Summary

Bertoncelj et al. introduce SCARIBOS, a regional configuration of the CROCO ocean model for the South CARIBbean Ocean System with a kilometre-scale horizontal resolution of 1/100 degree. The authors use four years (2020-2024) of surface velocity fields output by the model to undertake three Lagrangian particle tracking experiments using the OceanParcels framework to explore the surface connectivity of flows surrounding the island of Curaçao. The Lagrangian experiments allow the authors to investigate (a) potential hotspots of marine pollutants around Curaçao, (b) intra-island coastal connectivity, and (c) the connectivity between the Curaçao coast and the neighbouring Aruba, Bonaire, Venezuelan islands, and the Venezuelan mainland. The authors should be commended for the Figures, especially those relating to the Lagrangian analysis, which convey the central findings both clearly and creatively. The manuscript is generally well written, although a more comprehensive description of the numerical modelling approach (including model validation), further exploration of the role of mesoscale eddies in driving surface connectivity, and an improved discussion on the limitations and wider relevance of the findings is needed. I would recommend the manuscript for publication subject to major revisions addressing the comments made below and the excellent suggestions made by Reviewer #1.

General Comments

- ***The current title:*** 'Flow patterns, hotspots and connectivity of land-derived substances at the sea surface of Curaçao in the Southern Caribbean' feels like a description of what the author's set-out to investigate in this study but does not give any indication of the main findings or conclusions drawn from the analysis. Although the title is perfectly acceptable in its current form, I wonder whether it could improved to highlight the findings most relevant for stakeholders / policymakers.
- ***Model description and validation:*** Given that this is the first documentation of the SCARIBOS simulation and it is likely this will be used by other studies in the future, further details are needed to improve the model description, including highlighting the absence of Stokes Drift, stating whether a current feedback parameterisation is implemented, commenting on key parameterisation choices of ocean physics (e.g. in the surface mixed layer), and including the frequency at which velocity and tracer fields are output (this will be especially relevant for future studies). Moreover, as highlighted by Reviewer #1, the validation of the simulation is currently insufficient to robustly conclude that it accurately represents the circulation of the Caribbean Sea (see specific comments below). Moving forward, I would suggest broadening the validation beyond Curaçao to the wider Caribbean Sea domain and to use several sources of observations,

including surface drifters deployed in the region during the simulated period (2020-2024).

- ***Extracting maximum value from the 1/100 degree SCARIBOS simulation***: the Lagrangian analyses presented in the study are all well motivated and provide new insights into surface connectivity in the region. However, on reaching the conclusions of the manuscript, I did not feel that the full potential of this state-of-the-science simulation had been extracted. Firstly, it would be valuable to know if the insights presented are critically dependent on resolving flow structures at 1/100 degree or could similar conclusions be drawn using a much lower resolution. One powerful way to illustrate this would be to spatially coarsen the surface velocity field and repeat one or more of the Scenarios to examine how this impacts marine connectivity. A natural caveat here would be that the coarsened velocity field still originates from one which explicitly represented (sub)mesoscale dynamics, however, identifying the critical threshold of horizontal resolution required to represent connectivity in this region would be an incredibly valuable contribution of this work and would extend beyond the present application to Curaçao.
  Similarly, I think the authors could better exploit the eddy-resolving nature of the simulation to further investigate the role of mesoscale eddies beyond the primarily qualitative descriptions included currently. A valuable example of such an approach is Roach and Speer (2019) - https://doi.org/10.1029/2018JC014845 - which identified the timescales of variability in the flow field which are responsible for the connectivity between the Ross Gyre and the Antarctic Circumpolar Current by coarsening their 5-day mean velocity field to 90-day means and a single time-mean field. This allowed them to separate the connectivity associated with high-frequency (e.g., mesoscale eddies) and low-frequency (e.g., seasonal variability) variability from the time-mean flow. Given SCARIBOS explicitly resolves the (sub)mesoscale, using such a time-coarsening approach in this study could provide new insights into the role of high-frequency flow features in establishing the surface connectivity around Curaçao. This may also offer further retrospective justification for the use of a 1/100 simulation and underscore the value of such regional models for informing policy making and marine planning.

