

SpeedyWeather.jl: Reinventing atmospheric general circulation models towards interactivity and extensibility

Milan Klöwer^{1,2¶}, Maximilian Gelbrecht^{3,4}, Daisuke Hotta^{5,6}, Justin Willmert⁷, Simone Silvestri¹, Gregory L Wagner¹, Alistair White¹,^{3,4}, Sam Hatfield⁶, David Meyer^{8,9}, Tom Kimpson^{2,10}, Navid C Constantinou¹¹, and Chris Hill¹

¹ Massachusetts Institute of Technology, Cambridge, MA, USA ² University of Oxford, UK ³ Technical University of Munich, Germany ⁴ Potsdam Institute for Climate Impact Research, Germany ⁵ Japan Meteorological Agency, Tsukuba, Japan ⁶ European Centre for Medium-Range Weather Forecasts, Reading, UK ⁷ University of Minnesota, Minneapolis, MN, USA ⁸ Imperial College London, UK ⁹ European Centre for Medium-Range Weather Forecasts, Bonn, Germany ¹⁰ University of Melbourne, Australia ¹¹ Australian National University, Canberra, Australia ¶ Corresponding author

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

Software

- [Review](#) ↗
- [Repository](#) ↗
- [Archive](#) ↗

Editor: [Open Journals](#) ↗

Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

SpeedyWeather.jl is a library to simulate and analyze the global atmospheric circulation on the sphere. It implements several 2D and 3D models solved with spherical harmonics:

- the primitive equations with and without humidity ([Figure 1](#)),
- the shallow water equations ([Figure 2](#)), and
- the barotropic vorticity equations.

Several simple parameterizations for unresolved physical processes such as precipitation or the boundary layer are implemented, and new ones can be externally defined and passed as an argument to the model constructor. SpeedyWeather.jl is an intermediate-complexity general circulation model ([Kucharski et al., 2013](#)) and research playground with an (almost) everything-flexible attitude. It can be thought of as a conceptual reinvention of the Fortran SPEEDY model ([Molteni, 2003](#)) in the Julia programming language ([Bezanson et al., 2017](#)).

SpeedyWeather.jl internally uses three sub-modules RingGrids, LowerTriangularMatrices, and SpeedyTransforms. RingGrids is a module that discretizes the sphere on iso-latitude rings and implements interpolations between various such grids. LowerTriangularMatrices is a module used to define the spectral space of the spherical harmonic coefficients. SpeedyTransforms implements the spectral transform between the grid-point space as defined by RingGrids and the spectral space defined in LowerTriangularMatrices. These three modules are independently usable and therefore make SpeedyWeather.jl, beyond its main purpose of simulating atmospheric motion, also a library for the analysis of gridded data on the sphere. Running and analyzing simulations can be interactively combined, enhancing user experience and productivity.

The user interface of SpeedyWeather.jl is heavily influenced by the Julia ocean model Oceananigans.jl ([Ramadhan et al., 2020](#)). A monolithic interface based on parameter files is avoided in favor of a library-style interface in which users write short scripts to run models rather than merely supplying parameters and input arrays. A model is created bottom-up by first defining the discretization and any non-default model components with their respective parameters. All components are then collected into a single model object which, once initialized, returns a simulation object. A simulation contains everything, the model with all parameters as created

before but also all prognostic and diagnostic variables. Such a simulation can then be run, but also accessed before and after to analyze or visualize the current variables, or individual terms of the equations. One can also adjust parameters or define new model components before resuming the simulation. While these steps can be written into a script for reproducibility, the same steps can be executed and interacted with one-by-one in Julia's read-evaluate-print loop (REPL) or in a single Jupyter or Pluto notebook. We thereby achieve an interactivity of a simulation and its various model components far beyond the options provided in a monolithic interface. At the same time, defaults, set to well-established test cases, enable even inexperienced users to run simulations in just a few lines of code.

To be extensible with new model components, SpeedyWeather.jl relies on Julia's multiple dispatch programming paradigm (Bezanson et al., 2017). Every model component is defined as a new type. For example, to define precipitation due to the physical process of large-scale condensation, one would define MyCondensation as a new subtype of AbstractCondensation. One then only needs to extend the initialize! and condensation! functions for this new type. Passing on condensation = MyCondensation() to the model constructor then implements this new model component without the need to branch off or overwrite existing model components. Conceptually similar scientific modelling paradigms have been very successful in the Python-based generic partial differential equation solver Dedalus (Burns et al., 2020), the process-oriented climate model CLIMLAB (Rose, 2018), and the Julia ocean model Oceananigans.jl (Ramadhan et al., 2020).

