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

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Summary

SpeedyWeather.jl is a library to simulate and analyze the global atmospheric circulation on the sphere. It implements several 2D and 3D models which solve different sets of equations:

- the primitive equations with and without humidity (Figure 1),
- the shallow water equations (Figure 2), and
- the barotropic vorticity equation (Figure 3).

The primitive equation model in SpeedyWeather.jl is an atmospheric general circulation model (Kucharski et al., 2013) with simple parameterizations for unresolved physical processes including precipitation or boundary layer mixing. 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). However, all models here are written in a modular way to make its components easily extensible. For example, a new parameterization can be externally defined and passed as an argument to the model constructor. Operators used inside SpeedyWeather.jl are exposed to the user, facilitating analysis of the simulation data. SpeedyWeather.jl is therefore, 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 (Mazlami et al., 2017), controlling most of the model's functionality through arguments of a single function or through parameter files (often called namelists in Fortran), is avoided in favor of a library-style interface. A model is constructed 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 constructed 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 some parameters 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 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.

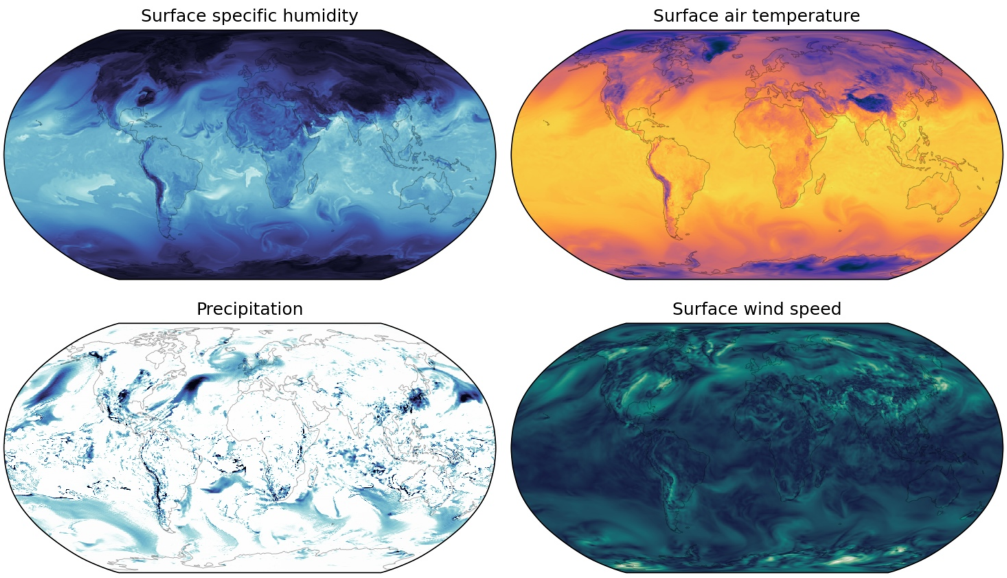

Figure 1: Surface humidity, air temperature, wind speed and precipitation simulated with the primitive equation model in SpeedyWeather.jl. Spectral resolution is T340 (about 40km) on an octahedral Gaussian grid (Malardel et al., 2016) with simple physics to represent unresolved processes such as surface fluxes including evaporation, and precipitation due to large-scale condensation and convection.

SpeedyWeather.jl relies on Julia's multiple dispatch programming paradigm (Bezanson et al., 2017) to be extensible with new components including parameterizations, forcing, drag, or even the grid. All such supported model components define an abstract type that can be subtyped to introduce, for example, a new parameterization. To define a new parameterization for convection in a given vertical column of the atmosphere, one would define `MyConvection` as a new subtype of `AbstractConvection`. One then only needs to extend the `initialize!` (executed once during model initialization) and `convection!` (executed on every time step) functions for this new type. Passing on `convection = MyConvection()` 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).

