

¹ VirtualShip for simulating oceanographic fieldwork anywhere in the global ocean

³ Jamie R. C. Atkins  ^{1,2}¶, Emma E. Daniels  ¹, Nick Hodgskin², Aart C. Stuurman¹, Iury Simoes-Sousa  ³, and Erik van Sebille  ^{1,2}

⁵ 1 Freudenthal Institute, Utrecht University, the Netherlands 2 Institute for Marine and Atmospheric Research, Utrecht University, the Netherlands 3 Woods Hole Oceanographic Institution, Falmouth, MA, USA ¶ Corresponding author

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

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Submitted: 01 January 1970

Published: unpublished

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⁸ Summary

⁹ VirtualShip is a Python-based package for simulating measurements as if they were coming from real-life oceanographic instruments, facilitating student training, expedition planning, and design of instrument/sampling strategies. The software exploits the customisability of the open-source Parcels Lagrangian simulation framework ([Delandmeter & van Sebille, 2019](#); [Lange & van Sebille, 2017](#)) and builds a virtual ocean by streaming data from the [Copernicus Marine Data Store](#) on-the-fly, enabling expeditions anywhere on the globe.

¹⁵ Statement of need

¹⁶ Marine science relies on fieldwork for data collection, yet sea-going opportunities are limited due to financial costs, logistical constraints, and environmental burdens. We present an alternative means, namely VirtualShip, for training scientists to conduct oceanographic fieldwork in an authentic manner, to plan future expeditions and deployments, and to directly compare observational and instrumental strategies with model data.

²¹ VirtualShip goes beyond simply extracting grid-cell values from model output. Instead, it uses programmable behaviours and sophisticated interpolation techniques (with Parcels underpinnings) to access data in exact locations and timings, as if they were being collected by real-world instruments. VirtualShip shares some functionality with existing tools, such as OceanSpy ([Almansa et al., 2019](#)) and VirtualFleet ([Maze & Balem, 2023](#)), but extends capabilities to mesh many different instrument deployments into a unified expedition simulation framework. Moreover, VirtualShip exploits readily available, streamable data via the Copernicus Marine Data Store, removing the need for users to download and manage large datasets locally and/or arrange for access to remote servers. VirtualShip can also integrate coordinate files exported from the [Marine Facilities Planning](#) (MFP) tool, giving users the option to define expedition waypoints via an intuitive web-based mapping interface.

³² Functionality

³³ VirtualShip simulates the deployment of virtual instruments commonly used in oceanographic fieldwork, with emphasis on realism in how users plan and execute expeditions. For example, users must consider ship speed and instrument deployment/recovery times to ensure their expedition is feasible within given time constraints. Possible instrument selections include surface Drifter ([Lumpkin et al., 2017](#)), CTD (Conductivity-Temperature-Depth; Johnson et al. (2007)), Argo float ([Jayne et al., 2017](#)), XBT (Expendable Bathythermograph; Goni et al. (2019)), underway ADCP (Acoustic Doppler Current Profiler; Kostaschuk et al. (2005)), and

⁴⁰ underway Underwater_temperature/salinity ([Gordon et al., 2014](#)) probes. More detail on
⁴¹ each instrument is available in the [documentation](#).

⁴² The software can simulate complex multidisciplinary expeditions. One example is a virtual
⁴³ expedition across the Agulhas Current and the South Eastern Atlantic that deploys a suite
⁴⁴ of instruments to sample physical and biogeochemical properties ([Figure 1](#)). Key circulation
⁴⁵ features appear early in the expedition track, with enhanced ADCP speeds marking the strong
⁴⁶ Agulhas Current ([Figure 1b](#)) and drifters that turn back toward the Indian Ocean indicating
⁴⁷ the Agulhas Retroflection ([Figure 1c](#)). The CTD profiles capture the vertical structure of
⁴⁸ temperature and oxygen along the route, including the warmer surface waters of the Agulhas
⁴⁹ region ([Figure 1d](#), early waypoints) and the Oxygen Minimum Zone in the South Eastern
⁵⁰ Atlantic ([Figure 1e](#), final waypoints).