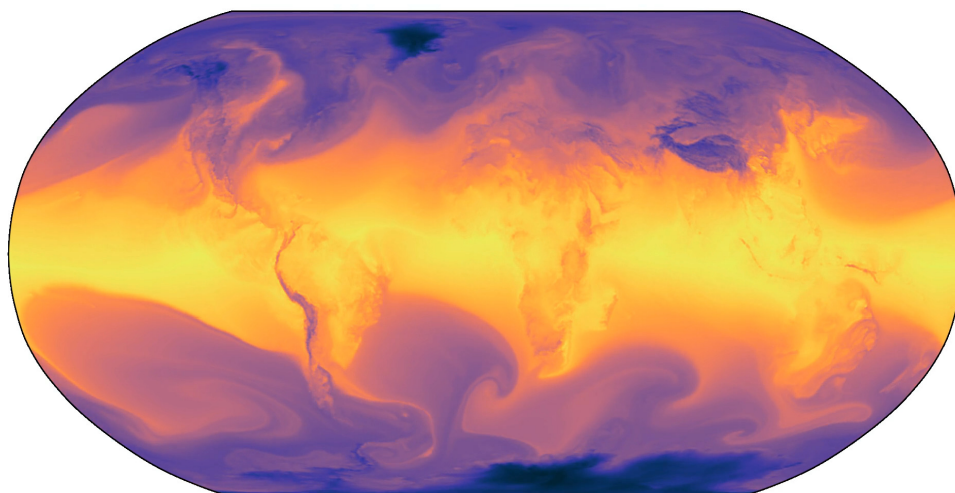


Figure 1: Surface temperature simulated with the primitive equation model in SpeedyWeather.jl. (Figure will be updated)

The dynamical core of SpeedyWeather.jl uses established numerics (Bourke, 1972; Hoskins & Simmons, 1975; Simmons et al., 1978; Simmons & Burridge, 1981), widely adopted in numerical weather prediction. It is based on the spherical harmonic transform (Reinecke & Seljebotn, 2013; Stompor, 2011) with a leapfrog-based semi-implicit time integration (Hoskins & Simmons, 1975) and a Robert-Asselin-Williams filter (Amezcuca et al., 2011; Williams, 2011). The spherical harmonic transform is grid-flexible (Willmert, 2020). Any iso-latitude ring-based grid can be used and new grids can be externally defined and passed in as an argument. Many grids are already implemented: the conventional Gaussian grid, a regular longitude-latitude grid, the octahedral Gaussian grid (Malardel et al., 2016), the octahedral Clenshaw-Curtis grid (Hotta & Ujiie, 2018), and the HEALPix grid (Górski et al., 2005). Both SpeedyWeather.jl and its spherical harmonic transform SpeedyTransforms are also number format-flexible. Single-precision floating-point numbers (Float32) are the default as adopted by other modelling efforts (Nakano et al., 2018; Váňa et al., 2017), but Float64 and other custom

number formats can be used with a single code basis (M. Klöwer et al., 2020; Milan Klöwer et al., 2022). Julia will compile to the choice of number format, the grid, and and other model components just-in-time. A simple parallelization across vertical layers is supported by Julia's multithreading. Output is stored as NetCDF files using [NCDatasets.jl](#).

Statement of need

SpeedyWeather.jl is a fresh approach to atmospheric models that have been very influential in many areas of scientific and high-performance computing as well as climate change mitigation and adaptation. Most weather, ocean and climate models are written in Fortran and have been developed over decades. From this tradition follows a specific programming style and associated user interface. SpeedyWeather.jl aims to overcome the constraints of traditional Fortran-based models. The modern trend sees simulations in Fortran and data analysis in Python, making virtually impossible to interact with various model components directly. In SpeedyWeather.jl, interfaces to the model components are exposed to the user. Furthermore, data-driven climate modelling (Rasp et al., 2018; Schneider et al., 2023), which replaces existing model components with machine learning, is more difficult in Fortran due to the lack of established machine learning frameworks (Meyer et al., 2022). In Julia, Flux.jl is available for machine learning (Innes et al., 2019) as well as automatic differentiation with Enzyme (Moses & Churavy, 2020), which calculates gradients, necessary to optimize network weights or parameters during training.

