AIBECS.jl: A tool for exploring global marine biogeochemical cycles.

Benoît Pasquier[*1,3], **François W. Primeau**[2], **and Seth G. John**[1]

1 Department of Earth Sciences, University of Southern California **2** Department of Earth System Science, University of California, Irvine **3** (now at) School of Mathematics and Statistics, University of New South Wales, Sydney

Summary

The ocean transports, mixes, and transforms chemical constituents on a multitude of time and length scales. Observations and models are both essential for making sense of this complex system. However, the days of just publishing data without any quantitative modelling are over, increasing pressure on sea-going oceanographers that are expected to be proficient in the use of biogeochemical models. And while the simplest of these models consist of only a few boxes (e.g., the two-box model of Archer et al., 2000), with solutions that are easily obtained by hand or on a simple desktop computer, the most advanced models have high-resolution three-dimensional meshes that require high-performance computing (HPC) clusters and a considerable amount of computational-science expertise (e.g., the MITgcm, Campin et al., 2021). A high barrier to entry for modelling in oceanography hinders advances in the field. AIBECS.jl (Pasquier, 2021) is a JuliaOcean-affiliated package written in Julia (Bezanson et al., 2017), which aims to lower this barrier by providing an easy-to-use, open-source, and modular framework for simulating global marine tracers in steady-state and biogeochemical parameter fitting.

A conceptual model of the cycle of any marine tracer essentially requires two components. (i) A model of how the tracer is transported (be it the ocean currents and eddies, gravitational settling, or a combination of those), and (ii) a model of the local sources and sinks at any location. AIBECS.jl is built on this concept and allows users to build numerical models of marine tracers by selecting a circulation and/or vertical transport of the tracer with particles and local sources and sinks. Tools for generating the steady-state equations, solving them, and then diagnosing and plotting the simulated tracers are also provided, either directly by AIBECS.jl, by its dependencies, or by satellite packages in the AIBECS and Julia ecosystem.

Box (1979) has remarked that, by definition, all models are wrong because they make simplifying assumptions. These assumptions can give rise to model parameters that can capture fundamental characteristics of the system. Once the model of the cycle of a marine tracer is implemented, it is thus natural to try to estimate biogeochemical parameters by minimizing model–observation mismatches, which may improves the skill of the model. Parameter optimization is generally more efficiently performed when first and second derivatives are available, and these derivatives can also be used to estimate parameter sensitivity (Thacker, 1989). AIBECS.jl was designed with parameter fitting in mind and provides, along with satellite packages, tools for generating first- and second-order derivatives automatically and efficiently.

The AIBECS.jl package builds on the vision of the AWESOME OCIM (A Working Environment for Simulating Ocean Movement and Elemental cycling within the Ocean Circulation Inverse

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*corresponding author

Model, or AO, John et al., 2020), which was designed to make three-dimensional element-cycling models more broadly accessible. Written in Julia — chosen for of its combined expressive power and efficiency and offering a truly open-source solution — the AIBECS.jl framework improves on the AO on a number of fronts to target education and research. Simple AIBECS.jl simulations can be produced in minutes in interactive notebooks while resource-hungry projects, e.g., for optimizing models with multiple tracers interacting nonlinearly within a high-resolution mesh, can be easily version-controlled, hosted, and run on HPC clusters.

Through a simple user interface, AIBECS.jl provides access to a variety of steady-state ocean circulation models. These currently include the Ocean Circulation Inverse Model (OCIM) v0.1 (Primeau et al., 2013), v1.0 (DeVries, 2014; DeVries & Primeau, 2011), and v2.0 (DeVries & Holzer, 2019), and the MITgcm-built Ocean Comprehensible Atlas (OCCA) ocean-state estimate model (Forget, 2010), of which the downloads are handled by the DataDeps.jl package (White et al., 2019). AIBECS.jl also offers classic two-box and three-box models (Archer et al., 2000; Sarmiento & Gruber, 2006). The OceanGrids.jl package, on which AIBECS depends, provides the underlying grid configuration types as well as regridding and interpolating routines. Swapping the underlying circulation model and grid requires a single-line-of-code change, facilitating intercomparison projects. As new circulation models that are represented in matrix form are made publicly available, they will be added to the collection. These could include past- and future-ocean circulation models, for paleoceanographic or climate-change studies, for example.

