

¹ ROMS-Tools: Reproducible and Scalable ² Preprocessing and Analysis for Regional Ocean ³ Modeling with ROMS

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¹⁰ Summary

¹¹ The ocean regulates Earth's climate and sustains marine ecosystems by circulating and storing
¹² heat, carbon, oxygen, and nutrients, while exchanging gases with the atmosphere. Scientists
¹³ study these processes using ocean models, which simulate the ocean on a grid. **Regional ocean**
¹⁴ **models** focus computational resources on a limited geographical area with fine grid spacing,
¹⁵ and can resolve fine-scale phenomena such as mesoscale and submesoscale features, tidal
¹⁶ dynamics, coastal currents, upwelling, and detailed biogeochemical (BGC) processes. A widely
¹⁷ used regional ocean model is the **Regional Ocean Modeling System (ROMS)** ([Shchepetkin &](#)
¹⁸ [McWilliams, 2005](#)). ROMS has been coupled to the Marine Biogeochemistry Library (MARBL)
¹⁹ ([Long et al., 2021; Molemaker & contributors, 2025a](#)) to link physical and BGC processes.
²⁰ ROMS-MARBL supports research on environmental management, fisheries, regional climate
impacts, and ocean-based carbon dioxide removal (CDR) strategies.

²¹ Configuring a regional ocean model like ROMS-MARBL is technically challenging. Setting up
a model requires initializing and forcing it with oceanic and atmospheric data from multiple
external sources in diverse formats, which can reach several petabytes for global datasets.
²⁵ These data must be subsetted, processed, and mapped onto the target domain's geometry,
producing input datasets of 10–100 terabytes for large regional models. Generating these
²⁶ input files is time-consuming, error-prone, and hard to reproduce, creating a bottleneck for
²⁷ both new and experienced users. The Python package ROMS-Tools addresses this challenge
²⁸ by providing efficient, task-backed ([Dask Development Team, 2016](#)), user-friendly tools that
²⁹ can be installed via Conda or PyPI and run interactively from Jupyter notebooks. It supports
³⁰ creating regional grids, preprocessing all required model inputs, and postprocessing and analysis.
³¹ Current capabilities are fully compatible with UCLA-ROMS ([Molemaker & contributors, 2025a,](#)
³² [2025b](#)), with potential support for other ROMS versions, such as Rutgers ROMS ([Arango &](#)
³³ [contributors, 2024](#)), in the future.

³⁵ Input Data and Preprocessing

³⁶ ROMS-Tools generates the following input files for ROMS-MARBL:

- ³⁷ 1. **Model Grid:** Customizable, curvilinear, and orthogonal grid designed to maintain a nearly
³⁸ uniform horizontal resolution across the domain. The grid is rotatable to align with
³⁹ coastlines and features a terrain-following vertical coordinate.
- ⁴⁰ 2. **Bathymetry:** Derived from **SRTM15** ([Tozer et al., 2019](#)).

- 41 3. **Land Mask:** Inferred from coastlines provided by **Natural Earth** or the Global Self-
42 consistent, Hierarchical, High-resolution Geography (**GSHHG**) Database ([Wessel &](#)
43 [Smith, 1996](#)).
44 4. **Physical Ocean Conditions:** Initial and open boundary conditions for sea surface height,
45 temperature, salinity, and velocities derived from the 1/12° Global Ocean Physics
46 Reanalysis (**GLORYS**) ([Lellouche et al., 2021](#)).
47 5. **BGC Ocean Conditions:** Initial and open boundary conditions for dissolved inorganic
48 carbon, alkalinity, and other biogeochemical tracers from Community Earth System
49 Model (**CESM**) output ([Yeager et al., 2022](#)) or hybrid observational-model sources
50 ([Garcia et al., 2019](#); [Huang et al., 2022](#); [Laevset et al., 2016](#); [Yang et al., 2020](#); [Yeager
51 et al., 2022](#))
52 6. **Meteorological forcing:** Wind, radiation, precipitation, and air temperature/humidity
53 processed from the global 1/4° ECMWF Reanalysis v5 (**ERA5**) ([Hersbach et al., 2020](#))
54 with optional corrections for radiation bias and coastal wind.
55 7. **BGC surface forcing:** Partial pressure of carbon dioxide, as well as iron, dust, and
56 nitrogen deposition from **CESM** output ([Yeager et al., 2022](#)) or hybrid observational-
57 model sources ([Hamilton et al., 2022](#); [Kok et al., 2021](#); [Landschützer et al., 2016](#); [Yeager
58 et al., 2022](#)).
59 8. **Tidal Forcing:** Tidal potential, elevation, and velocities derived from **TPXO** ([Egbert &
60 Erofeeva, 2002](#)) including self-attraction and loading (SAL) corrections.
61 9. **River Forcing:** Freshwater runoff derived from **Dai & Trenberth** ([Dai & Trenberth, 2002](#))
62 or user-provided custom files.
63 10. **CDR Forcing:** User-defined interventions that inject BGC tracers at point sources or
64 as larger-scale Gaussian perturbations, designed to simulate CDR interventions. The
65 CDR forcing provides an external forcing term prescribed as volume and tracer fluxes
66 (e.g., alkalinity for ocean alkalinity enhancement, iron for iron fertilization, or other BGC
67 constituents). Users can specify the magnitude, spatial footprint, and time dependence
68 of the forcing, enabling flexible representation of CDR interventions.

