

# <sup>1</sup> ROMS-Tools: Reproducible and Scalable <sup>2</sup> Preprocessing and Analysis for Regional Ocean <sup>3</sup> Modeling with ROMS

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## Software

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## <sup>10</sup> Summary

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

<sup>21</sup> 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.  
<sup>25</sup> 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  
<sup>26</sup> input files is time-consuming, error-prone, and hard to reproduce, creating a bottleneck for  
<sup>27</sup> both new and experienced users. The Python package ROMS-Tools addresses this challenge  
<sup>28</sup> by providing efficient, task-backed ([Dask Development Team, 2016](#)), user-friendly tools that  
<sup>29</sup> can be installed via Conda or PyPI and run interactively from Jupyter notebooks. It supports  
<sup>30</sup> creating regional grids, preprocessing all required model inputs, and postprocessing and analysis.  
<sup>31</sup> Current capabilities are fully compatible with UCLA-ROMS ([Molemaker & contributors, 2025a,](#)  
<sup>32</sup> [2025b](#)), with potential support for other ROMS versions, such as Rutgers ROMS ([Arango &](#)  
<sup>33</sup> [contributors, 2024](#)), in the future.

## <sup>35</sup> Input Data and Preprocessing

<sup>36</sup> ROMS-Tools generates the following input files for ROMS-MARBL:

- <sup>37</sup> 1. **Model Grid:** Customizable, curvilinear, and orthogonal grid designed to maintain a nearly  
<sup>38</sup> uniform horizontal resolution across the domain. The grid is rotatable to align with  
<sup>39</sup> coastlines and features a terrain-following vertical coordinate.
- <sup>40</sup> 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.

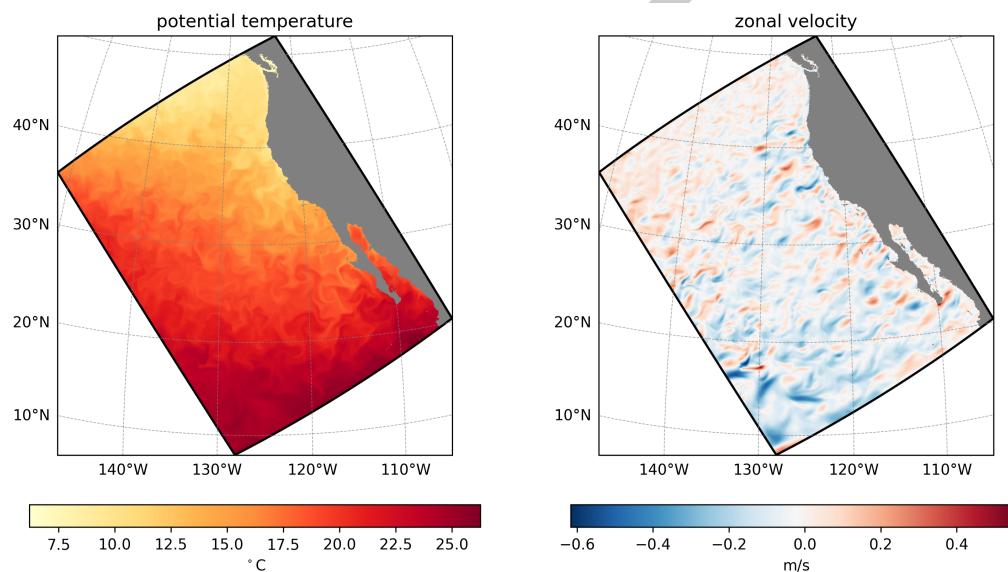
69     Some source datasets are accessed automatically by the package, including Natural Earth, Dai  
70       & Trenberth runoff, and ERA5 meteorology, while users must manually download SRTM15,  
71       GSHHG, GLORYS, the BGC datasets, and TPXO tidal files. Although these are the datasets  
72       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.<sup>1</sup>

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

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.