With SpeedyWeather.jl we hope to provide a platform for data-driven atmospheric modelling and in general an interactive model that makes difficult problems easy to simulate. Climate models that are user-friendly, trainable, but also easily extensible will suddenly make many complex research ideas possible.

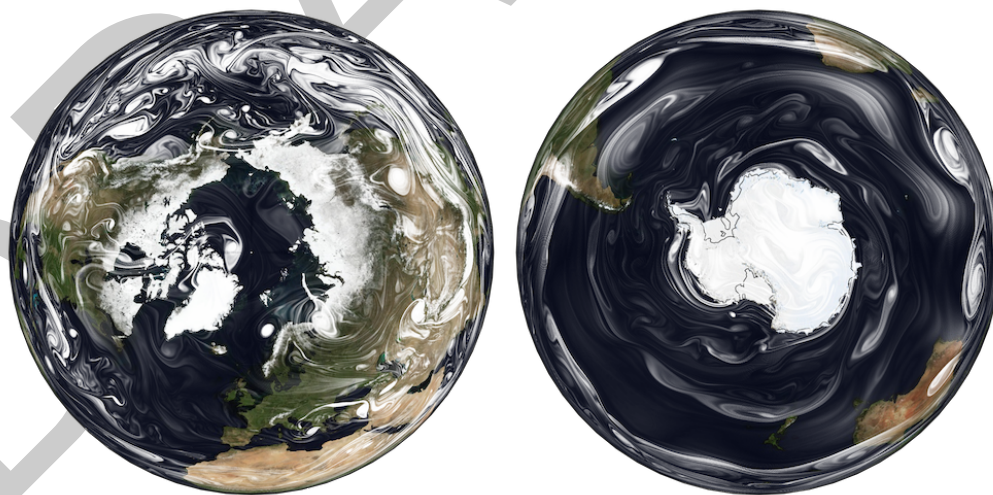


Figure 2: Relative vorticity simulated with the shallow water model in SpeedyWeather.jl. The simulation used a spectral resolution of T1023 (about 20 km) and Float32 arithmetic on an octahedral Clenshaw-Curtis grid (Hotta & Ujiie, 2018). Relative vorticity is visualized with Matplotlib (Hunter, 2007) and Cartopy (Met Office, 2010 - 2015) using a transparent-to-white colormap to mimic the appearance of clouds. Underlaid is NASA's blue marble from June 2004.

Acknowledgements

We acknowledge contributions from Mosè Giordano, Valentin Churavy, and Pietro Monticone who have also committed to the SpeedyWeather.jl repository, and the wider Julia community

for help and support. MK acknowledges funding from the National Science Foundation (Chris please add). MK and TK acknowledge funding from the European Research Council under the European Union's Horizon 2020 research and innovation programme for the ITHACA grant (no. 741112). NCC acknowledges support by the Australian Research Council DECRA Fellowship DE210100749.