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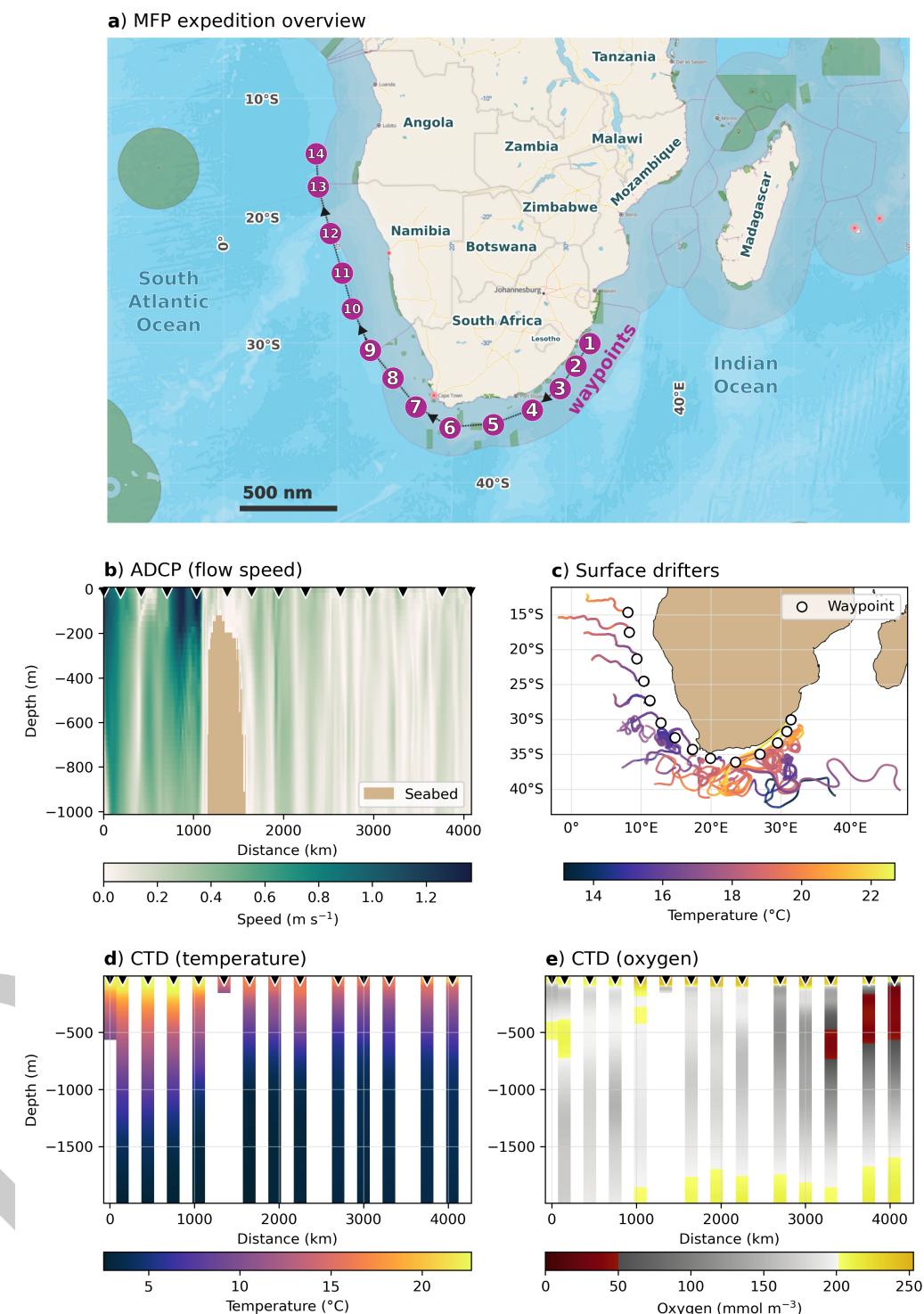


Figure 1: Example VirtualShip expedition simulated in July/August 2023. Expedition waypoints displayed via the NIOZ MFP tool (a), Underway ADCP measurements (b), Surface drifter releases (c; 90-day lifetime per drifter), and CTD vertical profiles for temperature (d) and oxygen (e). Black triangles in b), d) and e) mark waypoint locations across the expedition route, corresponding to the purple markers in a).