AIBECS.jl also provides extra functionality to facilitate the generation of numerical models. Tooling to simulate gravitational settling of tracers with non-buoyant particles is provided by the `transportoperator` function. In addition, AIBECS provides access to a number of predefined fields that can be used to generate source and sink processes. Fine-resolution (1-arc-minute) topography from the ETOPO1 dataset (Amante & Eakins, 2009) can be used for a refined interception of particulate fluxes by subgrid topographic features not captured by coarser circulation models. For aeolian deposition, AIBECS.jl includes aerosol-type- and region-of-origin-partitioned dust deposition fields (Chien et al., 2016; Kok et al., 2021). Datasets for global river discharge (Dai, 2017; Dai & Trenberth, 2002) and surface groundwater discharge (Luijendijk et al., 2019, 2020) are included. For hydrothermal-sourced tracers, the helium fluxes from the Earth's mantle computed with the OCIM v1.0 and v2.0 are available when loading the corresponding circulation models (DeVries, 2014; DeVries & Holzer, 2019). AIBECS.jl also provides access to the data included with the AWESOME OCIM framework (John et al., 2020), namely data from the Global Ocean Data Analysis Project (GLODAP, Lauvset et al., 2016; Olsen et al., 2016), P-cycling modelled fields from Weber et al. (2018), nepheloid layers (Gardner, Richardson, & Mishonov, 2018; Gardner, Richardson, Mishonov, & Biscaye, 2018; Taburet et al., 2019), as well as other data already present within AIBECS or satellite packages. Also useful to global biogeochemistry modelling are data from the World Ocean Atlas (Garcia et al., 2018) that can be downloaded, assisted by external package WorldOceanAtlasTools.jl (Pasquier, 2019). Similarly, GEOTRACES data (Schlitzer et al., 2018) can be handled by the GEOTRACES.jl package (although GEOTRACES requires manual download of the data). More advanced usage such as optimization is facilitated by the F1Method.jl package (Pasquier, 2020), which provides efficient gradient and Hessian computations of objective functions defined through AIBECS.jl, which can then be directly fed to optimization routines from, e.g., the Optim.jl package (Mogensen & Riseth, 2018). Finally, plotting recipes for the Plots.jl package (Breloff, 2021), are available.

Internally, AIBECS.jl uses a quasi-Newton solver (Kelley, 2003) translated from MATLAB to Julia and tailored to the context of marine tracers to solve/simulate tracers. AIBECS uses forward-mode auto-differentiation from the ForwardDiff.jl package (Revels et al., 2016) for the nonlinear parts of the system of ordinary differential equations to generate the Jacobian required for the solver. Metadata such as units and prior distributions can be attached to model parameters, which are handled with the help of the UnPack.jl, FieldMetadata.jl, Flatten.jl, DataFrames.jl, Distributions.jl (Besançon et al., 2021; Lin et al., 2019), Unitful.jl, and

Bijectors.jl dependencies.

The AIBECS.jl package is registered with Julia's default package registry (GENERAL), such that installation takes a single line of code from within Julia. The package documentation, which is built through continuous integration (CI), includes tutorials and how-to guides that are both available online for consultation and as runnable Jupyter notebooks. Continuous integration through GitHub actions also includes a fairly complete suite of tests.

