

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

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⁹ Summary

¹⁰ The ocean regulates Earth's climate and sustains marine ecosystems by circulating and storing
¹¹ heat, carbon, oxygen, and nutrients, while exchanging heat and gases with the atmosphere.
¹² Scientists study these processes using ocean models, which simulate the ocean on a grid.
¹³ **Regional ocean models** focus computational resources on a limited geographical area with fine
¹⁴ grid spacing, and can resolve fine-scale phenomena such as mesoscale and submesoscale features,
¹⁵ tidal dynamics, coastal currents, upwelling, and detailed biogeochemical (BGC) processes.
¹⁶ A widely used regional ocean model is the **Regional Ocean Modeling System (ROMS)**
¹⁷ ([Shchepetkin & McWilliams, 2005](#)). ROMS has been coupled to the Marine Biogeochemistry
¹⁸ Library (MARBL) ([Long et al., 2021](#); [Molemaker & contributors, 2025a](#)) to link physical and
¹⁹ BGC processes. ROMS-MARBL supports research on environmental management, fisheries,
²⁰ regional climate impacts, and ocean-based carbon dioxide removal (CDR) strategies.

²¹ Configuring a regional ocean model like ROMS-MARBL is technically challenging; it requires
initialization and time-dependent forcing from oceanic and atmospheric data drawn from
multiple external sources in diverse formats. These global datasets can reach several petabytes
²² and must be subsetted, processed, and mapped onto the target domain's geometry, yielding
²³ input datasets of 10–100 terabytes for large regional models. Generating these input files is
²⁴ time-consuming, error-prone, and hard to reproduce, creating a bottleneck for both new and
²⁵ experienced users. The Python package ROMS-Tools addresses this challenge by providing
²⁶ efficient, dask-backed ([Dask Development Team, 2016](#)), user-friendly tools that can be installed
²⁷ via Conda or PyPI and run interactively from Jupyter notebooks. The package supports creating
²⁸ regional grids, preprocessing all required model inputs, and postprocessing and analysis. Current
²⁹ capabilities are fully compatible with UCLA-ROMS ([Molemaker & contributors, 2025a, 2025b](#)),
³⁰ with potential support for other ROMS versions, such as Rutgers ROMS ([Arango & contributors,](#)
³¹ [2024](#)), in the future.

³⁴ Input Data and Preprocessing

³⁵ ROMS-Tools generates the following input files for ROMS-MARBL:

- ³⁶ 1. **Model Grid:** Customizable, curvilinear, and orthogonal grid designed to maintain a nearly
³⁷ uniform horizontal resolution across the domain. The grid is rotatable to align with
³⁸ coastlines and features a terrain-following vertical coordinate.
- ³⁹ 2. **Bathymetry:** Derived from **SRTM15** ([Tozer et al., 2019](#)).
- ⁴⁰ 3. **Land Mask:** Inferred from coastlines provided by **Natural Earth** or the Global Self-
⁴¹ consistent, Hierarchical, High-resolution Geography (**GSHHG**) Database ([Wessel &](#)

Smith, 1996).

4. **Physical Ocean Conditions:** Initial and open boundary conditions for sea surface height, temperature, salinity, and velocities derived from the $1/12^\circ$ Global Ocean Physics Reanalysis (**GLORYS**) ([Lelloche et al., 2021](#)).
 5. **BGC Ocean Conditions:** Initial and open boundary conditions for dissolved inorganic carbon, alkalinity, and other biogeochemical tracers from Community Earth System Model (**CESM**) output ([Yeager et al., 2022](#)) or hybrid observational-model sources ([Garcia et al., 2019](#); [Huang et al., 2022](#); [Lauvset et al., 2016](#); [Yang et al., 2020](#); [Yeager et al., 2022](#)).
 6. **Meteorological forcing:** Wind, radiation, precipitation, and air temperature/humidity processed from the global $1/4^\circ$ ECMWF Reanalysis v5 (**ERA5**) ([Hersbach et al., 2020](#)) with optional corrections for radiation bias and coastal wind.
 7. **BGC surface forcing:** Partial pressure of carbon dioxide, as well as iron, dust, and nitrogen deposition from **CESM** output ([Yeager et al., 2022](#)) or hybrid observational-model sources ([Hamilton et al., 2022](#); [Kok et al., 2021](#); [Landschützer et al., 2016](#); [Yeager et al., 2022](#)).
 8. **Tidal Forcing:** Tidal potential, elevation, and velocities derived from **TPXO** ([Egbert & Erofeeva, 2002](#)) including self-attraction and loading (SAL) corrections.
 9. **River Forcing:** Freshwater runoff derived from **Dai & Trenberth** ([Dai & Trenberth, 2002](#)) or user-provided custom files.
 10. **CDR Forcing:** User-defined interventions that inject BGC tracers at point sources or as larger-scale Gaussian perturbations to simulate CDR interventions. The CDR forcing is prescribed as volume and tracer fluxes (e.g., alkalinity for ocean alkalinity enhancement, iron for iron fertilization, or other BGC constituents). Users can control the magnitude, spatial footprint, and temporal evolution, allowing flexible representation of CDR interventions.

