AUTHOR'S RESPONSE

ANSWER TO Referee #1

RC1: The manuscript investigates the Gulf of Trieste circulation dynamics (North Adriatic Sea) under the influence of an extreme wind and precipitation event. The analysis is mainly based on the sea surface currents as measured by a HF radar network combined with time series of wind and river forcing in the area. The authors further support the interpretation of their results by including the comparison of the HF radar sea surface currents with a regional model output subject to the same forcings. As a whole, the manuscript reads very well, but I would further clarify some methodological and discussion aspects. Therefore, I would suggest major revision.

AC: We thank the reviewer for the positive evaluation of our manuscript and for recognising the quality of the analysis and writing. We also appreciate the constructive comments and suggestions, which we believe will help to improve the clarity and scientific impact of the work.

RC1: These general aspects would need to be further clarified:
Given the richness of information resolved across the extended coverage of a HF radar network, considering the variability of HF radar surface currents shown in figure 7 and the variety of current patterns evident within each single map, what is the representativeness of the four isolated points that the authors picked for the comparison of wind vs current time series in figure 5? Would the angle and magnitude comparison look the same if the authors had picked a neighboring point? And within what radius? Please comment or complement with other metrics, eventually identifying "areas" with corresponding spatial averages, instead of referring to single points, in order to make fullest use of the sea currents variability resolved by HF radar maps.

AC: Thank you for this valuable comment. In response, we have calculated spatial maps of complex vector correlation (u+iv) between each selected radar point (HFR_I, HFR_C, HFR_O, HFR_L) and the entire HFR range. The aim is to assess the spatial representativeness of these reference points within the radar field, i.e. to check whether the local current dynamics at these sites reflect broader, coherent patterns in their surroundings.
The results are shown in the attached maps:

- Figure RC1.1a (HFR_I): correlation map centred on the Isonzo Delta.
- Figure RC1.1b (HFR_C): correlation map centred on the central point.
- Figure RC1.1c (HFR_O): correlation map centred on the offshore point.

- Figure RC1.1d (HFR_L): correlation map centred on the westernmost selected point.

To help define the spatial extent of the coherence, contour lines have been added to highlight areas where the correlation exceeds 0.9.

These maps show that each selected point is embedded in a spatially coherent region with high correlation, supporting the idea that the selected locations are not isolated outliers but reflect larger, dynamically consistent areas. This strengthens the interpretation of the wind–current time series comparisons shown in Figure 5.