Statement of need

Pioneered by Schlitzer (1993) to study the ocean circulation using ventilation tracers such as radiocarbon (see also Schlitzer, 2000), the low computational costs of steady-state circulation models allow for efficient optimization and inference/estimation of biogeochemical parameters. Today, despite reduced resolution and steady-state assumption, data-constrained matrix-transport models such as the OCIM are at the forefront of oceanographic research. This is evidenced for example by the growing number of high-profile studies that use such models for parameter estimation published in recent years (e.g., DeVries et al., 2017, 2012, 2013; DeVries, 2014; DeVries & Deutsch, 2014; DeVries & Weber, 2017; Roshan & DeVries, 2017; Teng et al., 2014; Wang et al., 2019; Weber et al., 2016; Weber & Deutsch, 2010). However, although the steady-state assumption and matrix representation simplify the simulation of tracers compared to traditional Ocean General Circulation Models (OGCMs), most studies that employ a steady-state matrix representation of marine cycling remain difficult to reproduce without significant computer-science and modelling expertise because they are built on private implementations. Comparisons between different circulation models are moreover complicated by the lack of standardization across models.

Hence, there is a need to facilitate the use of steady-state ocean-circulation models by providing: (i) an integrated framework for handling a number of different ocean-circulation models with tools for swapping circulations (including interpolating from one model grid to another), (ii) a user-friendly interface for translating mathematical models of biogeochemical cycles into the corresponding code (e.g., for sources, sinks, and vertical transport of tracers), and (iii) solvers for efficient simulations, optimization, diagnosis, and statistical analysis.

AIBECS.jl provides a free, open-source, unified framework for biogeochemical-tracer-modelling studies that use steady-state circulation models. Among other advantages over existing solutions (i.e., the AO), AIBECS.jl offers better computational efficiency, enhanced versatility, composability with other Julia packages, and ease of reproducibility (granted by version control and Julia's package manager) and improved syntax, which are pillars of modern scientific dissemination. Thus, AIBECS users may include sea-going oceanographers and educators who will benefit from its simplicity, as well as more experienced modellers who can leverage its computational advantages. AIBECS.jl has been used for teaching and is currently used for research focused on marine trace metals.

The publication of circulation models as transport matrices from existing general circulation models (Bardin et al., 2014, 2016; Khatiwala et al., 2005; Khatiwala, 2007; Kvale et al., 2017; Zanna et al., 2019), and hopefully, future publication of transport matrix estimates from standard ocean general circulation models (e.g., Chamberlain et al., 2019) will increase the collection of circulations available from AIBECS.jl. Of particular interest to the broader community to facilitate the simulation of past and future marine biogeochemical states would be transport matrix models extracted from the Climate Model Intercomparison Project (CMIP), which includes past and future simulations of the ocean circulation.

Further devepment could include exposing advanced Grren-function-based diagnostic tools (e.g., Holzer et al., 2021; Pasquier & Holzer, 2018), coupling tracers on different grids, Newton–Krylov solvers for cyclo-stationary states (e.g., CYCLOCIM: Huang et al., 2021), or time-dependent solvers for transient biogeochemical simualtions provided, e.g., by the SciML

ecosystem (Rackauckas & Nie, 2017). Bridging packages could be implemented for improved composability with statistical packages (e.g., Turing.jl: Ge et al., 2018), optimization tools, and plotting software (e.g., Makie.jl: Danisch et al., 2021; Danisch & Krumbiegel, 2021).

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References

Amante, C., & Eakins, B. W. (2009). ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis [Data set]. In *NOAA Technical Memorandum NESDIS NGDC-24*. National Geophysical Data Center, NOAA. https://doi.org/10.7289/V5C8276M

Archer, D. E., Eshel, G., Winguth, A., Broecker, W., Pierrehumbert, R., Tobis, M., & Jacob, R. (2000). Atmospheric pCO_2 sensitivity to the biological pump in the ocean. *Global Biogeochemical Cycles*, *14*(4), 1219–1230. https://doi.org/10.1029/1999GB001216

Bardin, A., Primeau, F., & Lindsay, K. (2014). An offline implicit solver for simulating prebomb radiocarbon. *Ocean Modelling*, *73*, 45–58. https://doi.org/10.1016/j.ocemod.2013.09.008

