***RC1**: 'Comment on egusphere-2023-2060', Anonymous Referee #1, 30 Nov 2023
AC1: Thank you for dedicating your time to the assessment of our manuscript. Below, the Referee's text is presented in black, and our response in blue; proposed changes to the manuscript are typed in red. Please be aware that the figure, table, and section numbering pertain to the revised version of the manuscript. Additional references are provided at the end of this document.

I recommend that this manuscript is accepted for publication with minor revisions.
The submitted manuscript describes new updates to the VISIR-2 weather routing software. The model has been developed from Matlab into Python and is available as an open-source model with no license.
A brief literature review is provided, alongside an in-depth methodology, providing a detailed explanation of each component of the model. The paper finishes by demonstrating VISIR-2's ability to minimise CO2 emissions in two case studies – one for a motor ship and one for a sailing ship.
The paper excels in its scientific reproducibility and I would like the congratulate the authors on the well-organised manuscript with impressive levels of additional detail provided, including the user manual. I believe that the modular implementation, released under a freely available GNU General Public License, has strong uses for the scientific community and the wider community. The paper excels in its presentation quality, in particular the presentation of the very clear figures. VISIR-2 benefits greatly from its validation and provides very useful and detailed insight into the model's computation time.
We sincerely appreciate the reviewer for dedicating their time and providing valuable feedback on our manuscript. Their insightful comments were instrumental in enhancing the quality and the presentation of our work.

That said, I believe the paper could improve in the following aspects.
I believe the manuscript would benefit from a clearer description of the inherent novelty of the model within the method section. The novel aspects of the model are not highlighted sufficiently in the method, and I finished reading the section wondering which parts of VISIR-2 form the novel features. I would also like to see this same novelty more clearly described in the introduction – here, the authors describe additional features well, but the section fails to comment on the novelty of these features in the context of the body of literature in this field.
The paper heavily focuses its novelty on the fact that their model has been developed as open source, modular and free to use (which VISIR-2 largely does with exceptional care and quality). While this is indeed useful, I believe the manuscript could benefit from a discussion on the novel quantitative implications of their CO2-saving results. (In fact, the authors also touch upon this in the first paragraph of their abstract: "…its quantitative impact has been explored only to a limited extent…".)
Thank you for emphasizing the need to better elucidate the novelty of VISIR-2 across the various sections of our manuscript. Indeed, its novelty extends beyond being an open-source model. VISIR-2 introduces several technical innovations and we are going to highlight the absolute novelties at various points throughout the revised manuscript. To summarise them:

- the unified modelling framework to account for involuntary ship speed loss through waves (Sect.2.1) now mentioned in Sect.1

- the capacity to account for currents advection for a vessel with a angle-dependent performance curve, and the solution of corresponding transcendental equation (Sect.2.1 and App.A) now mentioned in Sect.2.1
- the use of a previously overlooked cartographic projection (Sect.2.2.1) now mentioned in Sect.2.2.1
- the use of a K-dimensional tree for indexing graph edges (Sect.2.2) now mentioned in Sect.2.2.3
- various options for spatio-temporal interpolation of environmental fields (Sect.2.3) mentioned in Sect.2.3.2
- a novel and versatile optimisation algorithm in presence of dynamic edge weights (Sect.2.4), here applied to minimize CO_2 emissions but adaptable to other metrics as well, like passenger comfort or radiated underwater noise now mentioned in Sect.2.4
- the visualization of the dynamic environmental fields along the route making use of isochrone-bounded sectors (Sect.2.6) now mentioned in Sect.2.6
- the modular structure of the software suite, benefitting R&D activities (Sect.2.7) mentioned in Sect.2.7
- the investigation of the distribution of the CO_2 savings, revealing a bi-exponential pattern Sect.5.2.1) now mentioned in Sect.5.2.1
- the use of wind, currents, and leeway in the computation of sailboat optimal routes (Sect.5.2.2) now mentioned in Sect.5.2.2

I don’t currently fully understand what novel academic question they try to answer with their analysis, or whether it is just used to showcase VISIR-2 (which it does a great job of). I believe that these quantitative novelties are present in the paper, but more work is needed to outline them in the results/discussion section. While outside the area of model development, the results of this paper are great work and I believe it would be of use to advance the field more generally. I would ideally like to see an explanation of how their quantitative results/discussion contribute to new science. This could also be brought out briefly in the abstract.