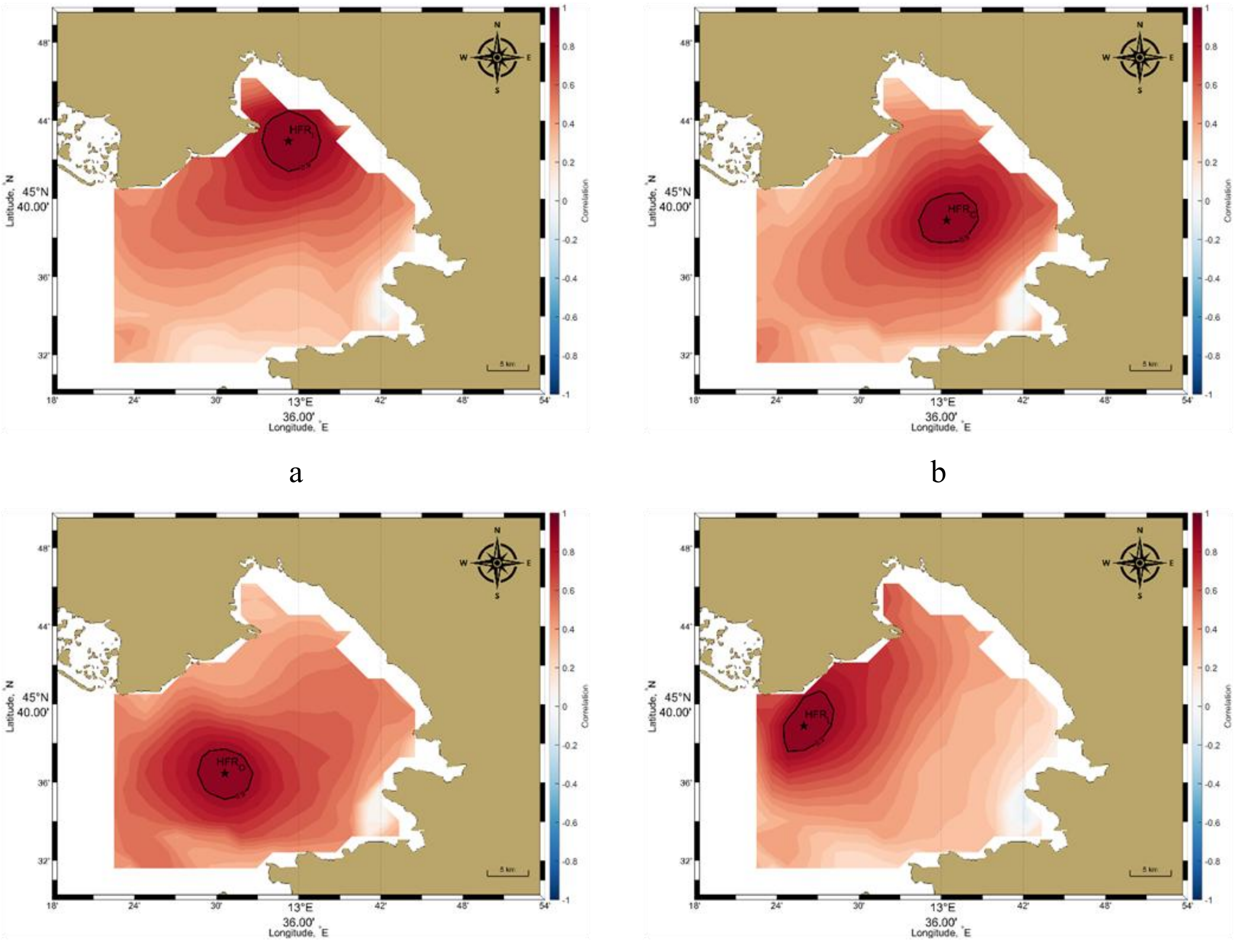


Figure RC1.1: (a) Correlation map centred on HFRI. (b) Correlation map centred on HFRC. (c) Correlation map centred on HFRO. (d) Correlation map centred on HFRL.

This clarification has been added to the manuscript in line 107 as follows: *The four selected radar points are representative of the surrounding areas in which the complex vector correlation exceeds 0.9 (Fig. S1 a-d).*

The figures have been added in supplementary materials (Fig. S1 a-d).

RC1: In the sections devoted to sea surface currents and wind it would be interesting to read the authors' conclusions on Ekman dynamics evidences with respect to the state of the art.

AC: To address your suggestion, we have performed a quantitative comparison between the observed surface currents and the theoretical Ekman current field using a cosine-based directional similarity approach (Han et al., 2012; Xu et al., 2025).

Jiawei Han, Micheline Kamber, Jian Pei, 2 - Getting to Know Your Data, Editor(s): Jiawei Han, Micheline Kamber, Jian Pei, In The Morgan Kaufmann Series in Data Management Systems, Data Mining: Concepts and Techniques (Third Edition), Morgan Kaufmann, 2012, Pages 39-82, ISBN 9780123814791, https://doi.org/10.1016/B978-0-12-381479-1.00002-2.

Xu, X., Ai, B., Zhao, J., & Liu, Y. (2025). Estimation of Eulerian sea surface currents and Lagrangian trajectory using ocean color elements from GOCI images in turbid coastal water. Journal of Geophysical Research: Oceans, 130, e2024JC022666. https://doi.org/10.1029/2024JC022666.