Bardin, A., Primeau, F., Lindsay, K., & Bradley, A. (2016). Evaluation of the accuracy of an offline seasonally-varying matrix transport model for simulating ideal age. *Ocean Modelling*, *105*, 25–33. https://doi.org/10.1016/j.ocemod.2016.07.003

Besançon, M., Papamarkou, T., Anthoff, D., Arslan, A., Byrne, S., Lin, D., & Pearson, J. (2021). Distributions.jl: Definition and modeling of probability distributions in the JuliaStats ecosystem. *Journal of Statistical Software*, *98*(16), 1–30. https://doi.org/10.18637/jss.v098.i16

Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, *59*(1), 65–98. https://doi.org/10.1137/141000671

Box, G. E. P. (1979). Robustness in the strategy of scientific model building. In R. L. Launer & G. N. Wilkinson (Eds.), *Robustness in statistics* (pp. 201–236). Academic Press. https://doi.org/10.1016/B978-0-12-438150-6.50018-2

Breloff, T. (2021). *Plots.jl* (Version v1.16.3) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.4725317

Campin, J.-M., Heimbach, P., Losch, M., Forget, G., edhill3, Adcroft, A., amolod, Menemenlis, D., dfer22, Hill, C., Jahn, O., Scott, J., stephdut, Mazloff, M., Fox-Kemper, B., antnguyen13, Doddridge, E., Fenty, I., Bates, M., … dussin, raphael. (2021). *MITgcm/MITgcm: checkpoint67z* (Version checkpoint67z) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.1409237

Chamberlain, M. A., Matear, R. J., Holzer, M., Bi, D., & Marsland, S. J. (2019). Transport matrices from standard ocean-model output and quantifying circulation response to climate change. *Ocean Modelling*, *135*, 1–13. https://doi.org/10.1016/j.ocemod.2019.01.005

Chien, C.-T., Mackey, K. R. M., Dutkiewicz, S., Mahowald, N. M., Prospero, J. M., & Paytan, A. (2016). Effects of African dust deposition on phytoplankton in the western

tropical Atlantic Ocean off Barbados. *Global Biogeochemical Cycles*, *30*(5), 716–734. https://doi.org/10.1002/2015GB005334

Dai, A. (2017). *Global river flow and continental discharge dataset* [Data set]. Research Data Archive at the National Center for Atmospheric Research, Computational; Information Systems Laboratory. https://doi.org/10.5065/D6V69H1T

Dai, A., & Trenberth, K. E. (2002). Estimates of Freshwater Discharge from Continents: Latitudinal and Seasonal Variations. *Journal of Hydrometeorology*, *3*(6), 660–687. https://doi.org/10.1175/1525-7541(2002)003%3C0660:EOFDFC%3E2.0.CO;2

Danisch, S., Krumbiege, J., & others. (2021). *JuliaPlots/makie.jl* (Version v0.15.0) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.3735092

Danisch, S., & Krumbiegel, J. (2021). Makie.jl: Flexible high-performance data visualization for julia. *Journal of Open Source Software*, *6*(65), 3349. https://doi.org/10.21105/joss.03349

DeVries, T. (2014). The oceanic anthropogenic CO_2 sink: Storage, air-sea fluxes, and transports over the industrial era. *Global Biogeochemical Cycles*, *28*(7), 631–647. https://doi.org/10.1002/2013GB004739

DeVries, T., & Deutsch, C. (2014). Large-scale variations in the stoichiometry of marine organic matter respiration. *Nature Geoscience*, *7*(12), 890–894. https://doi.org/10.1038/ngeo2300

DeVries, T., Deutsch, C., Rafter, P. A., & Primeau, F. (2013). Marine denitrification rates determined from a global 3-D inverse model. *Biogeosciences*, *10*(4), 2481–2496. https://doi.org/10.5194/bg-10-2481-2013

DeVries, T., & Holzer, M. (2019). Radiocarbon and helium isotope constraints on deep ocean ventilation and mantle-[3]He sources. *Journal of Geophysical Research: Oceans*, *124*(5), 3036–3057. https://doi.org/10.1029/2018JC014716