⁵¹ The software is designed to be highly intuitive to the user. It is wrapped into three high-level
⁵² command line interface commands (using Click):

- 53 1. `virtualship init`: Initialises the expedition directory structure and an `expedition.yaml`
54 configuration file, which controls the expedition route, instrument choices and deploy-
55 ment timings. A common workflow is for users to import pre-determined waypoint
56 coordinates using the `--from-mfp` flag in combination with a coordinates `.csv` or `.xlsx`
57 file (e.g. exported from the [MFP](#) tool).
- 58 2. `virtualship plan`: Launches a user-friendly Terminal-based expedition planning User
59 Interface (UI), built using [Textual](#). This allows users to intuitively set their waypoint
60 timings and instrument selections, and also modify their waypoint locations.
- 61 3. `virtualship run`: Executes the virtual expedition according to the planned configuration.
62 This includes streaming data via the [Copernicus Marine Data Store](#), simulating the
63 instrument behaviours and sampling, and saving the output in [Zarr](#) format.

64 A full example workflow is outlined in the [Quickstart Guide](#) documentation.

65 Implementation

66 Under the hood, VirtualShip is modular and extensible. The workflows are designed around
67 Instrument base classes and instrument-specific subclasses and methods. This means the
68 platform can be easily extended to add new instrument types. Instrument behaviours are coded
69 as Parcels kernels, which allows for extensive customisability. For example, a Drifter advects
70 passively with ocean currents, a CTD performs vertical profiling in the water column and an
71 ArgoFloat cycles between ascent, descent and drift phases, all whilst sampling physical and/or
72 biogeochemical fields at their respective locations and times.

73 Moreover, the data ingestion system relies on Analysis-Ready and Cloud-Optimized data
74 (ARCO; Stern et al. (2022), Abernathey et al. (2021)) streamed directly from the Copernicus
75 Marine Data Store, via the [copernicusmarine](#) Python toolbox. This means users can simulate
76 expeditions anywhere in the global ocean without downloading large datasets by default.
77 Leveraging the suite of [physics and biogeochemical products](#) available on the Copernicus
78 platform, expeditions are possible from 1993 to present and forecasted two weeks into the
79 future. There is also an [option](#) for the user to specify local NetCDF files for data ingestion, if
80 preferred.

81 Applications and future outlook

82 VirtualShip has already been extensively applied in Master's teaching settings at Utrecht
83 University as part of the [VirtualShip Classroom](#) initiative. Educational assignments and tutorials
84 have been developed alongside to integrate the tool into coursework, including projects where
85 students design their own research question(s) and execute their fieldwork and analysis using
86 VirtualShip. Its application has been shown to be successful, with students reporting increased
87 self-efficacy and knowledge in executing oceanographic fieldwork (Daniels et al., 2025).

88 The package opens space for many other research applications. It can support real-life
89 expedition planning by letting users test sampling routes before going to sea. It also provides
90 tooling to explore real-time adaptive strategies in which sampling plans shift as forecasts or
91 observations update. The same workflow can also be used to investigate sampling efficiency,
92 for example, examining how waypoint number or spacing shapes the ability to capture features
93 of interest. Moreover, the software is well-suited for developing Observation System Simulation
94 Experiments (OSSEs; e.g. Errico et al. (2013)) to test and optimise observational strategies
95 in a cost- and time-efficient manner.

96 Both the customisability of the VirtualShip platform and the exciting potential for new
97 ARCO-based data hosting services in domains beyond oceanography (e.g., [atmospheric science](#))
98 means there is potential to extend VirtualShip (or "VirtualShip-like" tools) to other domains
99 in the future. Furthermore, as the Parcels underpinnings themselves continue to evolve, with

100 a future (at time of writing) [v4.0 release](#) focusing on alignment with [Pangeo](#) standards and
101 Xarray data structures ([Hoyer & Hamman, 2017](#)), VirtualShip will also benefit from these
102 improvements, further enhancing its capabilities, extensibility and compatibility with modern
103 cloud-based data pipelines.

104 Acknowledgements

105 The VirtualShip project is funded through the Utrecht University-NIOZ (Royal Netherlands
106 Institute for Sea Research) collaboration.

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