Specific Comments

Abstract

Lines 11-12: Suggest replacing ‘, as these substances…’ with ‘since these substances can be transported towards reef sites by ocean currents’ given that its already implied that the substance has entered the ocean.

Lines 13-16: Suggest combining the two sentences beginning with 'SCARIBOS, a fine-resolution…' and 'SCARIBOS covers the…' to reduce repetition. Then 'Furthermore,' can be dropped in the following sentence as it is not needed.

Lines 19-21: Suggest condensing these two sentences to be less ambiguous. For example: 'Our results reveal two dominant processes influencing the hotspot locations of positively buoyant substances…'

Line 24: As a non-domain expert on marine pollutants, I was surprised to see justification of this work as providing valuable information for marine conservation and environmental management at the end of the Abstract. The need for kilometre-scale modelling of ocean connectivity to inform stakeholders' decision-making struck me as an important motivation for pursuing the study alongside the current 'problem statement' highlighting the general decline of coral reef communities.

Introduction

Line 28: Suggest being more specific on the rates of coral reef decline, by how much has this changed already? Is this accelerating? This would further strengthen the motivation for the study.

Lines 30-32: Suggest combining these two sentences: 'are susceptible to accumulating pollutants, bacteria and viruses originating from urban areas, …'

Lines 34-35: As a non-domain expert, it would be interesting to know how the threat posed by the accumulation of marine pollutants and harmful biological substances around coral reefs compares to other threats, such as marine heat waves and ocean acidification. Why is this threat especially worth investigating?

Lines 36-46: Suggest revising or restructuring this paragraph as it's currently difficult to follow: it begins with a recognition that remote sources of marine pollutants are important for coral reefs, then proceeds to discuss why existing numerical model simulations are insufficient to represent the local ocean dynamics of the Caribbean, and concludes that developing a SCARIBOS model is the answer to this challenge. I wondered whether an alternative framing of this paragraph could be to highlight that in almost all ocean general circulation models, most notably the CMIP6 ensemble, Caribbean small island states are (at best) represented by a single grid cell or not at all, hence we are currently not in a position to translate global nor regional scale insights to local communities (who may be significantly impacted by unresolved processes). Thus, developing fine-resolution regional configurations like SCARIBOS provides a means to represent these regions more accurately and inform marine conservation and environmental management efforts.

Lines 44-47: Suggest refining this conclusion to be more precise. The preceding text highlights that there is only limited high-resolution ocean model data for the Caribbean

Sea, but why does it follow that we need a high-resolution model of Curaçao specifically. Is the coral reef environment here particular at risk or subject to emerging risks? Or are the ocean dynamics here representative of the wider region, such that the insights drawn from this study are applicable elsewhere?

Line 49: Suggest modifying to ‘our research investigates **the** dominant surface ocean current patterns and substance transport **pathways** around Curaçao…’

Line 50: Do you mean monthly to inter-annual **variability** rather than environmental changes? I found this to be ambiguous as ocean variability is discussed later in the text.

Line 51: Suggest using vertical **extent** here and elsewhere rather than reach in this context.

Lines 59-67: Not entirely sure this paragraph summarising the methodology is necessary on reading the full text since the description of the model and methods directly follows the introduction. As a compromise, it could be condensed to focus on the development of SCARIBOS as an answer to the research question which is nicely presented in the previous paragraph.

Methods

Figure 1: Suggest here and elsewhere ensuring that the colourbar ticks and contour levels are aligned to make it clear that the sea floor in the regions shown in white, for example, lies between 0-500 m depth etc.

Line 92: More appropriate, given the geographical location of this study, to refer to the Atlantic Meridional Overturning Circulation since you are referring to the warm upper limb waters feeding the Florida Straits.

Lines 120-121: Is this really a sufficient model spin-up time to ensure that the Lagrangian experiments are not capturing the ongoing adjustment of the mean flow and eddy kinetic energy fields? How was this determined? Further details should be included here.

Lines 122-125: What is the spatial resolution of the bathymetry product linearly interpolated from? What manual adjustments were made to the bathymetry? Further details on how this was undertaken and to what extent this (presumably) improved the resulting flow structures around the island should be included.