References

- Amezcuca, J., Kalnay, E., & Williams, P. D. (2011). The Effects of the RAW Filter on the Climatology and Forecast Skill of the SPEEDY Model. *Monthly Weather Review*, 139(2), 608–619. <https://doi.org/10.1175/2010MWR3530.1>
- Bezanson, Jeff., Edelman, Alan., Karpinski, Stefan., & Shah, V. B. (2017). Julia: A Fresh Approach to Numerical Computing. *SIAM Review*, 59(1), 65–98. <https://doi.org/10.1137/141000671>
- Bourke, W. (1972). An Efficient, One-Level, Primitive-Equation Spectral Model. *Monthly Weather Review*, 100(9), 683–689. [https://doi.org/10.1175/1520-0493\(1972\)100%3C0683:AEOPSM%3E2.3.CO;2](https://doi.org/10.1175/1520-0493(1972)100%3C0683:AEOPSM%3E2.3.CO;2)
- Burns, K. J., Vasil, G. M., Oishi, J. S., Lecoanet, D., & Brown, B. P. (2020). Dedalus: A flexible framework for numerical simulations with spectral methods. *Physical Review Research*, 2(2), 023068. <https://doi.org/10.1103/PhysRevResearch.2.023068>
- Górski, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., & Bartelmann, M. (2005). HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere. *The Astrophysical Journal*, 622(2), 759. <https://doi.org/10.1086/427976>
- Hoskins, B. J., & Simmons, A. J. (1975). A multi-layer spectral model and the semi-implicit method. *Quarterly Journal of the Royal Meteorological Society*, 101(429), 637–655. <https://doi.org/10.1002/qj.49710142918>
- Hotta, D., & Ujiie, M. (2018). A nestable, multigrid-friendly grid on a sphere for global spectral models based on Clenshaw–Curtis quadrature. *Quarterly Journal of the Royal Meteorological Society*, 144(714), 1382–1397. <https://doi.org/10.1002/qj.3282>
- Hunter, J. D. (2007). Matplotlib: A 2D Graphics Environment. *Computing in Science & Engineering*, 9(3), 90–95. <https://doi.org/10.1109/MCSE.2007.55>
- Innes, M., Edelman, A., Fischer, K., Rackauckas, C., Saba, E., Shah, V. B., & Tebbutt, W. (2019). A Differentiable Programming System to Bridge Machine Learning and Scientific Computing (No. arXiv:1907.07587). arXiv. <https://doi.org/10.48550/arXiv.1907.07587>
- Klöwer, M., Düben, P. D., & Palmer, T. N. (2020). Number formats, error mitigation, and scope for 16-bit arithmetics in weather and climate modeling analyzed with a shallow water model. *Journal of Advances in Modeling Earth Systems*, 12(10), e2020MS002246. <https://doi.org/https://doi.org/10.1029/2020MS002246>
- Klöwer, Milan, Hatfield, S., Croci, M., Düben, P. D., & Palmer, T. N. (2022). Fluid Simulations Accelerated With 16 Bits: Approaching 4x Speedup on A64FX by Squeezing ShallowWaters.jl Into Float16. *Journal of Advances in Modeling Earth Systems*, 14(2), e2021MS002684. <https://doi.org/10.1029/2021MS002684>
- Kucharski, F., Molteni, F., King, M. P., Farneti, R., Kang, I.-S., & Feudale, L. (2013). On the Need of Intermediate Complexity General Circulation Models: A “SPEEDY” Example. *Bulletin of the American Meteorological Society*, 94(1), 25–30. <https://doi.org/10.1175/BAMS-D-11-00238.1>