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

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

- **Bathymetry processing:** The bathymetry is smoothed in two stages, first across the entire model domain and then locally in areas with steep slopes, to ensure local steepness ratios do not exceed a prescribed threshold in order to reduce pressure-gradient errors. A minimum depth is enforced to prevent water levels from becoming negative during large tidal excursions.
 - **Mask definition:** The land-sea mask is generated by comparing the ROMS grid's horizontal coordinates with a coastline dataset using the `regionmask` package ([Hauser et al., 2024](#)). Enclosed basins are subsequently filled with land.
 - **Land value handling:** Land values are filled via an algebraic multigrid method using `pyamg` ([Bell et al., 2023](#)) prior to horizontal regridding. This extends ocean values into land areas to resolve discrepancies between source data and ROMS land masks, preventing land-originating values from appearing in ocean cells.
 - **Regridding:** Ocean and atmospheric fields are horizontally and vertically regridded from standard latitude-longitude-depth grids to the model's curvilinear grid with a terrain-following vertical coordinate using `xarray` ([Hoyer & Hamman, 2017](#)) and `xgcm` ([Busecke & contributors, 2025](#)). Velocities are rotated to align with the curvilinear ROMS grid.
 - **Longitude conventions:** ROMS-Tools handles differences in longitude conventions, converting between $[-180^\circ, 180^\circ]$ and $[0^\circ, 360^\circ]$ as needed.
 - **River locations:** Rivers that fall within the model domain are automatically identified and relocated to the nearest coastal grid cell. Rivers that need to be shifted manually or

95 span multiple cells can be configured by the user.
 96 ▪ **Data streaming:** ERA5 atmospheric data can be accessed directly from the cloud,
 97 removing the need for users to pre-download large datasets locally. Similar streaming
 98 capabilities may be implemented for other datasets in the future.
 99 Users can quickly design and visualize regional grids and inspect all input fields with built-in
 100 plotting utilities. An example of surface initial conditions generated for a California Current
 101 System simulation at 5 km horizontal grid spacing is shown in [Figure 1](#).

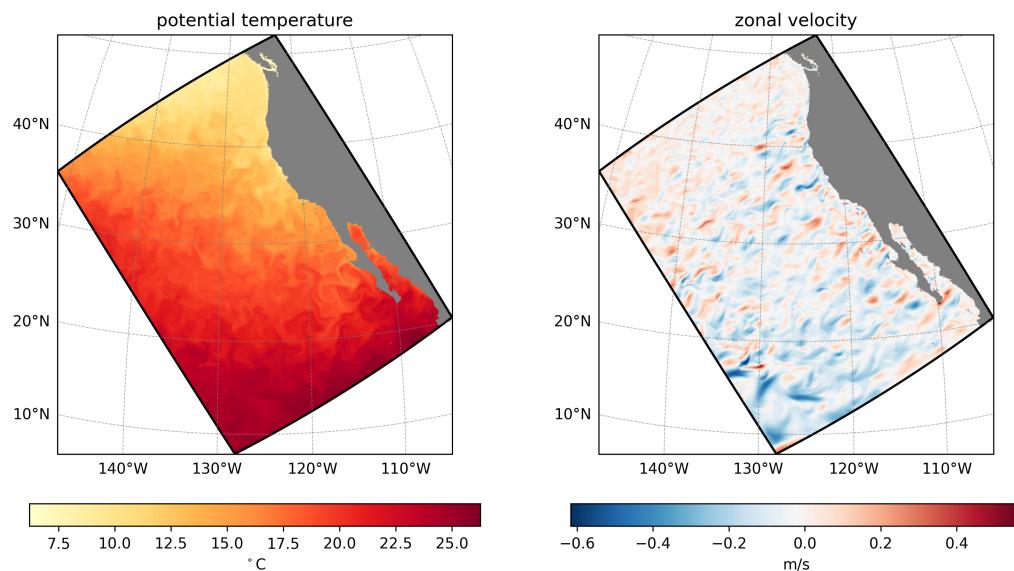


Figure 1: Surface initial conditions for the California Current System created with ROMS-Tools from GLORYS. Left: potential temperature. Right: zonal velocity. Shown for January 1, 2000.

