid repetition and to welcome the other reviewer's suggestions regarding the signature of the bottom eddy in the surface fields. Former Figures 5 (Po runoff) and 6 (multi-year Brunt-Väisälä frequency) have been moved to the Appendix to reduce the number of figures in the main text. The captions of all figures have been carefully revised to make sure they contain all the necessary information.

The total number of figures has been reduced to 11. The Appendix now consists of three sections: Appendix A: Mixed Layer Depth (MLD) revisited, Appendix B: Drought and Appendix C: CTD and MITgcm temperature profiles.



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