- 147 Malardel, S., Wedi, N., Deconinck, N., Diamantakis, M., Kuehnlein, C., Mozdzyński, G.,
148 Hamrud, M., & Smolarkiewicz, P. (2016). A new grid for the IFS. In *ECMWF Newsletter*.
149 <https://www.ecmwf.int/node/15041>.
- 150 Met Office. (2010 - 2015). *Cartopy: A cartographic python library with a matplotlib interface*.
151 <https://scitools.org.uk/cartopy>
- 152 Meyer, D., Grimmond, S., Dueben, P., Hogan, R., & Reeuwijk, M. van. (2022). Machine
153 learning emulation of urban land surface processes. *Journal of Advances in Modeling Earth*
154 *Systems*, 14(3). <https://doi.org/10.1029/2021ms002744>
- 155 Molteni, F. (2003). Atmospheric simulations using a GCM with simplified physical param-
156 etrizations. I: Model climatology and variability in multi-decadal experiments. *Climate*
157 *Dynamics*, 20(2), 175–191. <https://doi.org/10.1007/s00382-002-0268-2>
- 158 Moses, W., & Churavy, V. (2020). Instead of Rewriting Foreign Code for Machine Learning,
159 Automatically Synthesize Fast Gradients. *Advances in Neural Information Processing*
160 *Systems*, 33, 12472–12485.
- 161 Nakano, M., Yashiro, H., Kodama, C., & Tomita, H. (2018). Single Precision in the Dynamical
162 Core of a Nonhydrostatic Global Atmospheric Model: Evaluation Using a Baroclinic
163 Wave Test Case. *Monthly Weather Review*, 146(2), 409–416. <https://doi.org/10.1175/MWR-D-17-0257.1>
- 164
- 165 Ramadhan, A., Wagner, G. L., Hill, C., Campin, J.-M., Churavy, V., Besard, T., Souza,
166 A., Edelman, A., Ferrari, R., & Marshall, J. (2020). Oceananigans.jl: Fast and friendly
167 geophysical fluid dynamics on GPUs. *Journal of Open Source Software*, 5(53), 2018.
168 <https://doi.org/10.21105/joss.02018>
- 169 Rasp, S., Pritchard, M. S., & Gentile, P. (2018). Deep learning to represent subgrid processes
170 in climate models. *Proceedings of the National Academy of Sciences*, 115(39), 9684–9689.
- 171 Reinecke, M., & Seljebotn, D. S. (2013). Libsharp - spherical harmonic transforms revisited.
172 *Astronomy and Astrophysics*, 554, A112. <https://doi.org/10.1051/0004-6361/201321494>
- 173 Rose, B. E. J. (2018). CLIMLAB: A Python toolkit for interactive, process-oriented climate
174 modeling. *Journal of Open Source Software*, 3(24), 659. [https://doi.org/10.21105/joss.](https://doi.org/10.21105/joss.00659)
175 [00659](https://doi.org/10.21105/joss.00659)
- 176 Schneider, T., Behera, S., Boccaletti, G., Deser, C., Emanuel, K., Ferrari, R., Leung, L. R., Lin,
177 N., Müller, T., Navarra, A., Ndiaye, O., Stuart, A., Tribbia, J., & Yamagata, T. (2023).
178 Harnessing AI and computing to advance climate modelling and prediction. *Nature Climate*
179 *Change*, 13(9), 887–889. <https://doi.org/10.1038/s41558-023-01769-3>
- 180 Simmons, A. J., & Burridge, D. M. (1981). An Energy and Angular-Momentum Conserving Ver-
181 tical Finite-Difference Scheme and Hybrid Vertical Coordinates. *Monthly Weather Review*,
182 109(4), 758–766. [https://doi.org/10.1175/1520-0493\(1981\)109%3C0758:AEAAMC%3E2.](https://doi.org/10.1175/1520-0493(1981)109%3C0758:AEAAMC%3E2.0.CO;2)
183 [0.CO;2](https://doi.org/10.1175/1520-0493(1981)109%3C0758:AEAAMC%3E2.0.CO;2)
- 184 Simmons, A. J., Hoskins, B. J., & Burridge, D. M. (1978). Stability of the Semi-Implicit
185 Method of Time Integration. *Monthly Weather Review*, 106(3), 405–412. [https://doi.org/](https://doi.org/10.1175/1520-0493(1978)106%3C0405:SOTSIM%3E2.0.CO;2)
186 [10.1175/1520-0493\(1978\)106%3C0405:SOTSIM%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1978)106%3C0405:SOTSIM%3E2.0.CO;2)
- 187 Stompor, R. (2011). *S2HAT: Scalable Spherical Harmonic Transform Library*. Astrophysics
188 Source Code Library, record ascl:1110.013.
- 189 Váňa, F., Düben, P., Lang, S., Palmer, T., Leutbecher, M., Salmond, D., & Carver, G. (2017).
190 Single Precision in Weather Forecasting Models: An Evaluation with the IFS. *Monthly*
191 *Weather Review*, 145(2), 495–502. <https://doi.org/10.1175/MWR-D-16-0228.1>
- 192 Williams, P. D. (2011). The RAW Filter: An Improvement to the Robert–Asselin Filter
193 in Semi-Implicit Integrations. *Monthly Weather Review*, 139(6), 1996–2007. <https://doi.org/10.1175/MWR-D-10-0228.1>

194 [//doi.org/10.1175/2010MWR3601.1](https://doi.org/10.1175/2010MWR3601.1)

195 Willmert, J. (2020). *Blog series: Notes on calculating the spherical harmonics*. [https:](https://justinwillmert.com/articles/2020/notes-on-calculating-the-spherical-harmonics/)
196 [//justinwillmert.com/articles/2020/notes-on-calculating-the-spherical-harmonics/](https://justinwillmert.com/articles/2020/notes-on-calculating-the-spherical-harmonics/).

DRAFT