102 Postprocessing and Analysis

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

108 Statement of Need

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

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

119 Tools from other modeling communities cannot simply be adopted, since each ocean model
 120 has distinct structural requirements. For example, the regional-mom6 package ([Barnes et al.,](#)

¹²¹ 2024), developed for the Modular Ocean Model v6 (MOM6) (Adcroft et al., 2019), cannot be
¹²² used to generate ROMS inputs, because ROMS employs a terrain-following vertical coordinate
¹²³ system that requires a specialized vertical regridding approach, whereas MOM6 accepts inputs
¹²⁴ on arbitrary depth levels and does not require vertical regridding at all. Several other differences
¹²⁵ further prevent cross-compatibility. Together, these limitations underscored the need for a
¹²⁶ modern, maintainable, and reproducible tool designed specifically for ROMS.¹

¹²⁷ ROMS-Tools was developed to meet this need. It draws on the legacy of the MATLAB
¹²⁸ preprocessing scripts developed at UCLA (Molemaker, 2024), which encapsulate decades of
¹²⁹ expertise in configuring regional ocean model inputs. While many of the core algorithms and
¹³⁰ design principles are retained, ROMS-Tools provides an open-source Python implementation of
¹³¹ these MATLAB tools using an object-oriented programming paradigm. This implementation
¹³² supports a modern workflow with high-level API calls, improving reproducibility, minimizing
¹³³ user errors, and allowing easy extension to new features, forcing datasets, and use cases. In
¹³⁴ some cases, ROMS-Tools diverges from the MATLAB implementation to take advantage of
¹³⁵ new methods or better integration with the modern Python ecosystem. By streamlining input
¹³⁶ generation and analysis, ROMS-Tools reduces technical overhead, lowers the barrier to entry,
¹³⁷ and enables scientists to focus on research rather than data preparation.

¹³⁸ Software Design

¹³⁹ ROMS-Tools is designed to balance **ease of use, flexibility, reproducibility, and scalability** by
¹⁴⁰ combining high-level user interfaces with a modular, extensible architecture.

¹⁴¹ Lessons from MATLAB Tools

¹⁴² The legacy MATLAB preprocessing scripts were powerful but required users to edit source
¹⁴³ code directly to configure simulations. This workflow led to frequent errors for new users,
¹⁴⁴ made it difficult to track completed steps, and limited reproducibility. ROMS-Tools addresses
¹⁴⁵ these issues with **high-level API calls**, automated error-prone steps, and explicit workflow state
¹⁴⁶ management via YAML.

¹⁴⁷ Design Trade-Offs

¹⁴⁸ A central design trade-off in ROMS-Tools is between **user control** and **automation**. Rather than
¹⁴⁹ enforcing a fixed workflow, the package exposes key choices such as physical options (e.g.,
¹⁵⁰ corrections for radiation or wind), interpolation and fill methods, and computational backends.
¹⁵¹ This approach contrasts with opinionated frameworks that fix defaults and directory structures
¹⁵² to maximize automation. While users must make explicit decisions, some steps remain
¹⁵³ automated to prevent errors. For example, bathymetry smoothing is applied automatically with
¹⁵⁴ a non-tunable parameter, since overly small smoothing factors could produce rough bathymetry
¹⁵⁵ and crash simulations due to pressure gradient errors. This design choice directly addresses
¹⁵⁶ issues new users faced in the MATLAB scripts, and balances **flexibility** and **safety**, enabling
¹⁵⁷ transparent experimentation without exposing users to avoidable pitfalls.

¹⁵⁸ Another key design consideration is balancing **modular, incremental workflow steps**
¹⁵⁹ with **reproducibility**. ROMS-Tools organizes tasks (such as creating InitialConditions,
¹⁶⁰ BoundaryForcing, and SurfaceForcing) into small, composable components that can be
¹⁶¹ executed, saved, and revisited independently, rather than following a monolithic, fixed
¹⁶² workflow. All components depend on the Grid, but once it is created, the remaining objects
¹⁶³ are independent. This modular approach avoids unnecessary recomputation when only some
¹⁶⁴ inputs change but requires careful tracking of workflow state. To ensure reproducibility,
¹⁶⁵ all configuration choices are stored in compact, text-based YAML files. These files are

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

166 version-controllable, easy to share, and eliminate the need to transfer large model input
167 NetCDF datasets. This design directly addresses the MATLAB scripts' lack of explicit workflow
168 tracking.