69 Some source datasets are accessed automatically by the package, including Natural Earth, Dai
70 & Trenberth runoff, and ERA5 meteorology, while users must manually download SRTM15,
71 GSHHG, GLORYS, the BGC datasets, and TPXO tidal files. Although these are the datasets
72 currently supported, the package's modular design makes it straightforward to add new sources
73 in the future.

74 To generate the model inputs, ROMS-Tools automates several intermediate processing steps,
75 including:

- 76 ▪ **Bathymetry processing:** The bathymetry is smoothed in two stages, first across the
77 entire model domain and then locally in areas with steep slopes, to ensure local steepness
78 ratios do not exceed a prescribed threshold in order to reduce pressure-gradient errors.
79 A minimum depth is enforced to prevent water levels from becoming negative during
80 large tidal excursions.
- 81 ▪ **Mask definition:** The land-sea mask is generated by comparing the ROMS grid's
82 horizontal coordinates with a coastline dataset using the `regionmask` package ([Hauser
83 et al., 2024](#)). Enclosed basins are subsequently filled with land.
- 84 ▪ **Land value handling:** Land values are filled via an algebraic multigrid method using `pyamg`
85 ([Bell et al., 2023](#)) prior to horizontal regridding. This extends ocean values into land
86 areas to resolve discrepancies between source data and ROMS land masks, preventing
87 land-originating values from appearing in ocean cells.
- 88 ▪ **Regridding:** Ocean and atmospheric fields are horizontally and vertically regridded from
89 standard latitude-longitude-depth grids to the model's curvilinear grid with a terrain-
90 following vertical coordinate using `xarray` ([Hoyer & Hamman, 2017](#)). Optional sea
91 surface height corrections can be applied, and velocities are rotated to align with the
92 curvilinear ROMS grid.
- 93 ▪ **Longitude conventions:** ROMS-Tools handles differences in longitude conventions,

94 converting between $[-180^\circ, 180^\circ]$ and $[0^\circ, 360^\circ]$ as needed.
 95 ▪ **River locations:** Rivers that fall within the model domain are automatically identified
 96 and relocated to the nearest coastal grid cell. Rivers that need to be shifted manually or
 97 span multiple cells can be configured by the user.
 98 ▪ **Data streaming:** ERA5 atmospheric data can be accessed directly from the cloud,
 99 removing the need for users to pre-download large datasets locally. Similar streaming
 100 capabilities may be implemented for other datasets in the future.

101 Users can quickly design and visualize regional grids and inspect all input fields with built-in
 102 plotting utilities. An example of surface initial conditions generated for a California Current
 103 System simulation at 5 km horizontal grid spacing is shown in [Figure 1](#).