DeVries, T., Holzer, M., & Primeau, F. (2017). Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature*, *542*(7640), 215–218. https://doi.org/10.1038/nature21068

DeVries, T., & Primeau, F. (2011). Dynamically and observationally constrained estimates of water-mass distributions and ages in the global ocean. *Journal of Physical Oceanography*, *41*, 2381–2401. https://doi.org/10.1175/JPO-D-10-05011.1

DeVries, T., Primeau, F., & Deutsch, C. (2012). The sequestration efficiency of the biological pump. *Geophysical Research Letters*, *39*(13). https://doi.org/10.1029/2012GL051963

DeVries, T., & Weber, T. (2017). The export and fate of organic matter in the ocean: New constraints from combining satellite and oceanographic tracer observations. *Global Biogeochemical Cycles*, *31*(3), 535–555. https://doi.org/10.1002/2016GB005551

Forget, G. (2010). Mapping ocean observations in a dynamical framework: A 2004–06 ocean atlas. *Journal of Physical Oceanography*, *40*(6), 1201–1221. https://doi.org/10.1175/2009JPO4043.1

Garcia, H. E., Weathers, K., Paver, C. R., Smolyar, I., Boyer, T. P., Locarnini, R. A., Zweng, M. M., Mishonov, A. V., Baranova, O. K., Seidov, D., & Reagan, J. R. (2018). *World Ocean Atlas 2018: Dissolved Inorganic Nutrients (phosphate, nitrate and nitrate+nitrite, silicate)*. *4*.

Gardner, W. D., Richardson, J., & Mishonov, A. V. (2018). Global assessment of benthic nepheloid layers and linkage with upper ocean dynamics. *Earth and Planetary Science Letters*, *482*, 126–134. https://doi.org/https://doi.org/10.1016/j.epsl.2017.11.008

Gardner, W. D., Richardson, J., Mishonov, A. V., & Biscaye, P. E. (2018). Global comparison of benthic nepheloid layers based on 52 years of nephelometer and transmissometer measurements. *Progress in Oceanography*, *168*, 100–111. https://doi.org/https://doi.org/10.1016/j.pocean.2018.09.008

Ge, H., Xu, K., & Ghahramani, Z. (2018). Turing: A language for flexible probabilistic inference. *International Conference on Artificial Intelligence and Statistics, AISTATS 2018, 9-11 April 2018, Playa Blanca, Lanzarote, Canary Islands, Spain*, 1682–1690. http://proceedings.mlr.press/v84/ge18b.html

Holzer, M., Kwon, E. Y., & Pasquier, B. (2021). A new metric of the biological carbon pump: Number of pump passages and its control on atmospheric pCO$_2$. *Global Biogeochemical Cycles*, *35*(6), e2020GB006863. https://doi.org/10.1029/2020GB006863

Huang, Q., Primeau, F., & DeVries, T. (2021). CYCLOCIM: A 4-d variational assimilation system for the climatological mean seasonal cycle of the ocean circulation. *Ocean Modelling*, *159*, 101762. https://doi.org/10.1016/j.ocemod.2021.101762

John, S. G., Liang, H., Weber, T., DeVries, T., Primeau, F., Moore, K., Holzer, M., Mahowald, N., Gardner, W., Mishonov, A., Richardson, J., Faugere, Y., & Taburet, G. (2020). AWESOME OCIM: A simple, flexible, and powerful tool for modeling elemental cycling in the oceans. *Chemical Geology*, *533*, 119403. https://doi.org/10.1016/j.chemgeo.2019.119403

Kelley, C. T. (2003). *Solving nonlinear equations with Newton's method* (pp. 1–25). SIAM. https://doi.org/10.1137/1.9780898718898.ch1

Khatiwala, S. (2007). A computational framework for simulation of biogeochemical tracers in the ocean. *Global Biogeochemical Cycles*, *21*(3). https://doi.org/10.1029/2007GB002923