<sup>1</sup>In 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 is used by two primary research communities. First, regional ocean modelers  
181 use it to generate reproducible input datasets for ROMS simulations; external users include  
182 researchers at **PNNL**, **WHOI**, and **UCLA**. Second, researchers in the ocean-based carbon  
183 dioxide removal (CDR) community use ROMS-Tools to configure reproducible ROMS-MARBL  
184 simulations of climate intervention scenarios, with adopters including **[C]Worthy**, **Carbon to  
185 Sea**, **Ebb Carbon**, and **SCCWRP**. All of these groups have contacted the developers directly  
186 or engaged in offline discussions regarding their use of the package.

187 Additional evidence of community uptake comes from public usage metrics. At the time of  
188 writing, the GitHub repository shows **119 unique cloners in the past 14 days**, with stars  
189 from users at institutions including the University of Waikato, NCAR, University of Maryland,  
190 National Oceanography Centre, McGill University, UC Santa Cruz, and others. Distribution  
191 statistics indicate **over 3,100 conda-forge downloads in the past six months**, including **68  
192 downloads of the most recent release (v3.3.0)**, and **more than 48,000 total PyPI downloads**  
193 (noting that PyPI counts include automated CI usage, whereas conda downloads do not).

194 ROMS-Tools is also integrated into broader workflows, including **C-Star**([Stephenson &  
195 contributors, 2025](#)), an open-source platform to provide scientifically credible monitoring,  
196 reporting, and verification (MRV) for the emerging marine carbon market.

## 197 AI Usage Disclosure

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

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## 206 References

- 207 Adcroft, A., Anderson, W., Balaji, V., Blanton, C., Bushuk, M., Dufour, C. O., Dunne, J.  
 208 P., Griffies, S. M., Hallberg, R., Harrison, M. J., Held, I. M., Jansen, M. F., John, J. G.,  
 209 Krasting, J. P., Langenhorst, A. R., Legg, S., Liang, Z., McHugh, C., Radhakrishnan,  
 210 A., ... Zhang, R. (2019). The GFDL Global Ocean and Sea Ice Model OM4.0: Model  
 211 Description and Simulation Features. *Journal of Advances in Modeling Earth Systems*,  
 212 11(10), 3167–3211. <https://doi.org/10.1029/2019MS001726>
- 213 Arango, H., & contributors. (2024). Rutgers ROMS. In *GitHub repository*. GitHub. <https://github.com/myroms/roms>
- 214 Barnes, A. J., Constantinou, N. C., Gibson, A. H., Kiss, A. E., Chapman, C., Reilly, J.,  
 215 Bhagtnani, D., & Yang, L. (2024). Regional-mom6: A Python package for automatic  
 216 generation of regional configurations for the Modular Ocean Model 6. *Journal of Open*  
 217 *Source Software*, 9(100), 6857. <https://doi.org/10.21105/joss.06857>