We contend that the quantification of ship weather routing's impact on reducing greenhouse gas (GHG) emissions still represents a significant gap in the current scientific literature. A wide range of percentage savings are reported, often lacking sufficient information to precisely understand the methodologies employed to achieve them. The situation becomes even more challenging when seeking open-source models. Indeed, we only encountered the openCPN system. As the maritime industry endeavors to adhere to the resolutions set forth by the International Maritime Organization (IMO) for emission reduction, it is imperative to meticulously evaluate the precise potential of both technical and operational measures to achieve this objective within the stipulated time frame. This is undoubtedly a subject area where we believe a thoroughly documented, open-source model like VISIR-2 could be highly relevant. Other potential applications are also conceivable, including the establishment of baselines for emission profiles. Such capabilities could be particularly valuable for agencies like the European Maritime Safety Agency (EMSA), which implements a system for monitoring, reporting, and verifying vessels' CO_2 emissions. Starting in 2024, maritime GHG emissions are incorporated into the European Union Emissions Trading System (EU-ETS). This entails shipowners, ship managers, or bareboat charterers (whoever bears the cost of fuel) surrendering allowances for their emissions within the EU-ETS. Saving fuel, such as through the implementation of smarter routes, has become

increasingly essential in light of these developments. Even with the adoption of zero- or low-carbon fuels like e-methanol or green ammonia, it remains critical to conserve these fuels as much as possible. This is particularly important considering that their unit price is significantly higher than traditional fossil fuels.
We are going to allocate the provided text concerning motivations for VISIR-2 across the Abstract, Introduction (Sect. 1), the Discussion (Sect. 6.2), and the Conclusions (Sect. 7) of the revised manuscript. In particular, regarding the quantitative contribution of the VISIR-2 model to new science, we have introduced a new Discussion section. It incorporates the aforementioned motivations for VISIR-2 and includes a detailed quantitative comparison with existing literature, as outlined in our response to the Referee's subsequent comment.

On a similar note, the results/discussion does a great job of highlighting the potential of weather routing as a CO2 reduction measure. However, there is almost no discussion on how their results compare to other studies in the literature. Where do their CO2 savings fit in the literature? Do they agree/disagree? What relative contribution is the paper making to this body of literature? I would like to see more discussion on this.
When comparing the carbon savings of VISIR-2 with those reported in the literature on ship weather routing, it is notable that only a limited number of peer-reviewed papers have addressed emission savings through ship routing thus far. A few findings available for comparison with the results of VISIR-2 are presented in what follows.

For the ferry case study examined in this manuscript, the CO_2 emissions, in the best-case scenario, can be halved compared to those along the least-distance route (Fig. 12). This is in numerical agreement with the broad (0.1 - 48)% range reported in Bouman et al. (2017)[Tab.2]. Notably, the upper limit reduction stands as an outlier, with the more probable values depicted in Bouman et al. (2017)[Fig.2] falling below 10%. This resonates well with the outcome presented in Fig. 12.b and Tab. 9 of the revised manuscript, based on thousands of reproducible numerical simulations for a ferry obtained via VISIR-2.

Applying the VOIDS model, Mason et al. (2023a)[Sect.3.2] discovered that, for eastbound routes of a Panamax bulk carrier in the North Atlantic, voyage optimisation contributed to carbon savings ranging from 2.2 to 13.2%. This is a narrower range compared to the present findings of VISIR-2. However, both a different vessel type (a ferry) and a different domain of sailing (the Western Mediterranean Sea) were considered in the VISIR-2 numerical experiments.

Miola et al. (2011) presented data from the second IMO GHG study, where the estimated CO2 abatement potential for weather routing on the emissions of 2020 was reported to be as low as 0.24%. In the same paper, also a DNV study on projected emissions in 2030 is cited, providing an estimate of 3.9% for the CO2 abatement potential through weather routing. The former figure compares well to the average emission reduction computed via VISIR-2 for the ferry downwind conditions and high engine load, the latter to results for upwind and low engine load (cf. Tab.8).

Lindstad et al. (2013) estimated the reduction in CO_2 emissions for a dry bulk Panamax vessel navigating in head seas during a typical stormy period in the North Atlantic. This reduction was determined when sailing on a 4,500 nautical miles (nmi) route compared to the shorter (yet stormier) least-distance route of 3,600 nmi. They found reductions ranging from 11 to 48%, depending on the speed of the vessel.