Khatiwala, S., Visbeck, M., & Cane, M. A. (2005). Accelerated simulation of passive tracers in ocean circulation models. *Ocean Modelling*, *9*(1), 51–69. https://doi.org/10.1016/j.ocemod.2004.04.002

Kok, J. F., Adebiyi, A. A., Albani, S., Balkanski, Y., Checa-Garcia, R., Chin, M., Colarco, P. R., Hamilton, D. S., Huang, Y., Ito, A., Klose, M., Li, L., Mahowald, N. M., Miller, R. L., Obiso, V., Pérez García-Pando, C., Rocha-Lima, A., & Wan, J. S. (2021). Contribution of the world's main dust source regions to the global cycle of desert dust. *Atmospheric Chemistry and Physics*, *21*(10), 8169–8193. https://doi.org/10.5194/acp-21-8169-2021

Kvale, K. F., Khatiwala, S., Dietze, H., Kriest, I., & Oschlies, A. (2017). Evaluation of the transport matrix method for simulation of ocean biogeochemical tracers. *Geoscientific Model Development*, *10*(6), 2425–2445. https://doi.org/10.5194/gmd-10-2425-2017

Lauvset, S. K., Key, R. M., Olsen, A., Heuven, S. van, Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishii, M., Perez, F. F., Suzuki, T., & Watelet, S. (2016). A new global interior ocean mapped climatology: The 1°×1° GLODAP version 2. *Earth System Science Data*, *8*(2), 325–340. https://doi.org/10.5194/essd-8-325-2016

Lin, D., White, J. M., Byrne, S., Bates, D., Noack, A., Pearson, J., Arslan, A., Squire, K., Anthoff, D., Papamarkou, T., Besançon, M., Drugowitsch, J., Schauer, M., & contributors, other. (2019). *JuliaStats/Distributions.jl: a Julia package for probability distributions and associated functions*. https://doi.org/10.5281/zenodo.2647458

Luijendijk, E., Gleeson, T., & Moosdorf, N. (2019). *Geospatial data and model results for a global model study of coastal groundwater discharge* [Data set]. PANGAEA. https://doi.org/10.1594/PANGAEA.907641

Luijendijk, E., Gleeson, T., & Moosdorf, N. (2020). Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-15064-8

Mogensen, P. K., & Riseth, A. N. (2018). Optim: A mathematical optimization package for Julia. *Journal of Open Source Software*, *3*(24), 615. https://doi.org/10.21105/joss.00615

Olsen, A., Key, R. M., Heuven, S. van, Lauvset, S. K., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishii, M., Pérez, F. F., & Suzuki, T. (2016). The global ocean data analysis project version 2 (GLODAPv2) – an internally consistent data product for the world ocean. *Earth System Science Data*, *8*(2), 297–323. https://doi.org/10.5194/essd-8-297-2016

Pasquier, B. (2019). *WorldOceanAtlasTools.jl: Download and process world ocean data in julia*. https://doi.org/10.5281/zenodo.2677666

Pasquier, B. (2021). *AIBECS.jl: The ideal tool for exploring global marine biogeochemical cycles* (Version v0.10.10) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.2864051

Pasquier, B. (2020). *F1Method.jl* (Version v0.4.0) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.4284133

Pasquier, B., & Holzer, M. (2018). The number of past and future regenerations of iron in the ocean and its intrinsic fertilization efficiency. *Biogeosciences*, *15*(23), 7177–7203. https://doi.org/10.5194/bg-15-7177-2018

Primeau, F., Holzer, M., & DeVries, T. (2013). Southern Ocean nutrient trapping and the efficiency of the biological pump. *Journal of Geophysical Research: Oceans*, *118*, 2547–2564. https://doi.org/10.1002/jgrc.20181

Rackauckas, C., & Nie, Q. (2017). DifferentialEquations.jl — A performant and feature-rich ecosystem for solving differential equations in Julia. *Journal of Open Research Software*, *5*(1), 15. https://doi.org/http://doi.org/10.5334/jors.151

Revels, J., Lubin, M., & Papamarkou, T. (2016). Forward-mode automatic differentiation in Julia. *arXiv:1607.07892 [cs.MS]*. https://arxiv.org/abs/1607.07892

Roshan, S., & DeVries, T. (2017). Efficient dissolved organic carbon production and export in the oligotrophic ocean. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-02227-3

Sarmiento, J. L., & Gruber, N. (2006). *Ocean biogeochemical dynamics* (p. 503). Princeton Univ. Press, Princeton; Oxford.