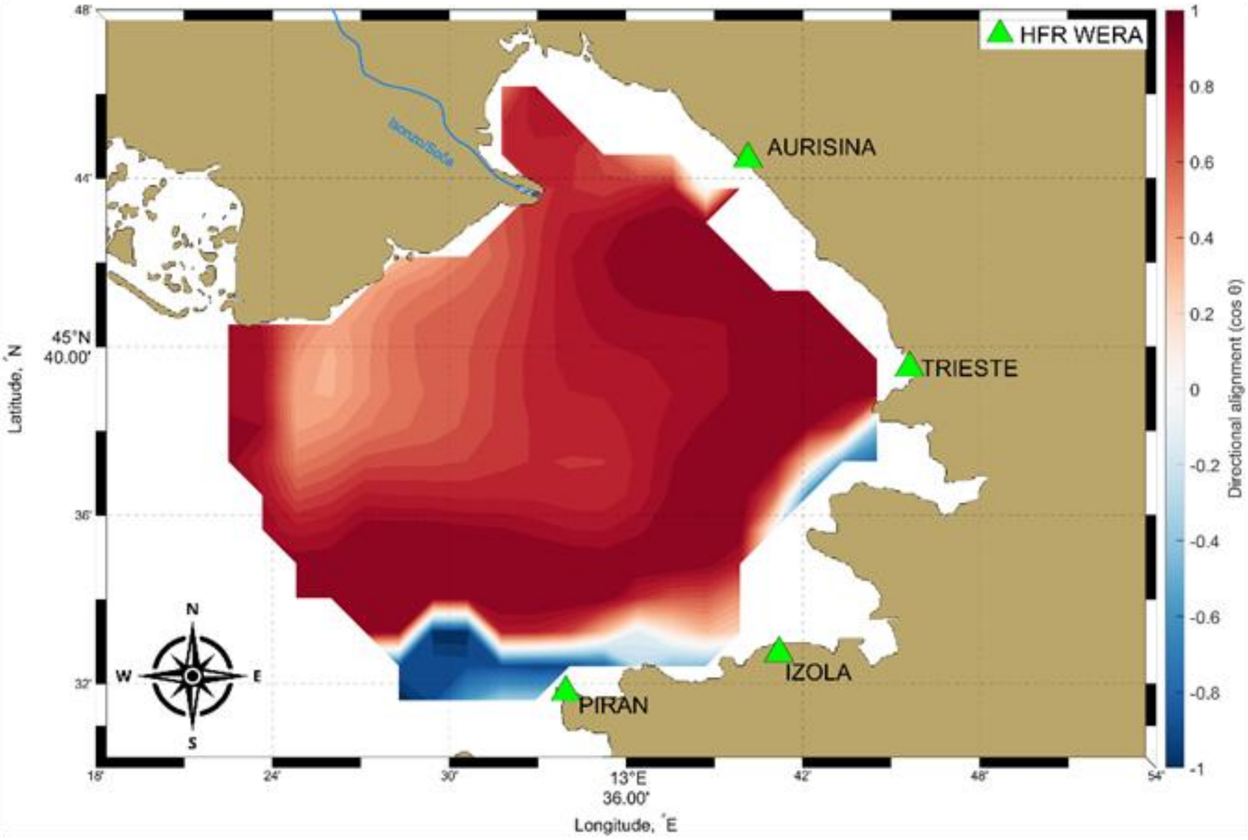
Our results show a clear and consistent pattern:

During Bora events, northeast wind, (Figure RC1.2a) the northwestern part of the GoT shows lower alignment values (light red, $\cos\theta<1$), indicating that the sea surface currents are not perfectly aligned with the theoretical Ekman direction. However, in these areas, the sea surface currents are well aligned with the wind direction.

During southerly wind events (Figure RC1.2b), the surface currents in the Gulf of Trieste agree well with the Ekman dynamics, especially in the inner part of the Gulf, and show high directional similarity values ($\cos\theta \sim 1$).

In contrast, in the central Gulf we observe areas with negative similarity values ($\cos\theta \sim -1$) during events with strong river discharge from the Isonzo (Figure RC1.2c). This highlights the important role of river discharge over currents, which counteract the wind-driven dynamics.

These results are consistent with the expected Ekman response to wind forcing, but also show the influence of other factors under certain conditions.