- 218 Bell, N., Olson, L. N., Schroder, J., & Southworth, B. (2023). PyAMG: Algebraic multigrid  
 219 solvers in python. *Journal of Open Source Software*, 8(87), 5495. <https://doi.org/10.21105/joss.05495>
- 220 Dai, A., & Trenberth, K. E. (2002). *Estimates of Freshwater Discharge from Continents:  
 221 Latitudinal and Seasonal Variations*. [https://journals.ametsoc.org/view/journals/hydr/3/6/1525-7541\\_2002\\_003\\_0660\\_eofdc\\_2\\_0\\_co\\_2.xml](https://journals.ametsoc.org/view/journals/hydr/3/6/1525-7541_2002_003_0660_eofdc_2_0_co_2.xml)
- 222 Dask Development Team. (2016). *Dask: Library for dynamic task scheduling*. <http://dask.pydata.org>
- 223 Egbert, G. D., & Erofeeva, S. Y. (2002). Efficient Inverse Modeling of Barotropic Ocean  
 224 Tides. *Journal of Atmospheric and Oceanic Technology*, 19(2), 183–204. [https://doi.org/10.1175/1520-0426\(2002\)019%3C0183:EIMOBO%3E2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019%3C0183:EIMOBO%3E2.0.CO;2)
- 225 Garcia, H. E., Boyer, T. P., Baranova, O. K., Locarnini, R. A., Mishonov, A. V., Grodsky,  
 226 A., Paver, C. R., Weathers, K. W., Smolyar, I. V., Reagan, J. R., Seidov, D., & Zweng,  
 227 M. M. (2019). *World ocean atlas 2018: Product documentation* (A. Mishonov, Ed.).  
 228 NOAA/NCEI.
- 229 Hamilton, D. S., Perron, M. M. G., Bond, T. C., Bowie, A. R., Buchholz, R. R., Guieu, C., Ito,  
 230 A., Maenhaut, W., Myriokefalakis, S., Olgun, N., Rathod, S. D., Schepanski, K., Tagliabue,  
 231 A., Wagner, R., & Mahowald, N. M. (2022). Earth, Wind, Fire, and Pollution: Aerosol  
 232 Nutrient Sources and Impacts on Ocean Biogeochemistry. *Annual Review of Marine Science*,  
 233 14(Volume 14, 2022), 303–330. <https://doi.org/10.1146/annurev-marine-031921-013612>
- 234 Hauser, M., Spring, A., Busecke, J., Driel, M. van, Lorenz, R., & readthedocs-assistant.  
 235 (2024). *Regionmask/regionmask: Version 0.12.1*. Zenodo. <https://doi.org/10.5281/zenodo.10849860>
- 236 Hedstrom, K., & contributors. (2023). Pyroms. In *GitHub repository*. GitHub. <https://github.com/ESMG/pyroms>
- 237 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas,  
 238 J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellán,  
 239 X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ... Thépaut, J.-N.  
 240 (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*,  
 241 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- 242 Hoyer, S., & Hamman, J. (2017). Xarray: ND labeled arrays and datasets in python. *Journal  
 243 of Open Research Software*, 5(1). <https://doi.org/10.5334/jors.148>
- 244 Huang, Y., Tagliabue, A., & Cassar, N. (2022). Data-Driven Modeling of Dissolved Iron in the  
 245 Global Ocean. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.837183>