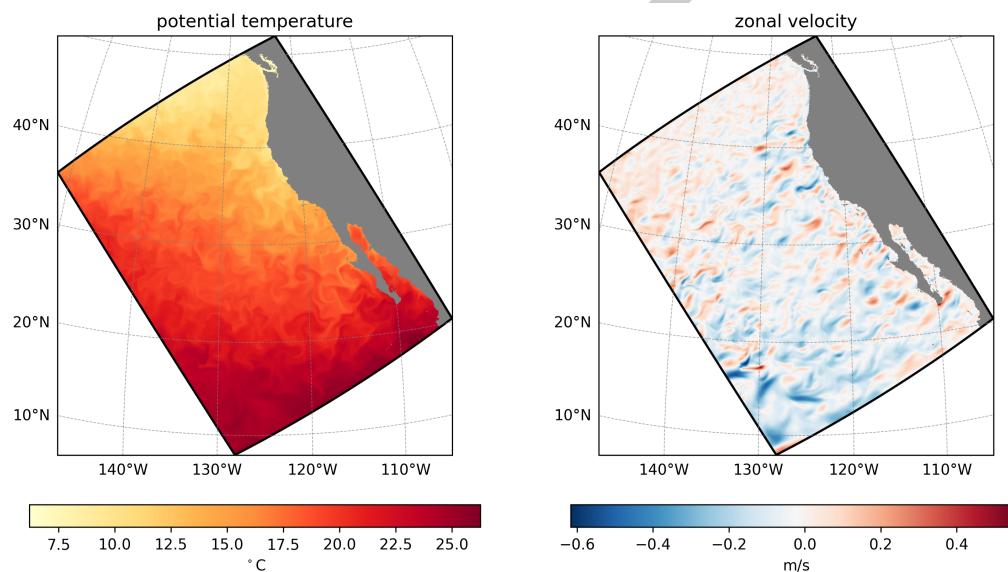


Figure 1: Surface initial conditions for the California Current System created with ROMS-Tools from GLORYS. Left: potential temperature. Right: zonal velocity. Shown for January 1, 2000.

104 Postprocessing and Analysis

105 ROMS-Tools provides tools for postprocessing and analyzing ROMS-MARBL output, including
 106 regridding from the native curvilinear, terrain-following grid to a standard latitude-longitude-
 107 depth grid using xesmf ([Zhuang et al., 2023](#)) and built-in plotting on both grids. The analysis
 108 layer also includes specialized utilities for evaluating carbon dioxide removal (CDR) interventions,
 109 such as generating carbon uptake and efficiency curves.

110 Statement of Need

111 Setting up a regional ocean model is a major technical undertaking. Traditionally, this
 112 work relied on a patchwork of custom scripts and lab-specific workflows, which can be time-
 113 consuming, error-prone, and difficult to reproduce. These challenges slow down science, create
 114 a steep barrier to entry for new researchers, and limit collaboration across groups.

115 Within the ROMS community, the preprocessing landscape has been shaped by tools like pyroms
 116 ([Hedstrom & contributors, 2023](#)). While providing valuable low-level utilities, pyroms presents
 117 challenges for new users: installation is cumbersome due to Python/Fortran dependencies, the
 118 API is inconsistent, documentation is limited, and it lacks tests, CI, and support for modern
 119 Python tools like xarray and dask. Since active development has largely ceased, its suitability
 120 for new projects, such as CDR simulations, is limited.

121 Tools from other modeling communities cannot simply be adopted, since each ocean model
122 has distinct structural requirements. For example, the new `regional-mom6` package ([Barnes](#)
123 [et al., 2024](#)), developed for the Modular Ocean Model v6 (MOM6) ([Adcroft et al., 2019](#)),
124 cannot be used to generate ROMS inputs, because ROMS employs a terrain-following vertical
125 coordinate system that requires a specialized vertical regridding approach, whereas MOM6
126 accepts inputs on arbitrary depth levels and does not require vertical regridding at all. Several
127 other differences further prevent cross-compatibility. Together, these limitations underscored
128 the need for a modern, maintainable, and reproducible tool designed specifically for ROMS.¹

129 ROMS-Tools was developed to meet this need. It draws on the legacy of the MATLAB
130 preprocessing scripts developed at UCLA ([Molemaker, 2024](#)), which encapsulate decades of
131 expertise in configuring regional ocean model inputs. While many of the core algorithms and
132 design principles are retained, ROMS-Tools provides an open-source Python implementation of
133 these MATLAB tools using an object-oriented programming paradigm. This implementation
134 enables a modernized workflow driven by high-level user API calls, enhancing reproducibility,
135 reducing the potential for user errors, and supporting extensibility for additional features, forcing
136 datasets, and use cases. In some cases, ROMS-Tools diverges from the MATLAB implementation
137 to take advantage of new methods or better integration with the modern Python ecosystem.
138 By streamlining input generation and analysis, ROMS-Tools reduces technical overhead, lowers
139 the barrier to entry, and enables scientists to focus on research rather than data preparation.

140 Software Design

141 ROMS-Tools is designed to balance **ease of use, flexibility, reproducibility, and scalability** by
142 combining high-level user interfaces with a modular, extensible architecture.