HFR WERA
AURISINA
TRIESTE
IZOLA
PIRAN
Isonzo/Soča
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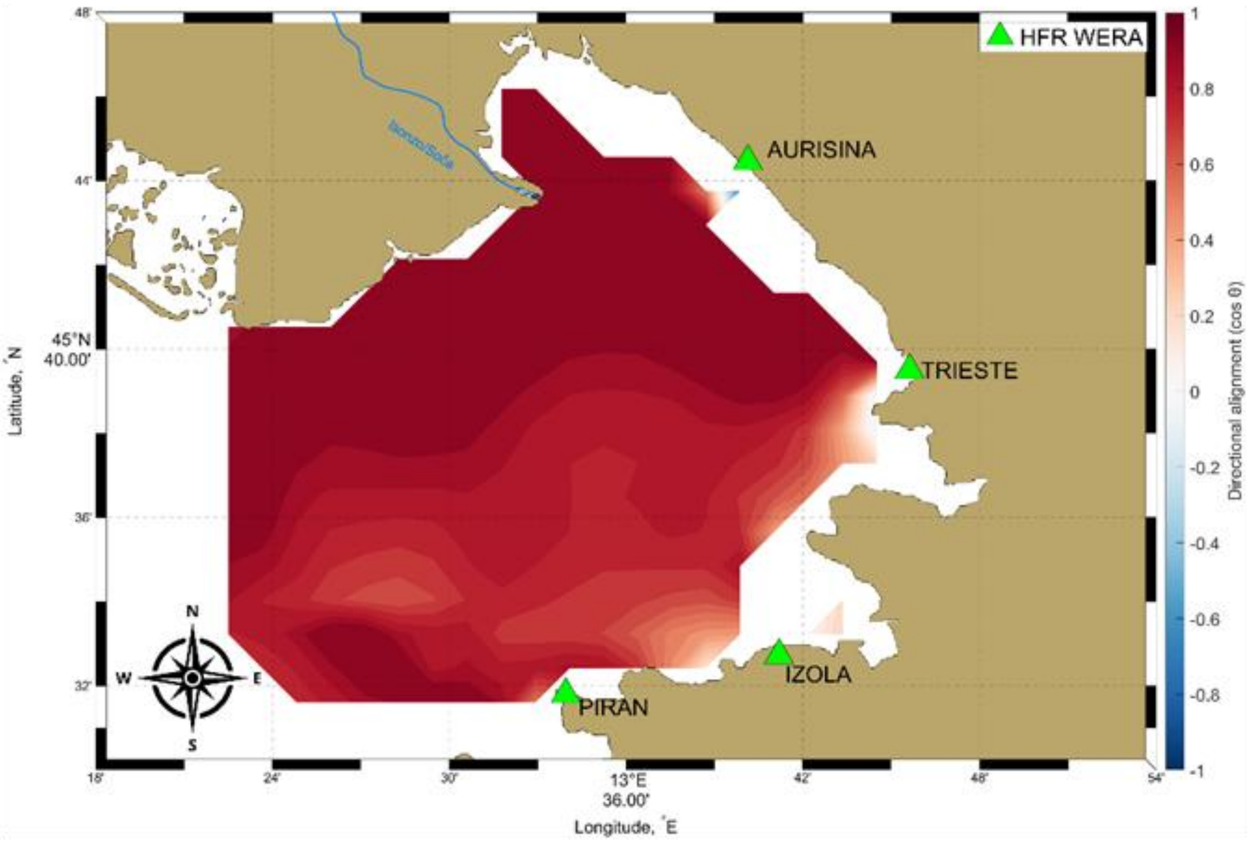
Latitude, ˚N
45°N 40.00'
Longitude, ˚E
13°E 36.00'
Directional alignment (cos θ)

