

VirtualShip for simulating oceanographic fieldwork anywhere in the global ocean

Jamie R. C. Atkins^{1,2¶}, Emma E. Daniels¹, Nick Hodgskin², Aart C. Stuurman¹, Iury Simoes-Sousa³, and Erik van Sebille^{1,2}

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

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Summary

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.

Statement of need

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.

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* ([Almansi 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.

Functionality

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](#).

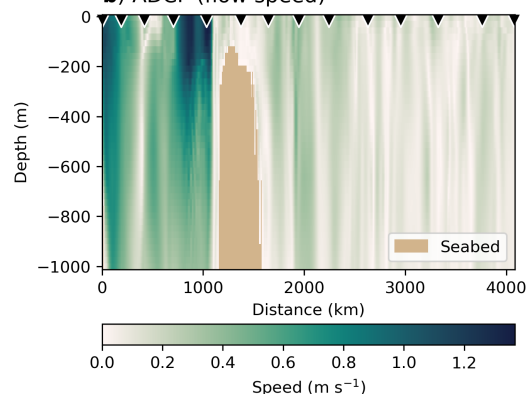
42 The software can simulate complex multidisciplinary expeditions. One example is a virtual
43 expedition across the Agulhas Current and the South Eastern Atlantic that deploys a suite
44 of instruments to sample physical and biogeochemical properties (Figure 1). Key circulation
45 features appear early 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 Retroflexion (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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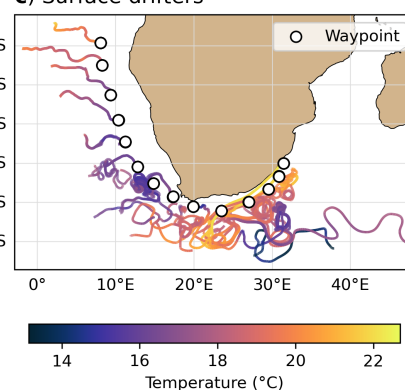
a) MFP expedition overview



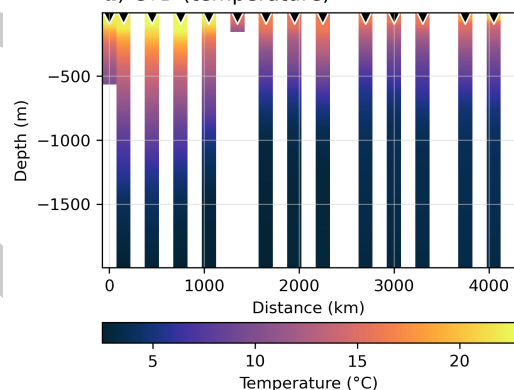
b) ADCP (flow speed)



c) Surface drifters



d) CTD (temperature)



e) CTD (oxygen)

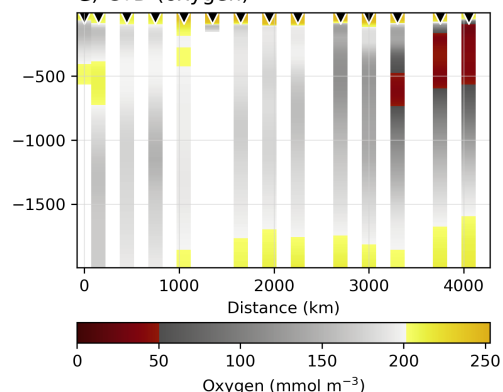


Figure 1: Example VirtualShip expedition simulated in July/August 2023. Expedition waypoints displayed via the NIOZ MFP tool (a), Underway ADCP measurements (b), Surface drifter releases (c; 90-day lifetime per drifter), and CTD vertical profiles for temperature (d) and oxygen (e). Black triangles in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

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

Implementation

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

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

Applications and future outlook

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

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

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

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

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