We note that, as e.g. in Mason et al.(2023a)[Fig.7], also VISIR-2 optimal routes exhibit spatial variations contingent on the departure date, forming a “bundle” as illustrated in Fig. 11.b. The shape of route boundaries was assessed for the United States’ Atlantic coast routes by means of AIS data in Breithaupt et al. (2017). While they found multimodal distributions depending on sailing direction, they did not attribute the preferential lanes to the presence of ocean currents but speculated that it was due to bathymetric constraints or artificial aids to navigation.

VISIR possesses a capability to incorporate ocean currents into the voyage optimisation process. As shown in Mannarini and Carelli (2019), this integration has proven to significantly reduce the duration of transatlantic routes. In the present manuscript, we reaffirm the positive impact of currents on ship route optimisation, extending their benefits also to the reduction of CO_2 emissions (Tab. 8) and to the determination of more faithful duration savings for sailboat routes 55 (Tab. 10).

In general, both average and extreme CO_2 emission percentage savings found in literature align well with the results obtained in the ferry case study presented in our manuscript. Nevertheless, engaging in a meaningful discussion of numerical differences, given the diverse range of vessel types, routes, environmental fields, and computational methods employed in the various published case studies, proves challenging.

VISIR-2 contributes to the existing body of literature by providing an open computational platform that facilitates the simulation of optimal ship routes in presence of waves, currents, and wind. These simulations are designed to be transparent, with customisable sea domain and vessel performance curves, allowing for thorough inspection, modification, and evaluation. This addresses the concern raised by Zis et al. (2020) regarding the necessity of benchmarking instances of optimal routes and the associated input data. By providing such benchmarks, VISIR-2 supports and streamlines the work of future researchers in the field. Hence, we believe that the critical task of evaluating inter- model differences will best be addressed through dedicated inter-comparison studies. As previously demonstrated with VISIR-1 (Mannarini et al., 2019), similar assessments could be conducted with VISIR-2 too.
The above text is going to be added in Sect.6.1.

That said, the level of detail in the results/discussion is brilliant and very commendable, a great job on that.
Some of my above suggestions have been completed to some extent in the conclusion - but should be strengthened in the other sections. No new information should be presented in the conclusion.
Thanks for this feedback.
As noted earlier, we have incorporated a new "Discussion" section (Sect.6) into the revised manuscript to specifically address this recommendation by the Referee. Additionally, the Conclusions have been revised to emphasize the results and their novelty while refraining from introducing any new information for the first time in the manuscript.

Alongside this, I have the following minor comments:

1. I believe a figure at the start of the method section that provides an outline of all steps of the model would help readers to understand the model structure more generally
   We are going to add a figure in Sect.2.7 providing a depiction of the VISIR-2 workflow across the various code modules:

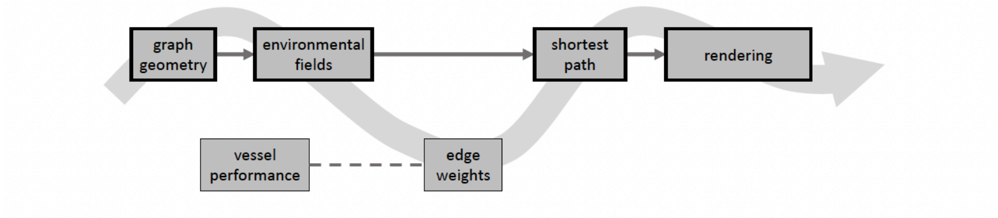


Figure 8. VISIR-2 workflow. Modules enclosed within thicker frames are intended for execution by the end-user, while the other modules can be modified for advanced usage. The data flow occurs along the wavy arrow, with routine calls along the dashed line.

2. h-hat is mentioned at the end of page 5 but I cannot see this variable in Figure 1.
   Thank you for noting this.
   We fix it by replacing the "*s*" versor and subscript with "*h*" in both the main text and Fig. 1.

3. Removing collinear edges is a great idea, one which I will test myself!
   Thank you for your feedback. Please be aware that we are renaming "collinear" to "quasi-collinear edges" in the revised manuscript, as their directions exhibit slight differences once a cartographic projection is applied. This will be detailed in a new Sect.2.2.3.

4. I found Section 2.3.2 Space interpolation confusing. I would consider rewording. A better description would be useful. Same with Figure 5. Please explain the meaning of Head and Tail and give a more clear description of the two interpolation methods. Indeed, please state the difference and why the two are necessary.
   Each graph edge acts as an arrow, conveying flow from ``tail'' to ``head" nodes.
   This is being clarified in Sect.2.2.2. and Fig.5a. Fig.5b makes clear the different impact of the two interpolation schemes as shown below.