a



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Longitude, ˚E
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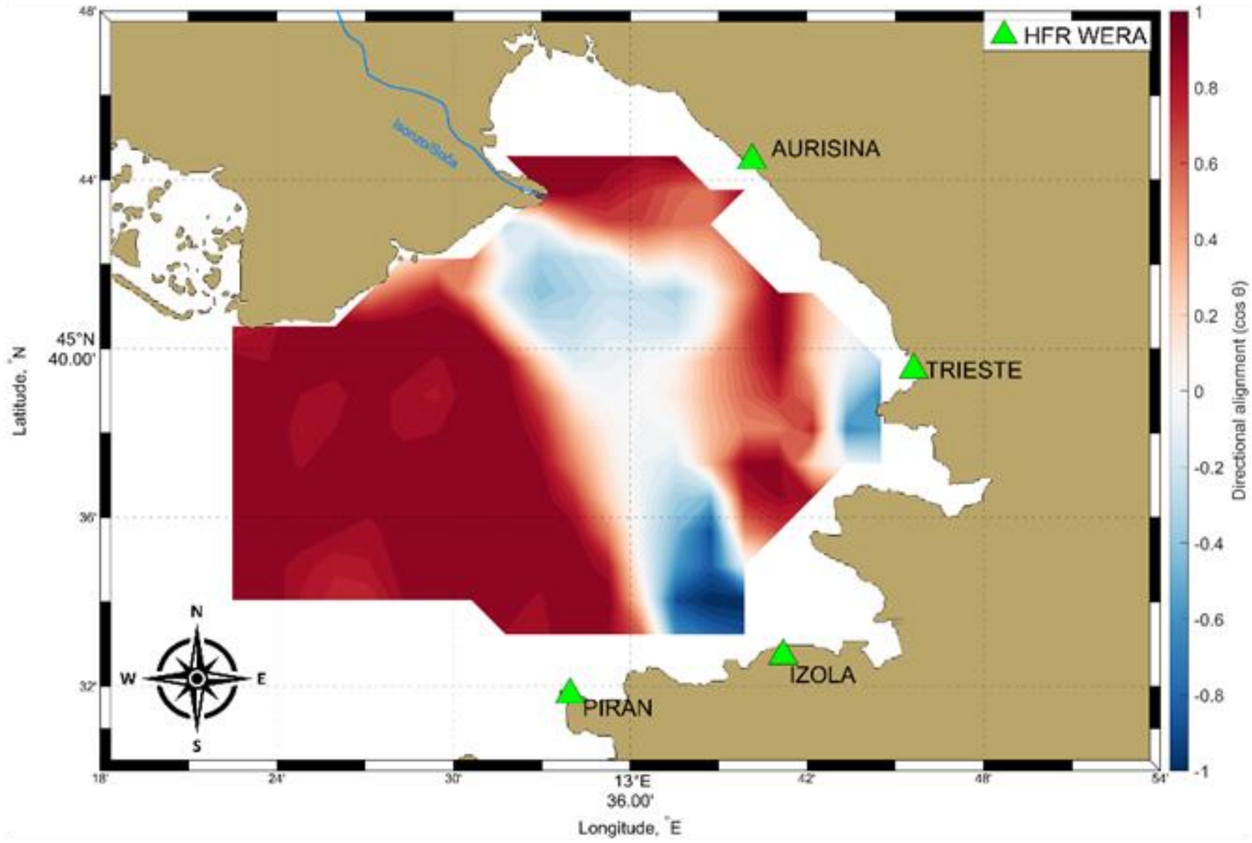
Directional alignment (cos θ)

b



c

Figure RC1.2: (a) Directional alignment (cos θ) map on 15 October 2023 19:00 UTC (Bora event). (b) Directional alignment (cos θ) map on 27 October 2023 05:00 UTC (Southerly wind event). (c) Directional alignment (cos θ) map on 28 October 2023 01:00 UTC (Southerly wind and strong river outflow event).

A brief discussion of the observed Ekman-type response and its variability has been added to the manuscript (lines 332-344):

To further evaluate the role of Ekman dynamics, we compared the direction of the observed surface current field with the theoretical Ekman current calculated from the WRF wind data.

A directional alignment was calculated using the cosine similarity of the angle (Han et al., 2012; Xu et al., 2025) between the current and Ekman vectors. This metric indicates the degree of agreement between the two vector fields, with values close to 1 indicating strong agreement with the Ekman direction.