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 (Amezcua 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 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 (Klöwer et al., 2020; 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 for the dynamical core, across horizontal grid points for the parameterizations) is supported by Julia's multithreading. No distributed-memory parallelization is currently supported, GPU support is planned.

SpeedyWeather.jl internally uses three sub-modules `RingGrids`, `LowerTriangularArrays`, and `SpeedyTransforms`. `RingGrids` is a module that discretizes the sphere on iso-latitude rings and implements interpolations between various such grids. `LowerTriangularArrays` facilitates the implementation of the spherical harmonics by organizing their coefficients in a lower triangular matrix representation. `SpeedyTransforms` implements the spectral transform between the grid-point space as defined by `RingGrids` and the spectral space defined in `LowerTriangularArrays`. These three modules are independently usable and therefore support SpeedyWeather's library-like user interface. Output is stored as NetCDF files using NCDatasets.jl (Barth, 2023).

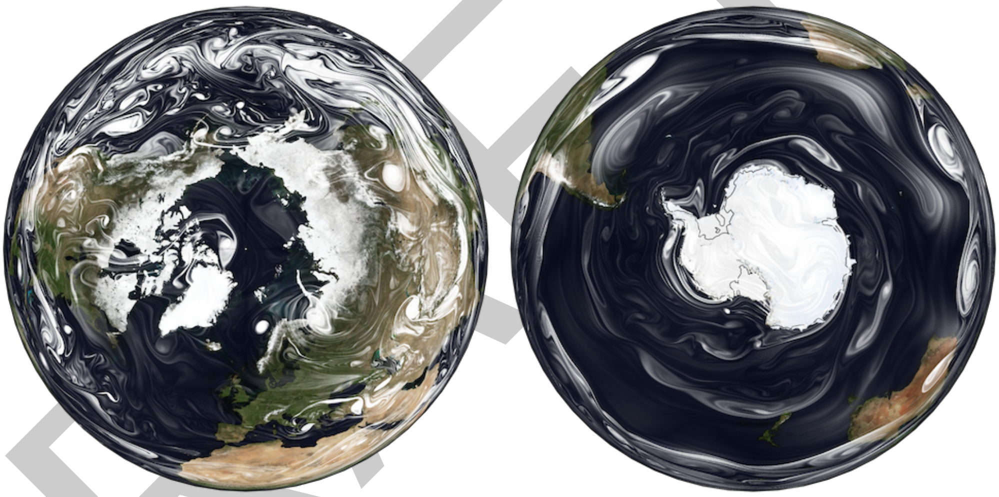

Figure 2: Relative vorticity simulated with the shallow water model in SpeedyWeather.jl. The simulation used a spectral resolution of T1023 (about 20 km) and Float32 arithmetic on an octahedral Clenshaw-Curtis grid (Hotta & Ujiie, 2018). Relative vorticity is visualized with Matplotlib (Hunter, 2007) 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.

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 (e.g. ICON (Giorgetta et al., 2018), CESM (Hurrell et al., 2013), MITgcm (Marshall et al., 1997), NEMO (Madec et al., 2017)) 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 (e.g. NumPy (Harris et al., 2020), Xarray (Hoyer & Hamman, 2017), Dask (Dask Development Team, 2016), Matplotlib (Hunter, 2007)), making it 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 (Innes et al., 2019) is available for machine learning as well as automatic differentiation with Enzyme (Moses & Churavy, 2020) for gradients-based optimization.

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.