Schlitzer, R. (1993). Determining the mean, large-scale circulation of the Atlantic with the adjoint method. *Journal of Physical Oceanography*, *23*(9), 1935–1952. https://doi.org/10.1175/1520-0485(1993)023%3C1935:DTMLSC%3E2.0.CO;2

Schlitzer, R. (2000). Applying the adjoint method for biogeochemical modeling: Export of particulate organic matter in the world ocean. *Geophysical Monograph-American Geophysical Union*, *114*, 107–124.

Schlitzer, R., Anderson, R. F., Dodas, E. M., Lohan, M., Geibert, W., Tagliabue, A., Bowie, A., Jeandel, C., Maldonado, M. T., Landing, W. M., Cockwell, D., Abadie, C., Abouchami, W., Achterberg, E. P., Agather, A., Aguliar-Islas, A., Aken, H. M. van, Andersen, M., Archer, C., … Shelley, Rachel. (2018). The GEOTRACES Intermediate Data Product 2017 [Data set]. In *Chemical Geology* (Vol. 493, pp. 210–223).

Taburet, G., Sanchez-Roman, A., Ballarotta, M., Pujol, M.-I., Legeais, J.-F., Fournier, F., Faugere, Y., & Dibarboure, G. (2019). DUACS DT2018: 25 years of reprocessed sea level altimetry products. *Ocean Science*, *15*(5), 1207–1224. https://doi.org/10.5194/os-15-1207-2019

Teng, Y.-C., Primeau, F., Moore, J. K., Lomas, M. W., & Martiny, A. C. (2014). Global-scale variations of the ratios of carbon to phosphorus in exported marine organic matter. *Nature Geoscience*, *7*(12), 895–898. https://doi.org/10.1038/ngeo2303

Thacker, W. C. (1989). The role of the Hessian matrix in fitting models to measurements. *Journal of Geophysical Research: Oceans*, *94*(C5), 6177–6196. https://doi.org/10.1029/JC094iC05p06177

Wang, W.-L., Moore, J. K., Martiny, A. C., & Primeau, F. (2019). Convergent estimates of marine nitrogen fixation. *Nature*, *566*(7743), 205–211. https://doi.org/10.1038/s41586-019-0911-2

Weber, T., Cram, J. A., Leung, S. W., DeVries, T., & Deutsch, C. (2016). Deep ocean nutrients imply large latitudinal variation in particle transfer efficiency. *Proceedings of the National Academy of Sciences*, *113*(31), 8606–8611. https://doi.org/10.1073/pnas.1604414113

Weber, T., & Deutsch, C. (2010). Ocean nutrient ratios governed by plankton biogeography. *Nature*, *467*(7315), 550–554. https://doi.org/10.1038/nature09403

Weber, T., John, S., Tagliabue, A., & DeVries, T. (2018). Biological uptake and reversible scavenging of zinc in the global ocean. *Science*, *361*(6397), 72–76. https://doi.org/10.1126/science.aap8532

White, L., Togneri, R., Liu, W., & Bennamoun, M. (2019). DataDeps.jl: Repeatable data setup for reproducible data science. *Journal of Open Research Software*, *7*. https://doi.org/10.5334/jors.244

Zanna, L., Khatiwala, S., Gregory, J. M., Ison, J., & Heimbach, P. (2019). Global reconstruction of historical ocean heat storage and transport. *Proceedings of the National Academy of Sciences*, *116*(4), 1126–1131. https://doi.org/10.1073/pnas.1808838115