The results show that during Bora wind event (Fig. S2a) the sea surface currents generally follow the expected Ekman response, especially in the southern and eastern parts of the GoT. However, in the northwestern part, lower alignment values (cos θ<1, light red) indicate that the sea surface currents are not fully aligned with the theoretical Ekman direction, but are perfectly aligned with the wind direction. During the southerly winds events (Fig. S2b), the surface currents show a strong correspondence with the Ekman dynamics. In contrast, the directional alignment decreases *significantly during episodes of intense river discharge with southerly winds (Fig. S2c), with values approaching -1 in the central GoT, in agreement with Figure 7c. This reversal indicates the current field appears to decouple from the wind, suggesting that other forcings may dominate the surface circulation.*

The figures have been added in supplementary materials (Fig. S2a-c). In this section, after the addition of these new figures (Figures S1a-d and Figures S2a.c), the figure named Figure S1 became S3; Figure S2 became S4 and Figure S3a-d became S5a-d.

RC1: Minor comments:
Line 70: the second "Cosoli et al. 2013" citation should go without parentheses.
AC: Done.

RC1: Line 161: please specify what Sentinel product was used. Images in the visible range? True color or other spectral ranges?
AC: We thank the reviewer for the suggestion. As requested, we have clarified the type of Sentinel product used. The following sentence has been added in line 163 of the revised manuscript: *In this study, true color images in the visible range were used, based on the Level 2A product, which provides the surface reflectance after atmospheric correction.*

RC1: Line 177: "Another image is from 4th November", please rephrase
AC: Done.

RC1: Line 214: closes
AC: Done.

ANSWER TO Referee #2

RC2: This study presents a timely and rigorously executed analysis of the October-November 2023 extreme event in the Gulf of Trieste (GoT), offering valuable insights into coastal dynamics under compound stressors. The integration of multi-platform observations (HF radar, Sentinel-2 imagery, hydrometric data, and wave measurements) with high-resolution numerical modeling represents a major strength, enabling a comprehensive assessment of how river discharge and wind forcing interact to modulate surface circulation. The identification of two novel mechanisms—the dominance of southerly winds over Bora in accelerating surface currents, and the capacity of intense Isonzo River runoff to override wind-driven circulation patterns – provides significant advances beyond existing literature. Particularly compelling is the demonstration that strong southerly winds alone can shift the GoT's typical cyclonic circulation to anticyclonic, independent of river discharge – a finding that challenges previous interpretations of this transition. The quantitative validation of model performance against HF radar data and the skillful diagnosis of model-wave coupling limitations during high-energy events further strengthen the work's scientific value for coastal hazard prediction.

AC: We would like to thank the reviewer for the thorough reading and the very positive evaluation of our work. We are pleased that the integration of observations and modelling as well as the identification of novel mechanisms in the surface circulation were recognised as a valuable contribution to the understanding of coastal dynamics under combined wind and river discharge influence. We appreciate the constructive feedback and address in the following responses the specific suggestions and questions raised to further improve the clarity and robustness of the manuscript.

RC2: Several areas require clarification to enhance impact. The substantial discrepancy between HF radar and buoy wave heights warrants deeper investigation beyond the brief mention in Section 3.4. Given the importance of wave-current interactions highlighted in Section 3.5, this discrepancy potentially undermines confidence in stress parameterizations; either methodological limitations of HF radar in freshwater-influenced conditions or bathymetric effects at Zarja buoy should be systematically analyzed.

AC: We note the reviewer's comment regarding the discrepancy between HF radar and buoy wave height measurements. As mentioned in Section 3.4, this problem is the subject of ongoing research in our group. A PhD student is currently working on the mentioned topics, in particular: i) on the calibration of the HFR wave heights using data from buys (as in Ursella et al., 2023); ii) on wave-current interactions and their influence on radar-based wave estimates. Further modelling developments are also underway to address and reduce these discrepancies.

L. Ursella, S. Aronica, V. Cardin, G. Ciraolo, D. Deponte, C. Lo Re, A. Orasi & F. Capodici (2023): Calibration and validation of high frequency coastal radar waves exploiting in-situ observations and modelled data in the south-west Sicily, Journal of Operational Oceanography, DOI: 10.1080/1755876X.2023.2215111

RC2: The choice of Edson et al. (2013) drag coefficient parameterization (Eq. 2), while justified as a global average, lacks validation against local measurements; sensitivity tests or comparison with region-specific formulations (e.g., Smith, 1988) would strengthen the wind stress interpretation.