169 Architecture

170 At the user-facing level, ROMS-Tools provides high-level objects such as Grid, InitialConditions,
171 and BoundaryForcing. Each object exposes a consistent interface (.ds, .plot(), .save(),
172 .to_yaml()), allowing users to call the same methods in sequence or inspect attributes that
173 are always present. This design reduces cognitive overhead, makes workflows predictable, and
174 removes the need for new users to edit raw scripts or manually track intermediate files, as was
175 required with the MATLAB tools.

176 Internally, ROMS-Tools follows a **layered, modular architecture**. Low-level classes
177 (`LatLonDataset`, `ROMSDataset`) handle data ingestion and preprocessing, including common
178 operations such as subdomain selection and lateral filling. Source-specific datasets (e.g.,
179 `ERA5Dataset`, `GLORYSDataset`, `SRTMDataset`) inherit from these base classes and encode
180 dataset-specific conventions like variable names, coordinates, and masking. Adding support
181 for a new data source typically requires only a small subclass to define variable mappings
182 while reusing existing logic, minimizing changes to the core code. High-level classes
183 (`Grid`, `InitialConditions`, `BoundaryForcing`) build on these low-level datasets to produce
184 ready-to-use modeling inputs, performing tasks such as regridding and final assembly. This
185 layered design enhances **extensibility and maintainability**, avoiding the pitfalls of the monolithic
186 MATLAB scripts.

187 Computational and Data Model Choices

188 ROMS-Tools is built on `xarray`, which provides a clear, consistent interface for exploring and
189 inspecting labeled, multi-dimensional geophysical datasets. Users can take advantage of
190 `xarray`'s intuitive indexing, plotting, and metadata handling. Optional dask support allows
191 workflows to scale from laptops to HPC systems, enabling parallel and out-of-core computation
192 for very large input and output datasets. By combining modern Python tools with a user-
193 friendly interface, ROMS-Tools addresses the usability challenges that hampered new users in
194 the MATLAB-based workflow.

195 Research Impact Statement

196 ROMS-Tools is used by two primary research communities. First, regional ocean modelers
197 use it to generate reproducible input datasets for ROMS simulations; external users include
198 researchers at **PNNL**, **WHOI**, and **UCLA**. Second, researchers in the ocean-based carbon
199 dioxide removal (CDR) community use ROMS-Tools to configure reproducible ROMS-MARBL
200 simulations of climate intervention scenarios, with adopters including **[C]Worthy**, **Carbon to
Sea**, **Ebb Carbon**, and **SCCWRP**. All of these groups have contacted the developers directly
201 or engaged with the project through GitHub or offline discussions. Several manuscripts from
202 these communities are currently in preparation.

204 Beyond standalone use, ROMS-Tools is integrated into broader scientific workflows, including
205 C-Star ([Stephenson & contributors, 2025](#)), an open-source platform that provides scientifically
206 credible monitoring, reporting, and verification (MRV) for the emerging marine carbon market.

207 Additional evidence of community uptake comes from public usage metrics. At the time of
208 writing, the GitHub repository shows **119 unique cloners in the past 14 days**, with stars
209 from users at institutions including the University of Waikato, NCAR, University of Maryland,
210 National Oceanography Centre, McGill University, UC Santa Cruz, and others. Distribution
211 statistics indicate **over 3,100 conda-forge downloads in the past six months**, including **68
212 downloads of the most recent release (v3.3.0)**, and **more than 48,000 total PyPI downloads**.

²¹³ PyPI counts include automated continuous integration (CI) usage by ROMS-Tools, in addition
²¹⁴ to direct user installations. In contrast, conda-forge downloads of v3.3.0 reflect exclusively
²¹⁵ human-initiated installs, as C-Star's CI workflows currently pin pre-v3.3.0 releases of ROMS-
²¹⁶ Tools.

²¹⁷ AI Usage Disclosure

²¹⁸ Generative AI tools were used to help write docstrings, develop tests, and improve the clarity
²¹⁹ and readability of both the ROMS-Tools documentation and manuscript text. All AI-assisted
²²⁰ content was reviewed and verified by the authors for technical accuracy and correctness.

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