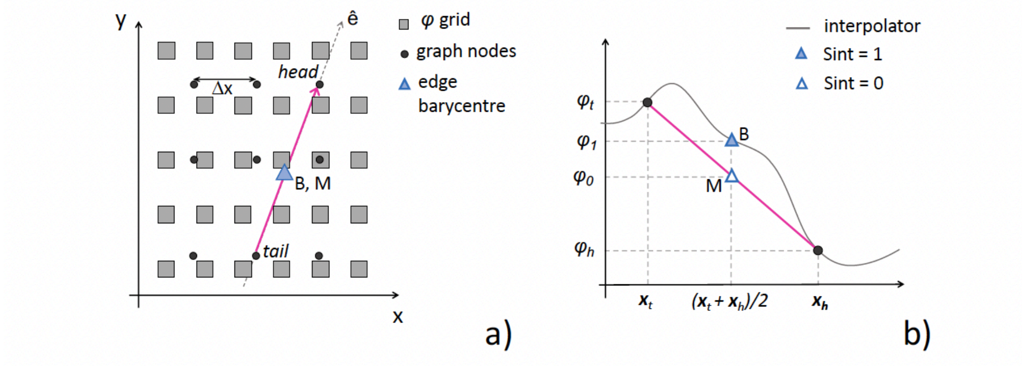


Figure 5. Spatial interpolation in VISIR-2. a) The squares represent grid nodes of the environmental field $\varphi(\boldsymbol{x})$, and the filled circles graph grid nodes. A graph edge is depicted as a magenta segment. b) Transect of a) along the edge direction $\hat{e}$, with the interpolator of φ as a grey solid line. The (0,1) subscripts refer to the value of the Sint parameter while h and t to the edge head and tail, respectively.

We have deeper investigated the effect of the two interpolation schemes, Sint=0 and Sint=1 which were originally devised in an attempt to reproduce benchmark results from VISIR-1 obtained from the *interp2* Matlab function.
We generated ideal z = f(x,y) fields: a plane, a paraboloid, and a family of saddles. Also, we generated a set of graph edges in the (x,y) plane, with different lengths and orientations. We interpolated the fields on each edge, using both schemes. We found that, as expected, as the edge length is reduced, the results for Sint=0 and Sint=1 converge to a common truth. However, depending on the specific saddle hypersurface and edge orientation, either Sint=0 or Sint=1 converge quicker.
Also, upon closer examination, the computational performance was found to be contrary to what was previously stated in the preprint: the Sint=1 option (evaluating the environmental field at the edge barycenter) is not computationally faster than the Sint=0 option (average of field values at the head and tail). Actually, the opposite holds true. The reason being that, in the case of Sint=1, the interpolator is applied at each edge, whereas with Sint=0, it is applied at each node. Given that the number of edges exceeds the number of nodes by a factor defined by Eq.20, for the degree of connectivity of the case studies (ν parameter) the computational time for Sint=1 is found to be approximately one order of magnitude higher.
Therefore, the new default scheme is set to be Sint=0.
The above text is used for the new Sect. 2.3.2. It refers to the new Supplement's figure which is reported also below.