AC: We thank the reviewer for the valuable comment regarding the use of the Edson et al. (2013) drag coefficient formulation. Following the suggestion, we compared it with the region-specific parameterisation of Geernaert et al. (1987), which is considered more suitable for shallow coastal waters such as the Gulf of Trieste. This formulation is indeed cited by Smith (1988), as mentioned by the reviewer, in the context of shallow water applications.

We implemented both formulations and performed a sensitivity comparison over a range of typical wind speeds (1–20 m/s). The results show that the two parameterisations provide almost identical values for the drag coefficient in the wind speed range relevant for our study. This justifies the use of the formulation of Edson et al. (2013), as it provides globally consistent values and remains locally representative under typical conditions.

We include here a figure that compares the two formulations of the drag coefficient (Figure RC2.1), Geernaert et al. (1987) and Edson et al. (2013), as a function of the 10 m wind speed (U_{10}). The plot illustrates the differences between the two approaches over a representative range of wind speeds and helps to illustrate their behaviour and support the choice made in our work.

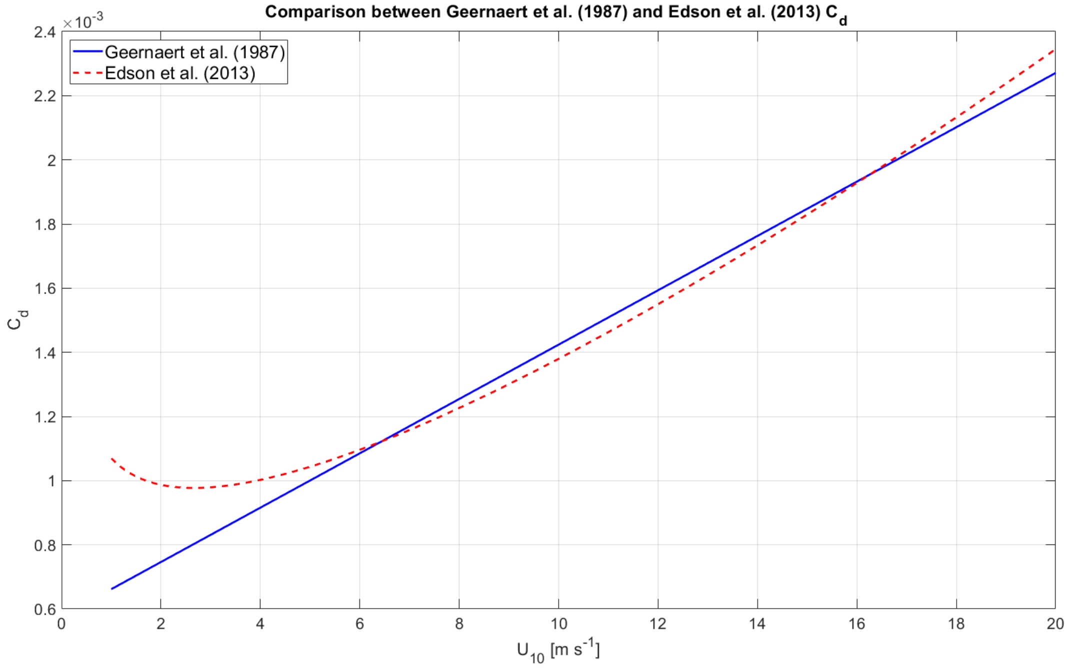


Figure RC2.1: Comparison between Geernaert Cd and Edson Cd.

RC2: The assertion that river runoff dominates over wind forcing during extreme discharge (Fig. 7c) appears partially contradicted by Fig. 5a-c, where current directions during the November 3rd peak show high variability rather than coherent river-driven patterns—this tension needs reconciliation.