- 253 Kok, J. F., Adebiyi, A. A., Albani, S., Balkanski, Y., Checa-Garcia, R., Chin, M., Colarco,  
 254 P. R., Hamilton, D. S., Huang, Y., Ito, A., Klose, M., Leung, D. M., Li, L., Mahowald,  
 255 N. M., Miller, R. L., Obiso, V., Pérez García-Pando, C., Rocha-Lima, A., Wan, J. S., &  
 256 Whicker, C. A. (2021). Improved representation of the global dust cycle using observational  
 257 constraints on dust properties and abundance. *Atmospheric Chemistry and Physics*, 21(10),  
 258 8127–8167. <https://doi.org/10.5194/acp-21-8127-2021>
- 259 Landschützer, P., Gruber, N., & Bakker, D. C. E. (2016). Decadal variations and trends  
 260 of the global ocean carbon sink. *Global Biogeochemical Cycles*, 30(10), 1396–1417.  
 261 <https://doi.org/10.1002/2015GB005359>
- 262 Lauvset, S. K., Key, R. M., Olsen, A., Heuven, S. van, Velo, A., Lin, X., Schirnick, C., Kozyr,  
 263 A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishii, M.,  
 264 Perez, F. F., Suzuki, T., & Watelet, S. (2016). A new global interior ocean mapped  
 265 climatology: The  $1^\circ \times 1^\circ$  GLODAP version 2. *Earth System Science Data*, 8(2), 325–340.  
 266 <https://doi.org/https://doi.org/10.5194/essd-8-325-2016>
- 267 Lellouche, E., Jean-Michel Greiner, Bourdallé-Badie, R., Garric, G., Melet, A., Drévillon,  
 268 M., Bricaud, C., Hamon, M., Le Galloudec, O., Regnier, C., Candela, T., Testut, C.-E.,  
 269 Gasparin, F., Ruggiero, G., Benkiran, M., Drillet, Y., & Le Traon, P.-Y. (2021). The  
 270 Copernicus Global  $1/12^\circ$  Oceanic and Sea Ice GLORYS12 Reanalysis. *Frontiers in Earth  
 271 Science*, 9. <https://doi.org/10.3389/feart.2021.698876>
- 272 Long, M. C., Moore, J. K., Lindsay, K., Levy, M., Doney, S. C., Luo, J. Y., Krumhardt, K.  
 273 M., Letscher, R. T., Grover, M., & Sylvester, Z. T. (2021). *Simulations With the Marine  
 274 Biogeochemistry Library (MARBL)*. <https://doi.org/10.1029/2021MS002647>
- 275 Molemaker, J. (2024). UCLA MATLAB tools. In *GitHub repository*. GitHub. <https://github.com/nmolem/ucla-tools>
- 277 Molemaker, J., & contributors. (2025a). UCLA-ROMS. In *GitHub repository*. GitHub.  
 278 <https://github.com/CESR-lab/ucla-roms>
- 279 Molemaker, J., & contributors. (2025b). UCLA-ROMS. In *GitHub repository*. GitHub.  
 280 <https://github.com/CWorthy-ocean/ucla-roms>
- 281 Shchepetkin, A. F., & McWilliams, J. C. (2005). The regional oceanic modeling system  
 282 (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model.  
 283 *Ocean Modelling*, 9(4), 347–404. <https://doi.org/10.1016/j.ocemod.2004.08.002>
- 284 Stephenson, D., & contributors. (2025). C-star. [C]Worthy. <https://github.com/CWorthy-ocean/C-Star>
- 286 Tozer, B., Sandwell, D. T., Smith, W. H. F., Olson, C., Beale, J. R., & Wessel, P. (2019).  
 287 Global Bathymetry and Topography at 15 Arc Sec: SRTM15+. *Earth and Space Science*,  
 288 6(10), 1847–1864. <https://doi.org/10.1029/2019EA000658>
- 289 Wessel, P., & Smith, W. H. F. (1996). A global, self-consistent, hierarchical, high-resolution  
 290 shoreline database. *Journal of Geophysical Research: Solid Earth*, 101(B4), 8741–8743.  
 291 <https://doi.org/10.1029/96JB00104>
- 292 Yang, S., Chang, B. X., Warner, M. J., Weber, T. S., Bourbonnais, A. M., Santoro, A. E.,  
 293 Kock, A., Sonnerup, R. E., Bullister, J. L., Wilson, S. T., & Bianchi, D. (2020). Global  
 294 reconstruction reduces the uncertainty of oceanic nitrous oxide emissions and reveals a  
 295 vigorous seasonal cycle. *Proceedings of the National Academy of Sciences of the United  
 296 States of America*, 117(22), 11954–11960. <https://doi.org/10.1073/pnas.1921914117>
- 297 Yeager, S. G., Rosenbloom, N., Glanville, A. A., Wu, X., Simpson, I., Li, H., Molina, M.  
 298 J., Krumhardt, K., Mogen, S., Lindsay, K., Lombardozzi, D., Wieder, W., Kim, W. M.,  
 299 Richter, J. H., Long, M., Danabasoglu, G., Bailey, D., Holland, M., Lovenduski, N., ...  
 300 King, T. (2022). The Seasonal-to-Multiyear Large Ensemble (SMYLE) prediction system

301 using the Community Earth System Model version 2. *Geoscientific Model Development*,  
302 15(16), 6451–6493. <https://doi.org/10.5194/gmd-15-6451-2022>

303 Zhuang, J., Dussin, R., Huard, D., Bourgault, P., Banihirwe, A., Raynaud, S., Malevich,  
304 B., Schupfner, M., Filipe, Levang, S., Gauthier, C., Jüling, A., Almansi, M., Scott,  
305 R., RondeauG, Rasp, S., Smith, T. J., Stachelek, J., Plough, M., & Li, X. (2023).  
306 xESMF: Universal regridder for geospatial data. In *GitHub repository*. Zenodo. <https://doi.org/10.5281/zenodo.4294774>  
307

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