Lines 129-131: Is the interpolation scheme used to downscale the GLORYS12V1 velocity and tracer fields bilinear or conservative (conservative-normed)?

Line 132: When applying the surface atmospheric forcing does SCARIBOS account for the current feedback to the atmosphere (CFB), which contributes to the oceanic circulation by damping mesoscale eddies. (i.e., Does CROCCO account for the fact that the ERA5 surface wind stress field acting on the ocean has already ‘felt’ the surface ocean currents and hence simulations forced without CFB overestimate the mean circulation and the mesoscale activity). An excellent discussion on the use of reanalysis winds to force ocean models in provided in Section 6 of Renault et al., (2020) - https://doi.org/10.1029/2019MS001715.

Lines 134-135: At what frequency are the 2-D (surface) and 3-D velocity and tracer fields output from the SCARBIOS model? Are daily mean fields being used as the inputs to OceanParcels? This is currently unclear and should be added to both the model description and the description of the Lagrangian experiments undertaken in this study.

Lines 189-193: Unfortunately, I do not think that sufficient validation has been undertaken to justify the conclusion that 'SCARIBOS accurately simulates surface-level dynamics'. In this section, the model has been shown to reproduce the sea level timeseries at a single location and time-average currents agree qualitatively with limited observations in magnitude and direction. Reviewer #1 has made a number of excellent suggestions on ways to improve this validation, which I will not repeat here. I strongly support the use of surface drifters to validate the surface flow field. More broadly, I also think that the authors should comment (either in the methods or discussion section) on the somewhat philosophical challenge of undertaking simulations at kilometre-scale resolution in regions where observations are sparse – how do we know what good looks like? This also relates to my more general comment; I think it would be valuable for the authors to consider what is the minimum horizontal resolution needed to investigate connectivity in the Caribbean Sea (see general comments above).

Line 197: Suggest acknowledging here that the velocity fields do not include Stokes Drift rather than leaving this until the Discussion.

Lines 204-205: To be clear, does this equate to releasing a single particle in each 1/100 grid cell? How sensitive are the results of Scenario 1 to these initial conditions given that (sub)mesoscale turbulence is explicitly resolved in this simulation? Conceivably, given how chaotic the underlying velocity field is, a small difference in the initial position of a particle could result in a very different final position following 30 days of advection. An insightful discussion of the chaotic behaviour of Lagrangian trajectories is presented (albeit applied to ocean ventilation in a much coarser OGCM) in MacGilchrist et al. (2017) - https://doi.org/10.1002/2017JC012875.

Lines 205-206: The statement: 'The internal particle simulation timestep is set to 5 min and trajectories are archived every hour' is repeated for all three experiments. Suggest outlining the common features of the three scenarios in a final paragraph to reduce repetition.

Lines 209-210: Did you also consider calculating Lagrangian PDFs by counting the number of unique entries into each given grid cell normalised by the total number of particles (i.e, calculating the likelihood that any given particle will enter a grid cell at least once during its lifetime)? In my experience, this can improve the clarity of Lagrangian PDF plots where recirculation features are dominant and better illustrate the net flow pathways.

Lines 215-216: Why are particles released every 12 hours in Scenario 2 compared with every 24 hours in Scenario 1? Is the initial time of release important relative to the diurnal cycle of atmospheric forcing, what time each day does this take place? It would be helpful for the authors to comment more on these uncertainties.

Lines 225-226: Why are particle released two coastal grid cells away? Presumably, beaching of particles could be a problem when using a numerical time-stepping scheme to determine the trajectories?

Lines 236-237: Suggest adding a brief description of the locations of the remaining 1% of particles in Scenario 3 which do not leave the domain. Are these locations consistent between particle releases? If so, would regions of high particle persistence be particularly concerning for marine pollution and environmental management?

Figure 4: Excellent Figure, the authors have done a great job of visualising the differences between the Scenarios. Suggested modification to the final line of the Figure caption: 'The destination area highlighted around Curaçao represents the region within which particles are tagged as reaching the Curaçao coast.'