AC: We thank the reviewer for this observation. Figure 7c is a snapshot derived from a 12-hour moving average centred on 28 October 2023 at 01:00 UTC, shortly after the peak river outflow on 27 October, showing an event where river forcing clearly dominates over wind forcing, with surface currents in the northern and central Gulf flowing in the opposite direction to the prevailing southerly wind. In contrast, Figures 5a-c show hourly time series of wind and current along with the weekly percentage of occurrence of different wind types (Bora, southerly wind, low winds, etc.), classified by wind direction sectors, at different locations in the Gulf. Despite the weekly aggregation, these figures show significant discrepancies between the prevailing wind direction and the direction of the surface current in the weeks from 22 to 28 October and from 29 October to 5 November, which coincide with the main river discharge peaks from the Pieris hydrometric station (on 27 October and 3 November, respectively).

These discrepancies - which are particularly evident in the grey segments of the directional histograms - support the hypothesis that river discharge plays a dominant role during these periods. This is also supported by the comparison of the wind and current fields in Figures 7a-c: wind-driven currents are more clearly visible during the events of 15 October (Bora wind) and 27 October (strong southerly wind and weak river outflow), while the river-driven circulation is clearly visible in the case of 28 October (southerly wind and strong river outflow). Although the offshore point HFR_O (Figure 5c) shows less variable direction of the sea surface currents, a signal consistent with the river-driven circulation is still recognisable. This is consistent with the surface current pattern observed in Figure 7c.

As a clarification, we want to emphasise that Figures 5a–c shows weekly percentage distribution of sea surface current direction and wind regime occurrences, whereas Figures 7a–c illustrate instantaneous conditions based on a 12-hour moving average.

In addition, we have further supported this interpretation by comparing the observed surface current fields with the theoretical Ekman currents derived from the wind forcing, Figures S2a-c in Supplement.pdf or Figures RC1.2a-c in this document (we refer the Reviewer 2 to our response to Reviewer 1). During the events of 15 and 27 October (Figures S2a-b in Supplement.pdf or Figures RC1.2a-b in this document), the surface currents show a strong agreement with the Ekman response, confirming wind-driven dynamics. In contrast, the comparison on 28 October (Figure S2c in Supplement.pdf or Figure RC1.2c in this document), during strong river outflows and southerly winds, shows a clear divergence between the observed and Ekman currents with opposite directions in the central part of the Gulf of Trieste. This confirms that wind forcing alone cannot explain the observed circulation on this day, supporting the hypothesis that river outflow played a dominant role. A description of this analysis has been added to the revised manuscript (lines 332-344).

RC2: Additionally, while the Sentinel-2 plume imagery is effectively utilized, quantitative analysis of plume extent evolution would complement the qualitative discussion.

AC: Unfortunately, a quantitative analysis of the plume extent evolution could not be carried out because no suitable Sentinel-2 images were available in the days before the event, as the persistent cloud cover obscured the area of interest. The only available image before 4 November is from 22 October (Figure 2b), which is itself partially obscured by clouds and does not allow reliable extraction of the plume boundaries.

RC2: Finally, streamlining repetitive elements and clarifying whether HFR1 or HFR_1 denotes the western point would improve readability.

AC: After carefully reviewing the manuscript, we have not found a single occurrence of the terms "HFR1" or "HFR_1". The north-western point is consistently referred to as "HFR_L" where "L" stands for "left" to indicate its relative position in the Gulf.

List of all relevant changes

In the Manuscript (the lines refer to the new manuscript)

- **Lines 107-108:** The four selected radar points are representative of the surrounding areas in which the complex vector correlation exceeds 0.9 (Fig. S1 a-d).
- **Lines 163-165**: In this study, true color images in the visible range were used, based on the Level 2A product, which provides the surface reflectance after atmospheric correction.
- **Lines 332-344**: To further evaluate the role of Ekman dynamics, we compared the direction of the observed surface current field with the theoretical Ekman current calculated from the WRF wind data.

  A directional alignment was calculated using the cosine similarity of the angle (Han et al., 2012; Xu et al., 2025) between the current and Ekman vectors. This metric indicates the degree of agreement between the two vector fields, with values close to 1 indicating strong agreement with the Ekman direction.

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In Supplement

- In Supplement.pdf, after the addition of the new figures (Figures S1a-d and Figures S2a.c), the figure named Figure S1 became S3; Figure S2 became S4 and Figure S3a-d became S5a-d.