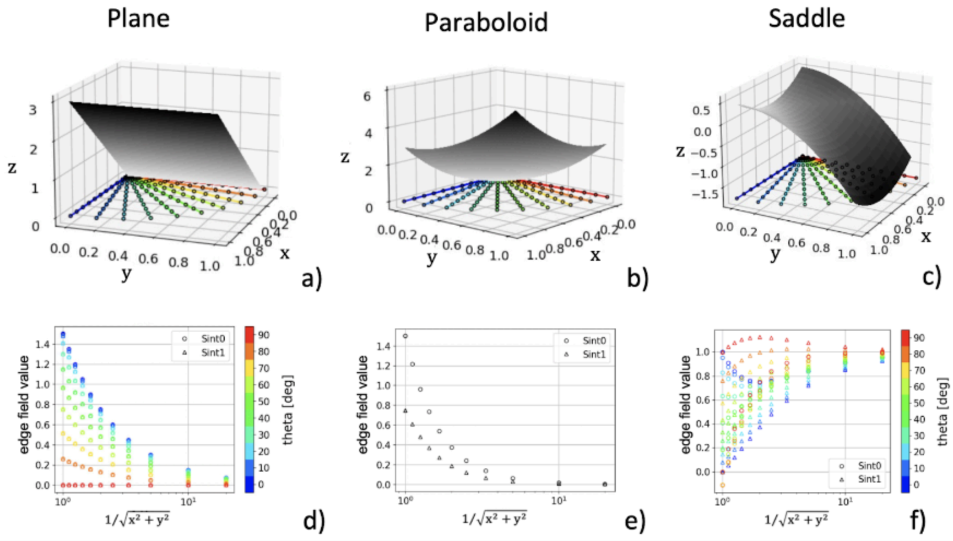


Fig. S0 a)-c) Test hypersurfaces (shaded in grey) and graph edges (coloured lines and markers indicating the edge head). d)-f) Edge representative values of the different hypersurfaces for both Sint=0 (circles) and Sint=1 (triangles).

In the revised VISIR-2 source code, we have now designated Sint=0 as the default interpolation scheme.

5. The least squares fit for the blue lines in Figure 9 doesn't seem to work. I'm not sure if an alternative is possible, but if my interpretation is correct, the solid blue line (total computation time) should not fall below the dashed blue line (Dijkstra component of computation time). While your interpretation is correct, we are still confident in the goodness of the fit. Minimal nonlinearities exist in the performance of both the total and Dijkstra's component of the least-distance routine, particularly

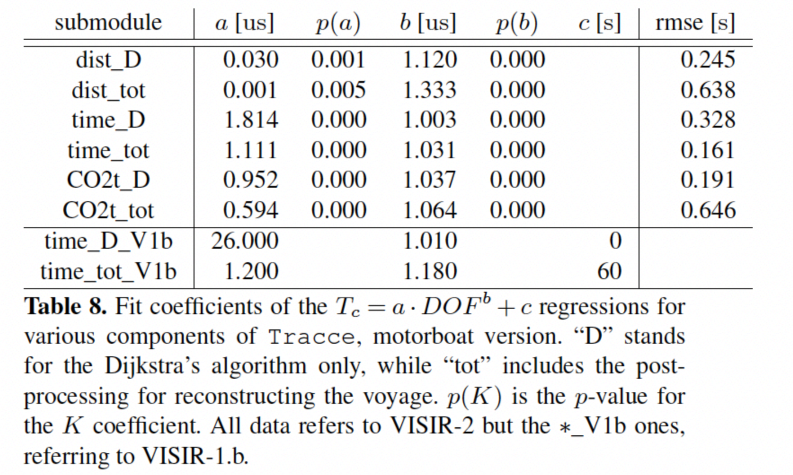
for numerical problems with a small number of degrees of freedom. However, the mismatch between the data and the fit line is minimal, typically a matter of a few tenths of a second (note the log-log scale in Fig.10). Notably, the power-law function successfully fits the computing time above a few tens of seconds, corresponding to numerical problems of more realistic size.

In fact, this is the same for the red and green lines also.

The red and green lines represent the least-time and least-CO2 routines, respectively. Due to their computation times being one order of magnitude larger than those of the least-distance routine, they are less sensitive to the nonlinearity.

All fit coefficients are found to be highly statistically significant and, for all fit models, the root mean square error (rmse) is confirmed to be smaller than one second.

To showcase the goodness of fit, we have incorporated both the rmse and the fit coefficients' *p*-values into Tab.8, making a corresponding point in the text.



submodule	a [us]	$p(a)$	b [us]	$p(b)$	c [s]	rmse [s]
dist_D	0.030	0.001	1.120	0.000		0.245
dist_tot	0.001	0.005	1.333	0.000		0.638
time_D	1.814	0.000	1.003	0.000		0.328
time_tot	1.111	0.000	1.031	0.000		0.161
CO2t_D	0.952	0.000	1.037	0.000		0.191
CO2t_tot	0.594	0.000	1.064	0.000		0.646
time_D_V1b	26.000		1.010		0	
time_tot_V1b	1.200		1.180		60	

Table 8. Fit coefficients of the $T_c = a \cdot DOF^b + c$ regressions for various components of `Tracce`, motorboat version. "D" stands for the Dijkstra's algorithm only, while "tot" includes the post-processing for reconstructing the voyage. $p(K)$ is the p-value for the K coefficient. All data refers to VISIR-2 but the $*$_V1b ones, referring to VISIR-1.b.

6. Section 5.1 Environmental fields – should the URL next to "a lower resolution (0.4, URL)" go as a footnote?
   Done.
   To be changed in Sect.5.1

7. Figure 10 b – super clear and very interesting. An engaging plot.
   Thank you for this feedback.

References

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