Results

Lines 250-257: In Figure 5b, interannual variability appears to dominate over seasonality, so I would suggest caution not to overinterpret monthly behaviour based on four years of surface velocity data. Caveating the discussion by highlighting the limited number of months available to sample (4 instances each) would be one approach.

Lines 263-266: Why is the analysis restricted to a single meridional cross section? A comparison of the 2-dimensional (longitude-latitude) flow field at various depths would properly account for the spatial dependence of the flow and to make the conclusion that the surface velocity field is representative of the upper ocean flow field more robust.

Lines 270-272: Are the T-S properties of the westward current consistent with AAIW at these latitudes? This would strongly support the inference.

Lines 273-280: This paragraph is quite confusing. The opening sentences largely repeat the findings above and third sentence seems to preface the say that the flow field is highly variable. I would also recommend removing 'observed' on Line 277 since (I think) you are still referring to the output of the SCARIBOS model here?

Lines 289-290: This concluding sentence feels slightly disjointed from the preceding text, which is a very nice synthesis. Perhaps, the component of the discussion that is missing is: is it reasonable to assume that the vertical motion of marine substances limited to the upper 10-20m which the surface velocity field is representative of?

Line 295: Suggest adding 'reveals significant monthly and inter-annual variability'. More generally, it would be interesting to assess statistically whether the variability seen between monthly release maps is stochastic versus seasonal-interannual in nature. A similarity metric, such as the Fraction of Unexplained Variance (FUV) could be used to compare months and assess how similar any given month is to its monthly climatology (e.g., what fraction of the PDF shown for April 2023 can be explained by the April (2020-2023) average).

Figure 8: As a non-domain expert, I found the large number of connectivity matrices in (c) to be difficult to interpret and, in contrast to the other Figures presented in the manuscript, to be the least effective at highlighting the key result of this Scenario. Two possible suggestions, which the authors are fully entitled to disregard, would be to replace the Source Zone numbers with geographical names as in (a) colouring font according to their location, and either masking or recolouring the 100% connectivity boxes (this value is known since particles are released here, but is the boldest feature in every subplot).

Discussion and Conclusions

Lines 370-372: This sentence could be clearer, suggest modifying to: 'There is {broad/strong/good} agreement between the surface current vectors simulated by SCARIBOS and those estimated from Lagrangian surface drifters in the Caribbean Sea between 1989 and 2003 (Richardson, 2005).'

Lines 369-375: Much of this discussion would be better placed in the methodology section validating the SCARBIOS model. This would ensure readers have greater confidence in the simulation's ability to represent the circulation in the Caribbean Sea before it is applied in the Lagrangian analysis, rather than discussing this retrospectively.

Lines 376-381: This brief discussion on cyclonic eddies is interesting, but I feel more could have been done in the Results to explore this (see earlier general comments on temporal coarsening), including coarsening the flow field in time to extract the signature of high-frequency flow components on the connectivity and persistence of marine pollution around Curaçao.

Lines 435-437: This raises an interesting discussion point on the residence times of particles around the coast, however, residence times were not addressed in the Results section. Was this intentional and based on a supplementary analysis of the particle residence times? It would be interesting (perhaps in future work) to combine the findings on the connectivity of positively buoyant marine substances with their residence timescales in coastal regions around Curaçao, since a highly connected reef with a low flushing (high residence) time scale would surely be more susceptible to marine pollutants.

Line 459-460: The absence of wave effects, including Stokes Drift, should be commented on in the methods section as it's an important limitation of the surface velocity field used in the Lagrangian analysis.

Lines 474-484: This concluding section on 'Implications and future directions' could be improved by emphasising the value of the SCARIBOS 1/100 simulation – what have we learnt with this model which is not attainable at lower resolution – and identifying several future questions which will directly inform policymakers and stakeholders. Currently, plastic debris, coral larvae and marine pollution are discussed collectively, but it would be interesting to know how SCARIBOS outputs could be used in each case, thereby underscoring its long-term value as both a scientific and societal resource. For example, could SCARBIOS be used to predict (or train an ML model to predict) pollutant spills and the resulting environmental impacts?