143 Design Trade-Offs

144 A central design trade-off in ROMS-Tools is between **automation** and **user control**. Rather than
145 enforcing a fixed workflow, the package exposes key choices, such as physical options (e.g.,
146 radiation or wind corrections), interpolation and fill methods, and computational backends.
147 This contrasts with more opinionated frameworks that fix defaults and directory structures to
148 maximize automation. While users make explicit decisions, some steps remain automated to
149 prevent errors; for example, bathymetry smoothing is applied automatically with a non-tunable
150 parameter, since overly small smoothing factors could produce rough bathymetry and crash
151 simulations. This approach balances flexibility and safety, enabling transparent experimentation
152 without exposing users to avoidable pitfalls.

153 Another key trade-off is between **monolithic workflows** and **incremental, modular steps**.
154 ROMS-Tools uses small, composable components, such as generating initial conditions,
155 boundary forcing, and surface forcing. Each component can be executed, saved, and revisited
156 independently. This avoids unnecessary recomputation when only some inputs change. To
157 ensure reproducibility despite a modular workflow, configuration choices are stored in compact,
158 text-based YAML files. These files are version-controllable, easy to share, and remove the
159 need to transfer large model input NetCDF datasets.

160 Architecture and Rationale

161 At the user-facing level, ROMS-Tools provides high-level objects such as `Grid`, `InitialConditions`,
162 and `BoundaryForcing`. Each object exposes a consistent interface (`.ds`, `.plot()`, `.save()`,
163 `.to_yaml()`), so users can always call the same methods in sequence or inspect attributes that
164 are guaranteed to exist. This object-oriented design reduces cognitive overhead and makes
165 workflows predictable and easy to follow.

¹In the future, packages like ROMS-Tools and `regional-mom6` could share a common backbone, with
model-specific adaptations layered on top.

166 Internally, ROMS-Tools uses a **layered, modular architecture**. Abstract base classes
167 (`LatLonDataset`, `ROMSDataset`) handle data ingestion and preprocessing. Source-specific
168 datasets (e.g., `ERA5Dataset`, `GLORYSDataset`, `SRTMDataset`) inherit from these base classes
169 and encode dataset-specific conventions, such as variable names, coordinates, and masking.
170 Common operations, like subdomain selection and lateral filling, are implemented once and
171 reused across datasets. Adding a new data source usually requires only a small subclass to
172 define variable mappings while reusing the existing subsetting, filling, regridding, and I/O logic.
173 This approach keeps changes to the core code minimal.

174 Computational and Data Model Choices

175 ROMS-Tools is built on `xarray`, which lets users take advantage of its clear, consistent interface
176 for exploring and inspecting datasets. The package integrates seamlessly with the broader
177 Pangeo ecosystem. Optional dask support allows workflows to scale from a laptop to HPC
178 systems, enabling parallel and out-of-core computation for very large input and output datasets.

179 Research Impact Statement

180 ROMS-Tools serves two primary user communities. First, ocean modelers developing new
181 regional domains rely on it to generate input datasets for ROMS simulations. External users
182 in this category include researchers at **PNNL**, **WHOI**, **UCLA**, and in **New Zealand and**
183 **Australia**. Second, researchers in the ocean-based carbon dioxide removal (CDR) community
184 use ROMS-Tools to set up reproducible ROMS-MARBL simulations of climate intervention
185 scenarios, with adopters such as **[C]Worthy**, **Carbon to Sea**, **Ebb Carbon**, and **SCCWRP**. All
186 of these users have contacted the developers directly or consulted offline regarding their use of
187 the package.

188 Broader engagement is evident from GitHub stars, with users from institutions including the
189 University of Waikato, NCAR, University of Maryland, National Oceanography Centre, Fathom
190 Science, McGill University, Gwangju Institute of Science and Technology, UC Santa Cruz,
191 RedLine Performance Solutions, and Submarine.

192 ROMS-Tools is also integrated into broader workflows, including **C-Star(?)**, an open-source
193 platform to provide scientifically credible monitoring, reporting, and verification (MRV) for the
194 emerging marine carbon market.

195 AI Usage Disclosure

196 Generative AI tools were used to assist with writing docstrings and developing tests for the
197 ROMS-Tools software, to improve the clarity and readability of the documentation, and to
198 shorten and edit portions of the manuscript text. All AI-assisted content was reviewed and
199 verified by the authors for technical accuracy and correctness.

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