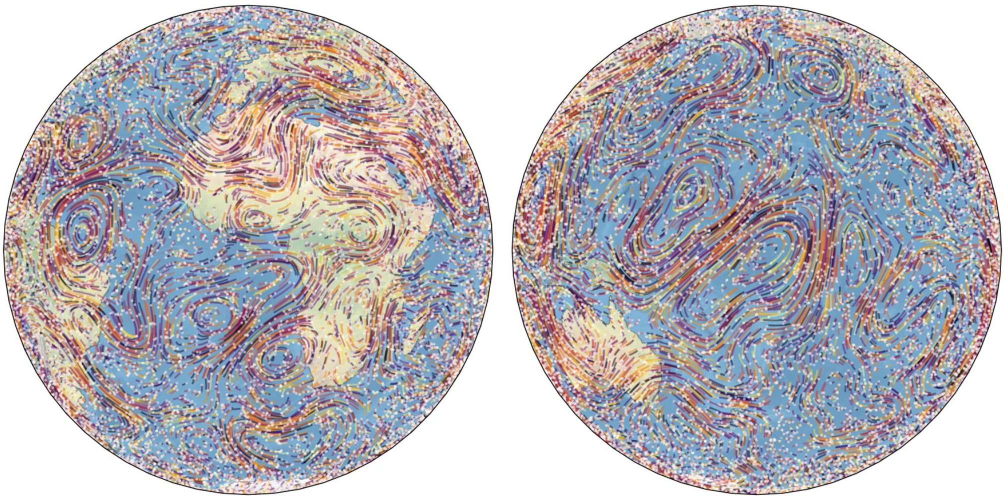

Figure 3: Particle trajectories advected in the barotropic vorticity model. The barotropic vorticity equations were stochastically stirred at wave numbers 8 to 40 for homogeneous turbulence on the sphere. The simulation was computed at T340 (about 40km global resolution). Visualized are 20,000 particles (white dots) with trajectories (colored randomly) for the previous 6 hours.

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References

Amezcua, 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

Barth, A. (2023). NCDatasets: A Julia package for manipulating netCDF data sets. In *GitHub repository*. https://github.com/Alexander-Barth/NCDatasets.jl; GitHub.

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

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

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

Dask Development Team. (2016). *Dask: Library for dynamic task scheduling*. http://dask.pydata.org

Giorgetta, M. A., Brokopf, R., Crueger, T., Esch, M., Fiedler, S., Helmert, J., Hohenegger, C., Kornblueh, L., Köhler, M., Manzini, E., Mauritsen, T., Nam, C., Raddatz, T., Rast, S., Reinert, D., Sakradzija, M., Schmidt, H., Schneck, R., Schnur, R., … Stevens, B. (2018). ICON-A, the Atmosphere Component of the ICON Earth System Model: I. Model Description. *Journal of Advances in Modeling Earth Systems*, *10*(7), 1613–1637. https://doi.org/10.1029/2017MS001242

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

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array Programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

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

Hoyer, S., & Hamman, J. (2017). Xarray: N-D labeled arrays and datasets in Python. *Journal of Open Research Software*, *5*(1). https://doi.org/10.5334/jors.148

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

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., … Marshall", S. (2013). The Community Earth System Model: A Framework for Collaborative Research. *Bulletin of the American Meteorological Society*, *94*(9), 1339–1360. https://doi.org/10.1175/BAMS-D-12-00121.1

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/10.1029/2020MS002246

Klöwer, M., 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

Madec, G., Bourdallé-Badie, R., Bouttier, P.-A., Bricaud, C., Bruciaferri, D., Calvert, D., Chanut, J., Clementi, E., Coward, A., Delrosso, D., Ethé, C., Flavoni, S., Graham, T., Harle, J., Iovino, D., Lea, D., Lévy, C., Lovato, T., Martin, N., … Vancoppenolle, M. (2017). *NEMO ocean engine*. https://doi.org/10.5281/zenodo.3248739

Malardel, S., Wedi, N., Deconinck, N., Diamantakis, M., Kuehnlein, C., Mozdzynski, G., Hamrud, M., & Smolarkiewicz, P. (2016). A New Grid for the IFS. In *ECMWF Newsletter*. https://www.ecmwf.int/node/15041. https://doi.org/10.21957/zwdu9u5i

Marshall, J., Adcroft, A., Hill, C., Perelman, L., & Heisey, C. (1997). A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. *Journal of Geophysical Research: Oceans*, *102*(C3), 5753–5766. https://doi.org/10.1029/96JC02775

Mazlami, G., Cito, J., & Leitner, P. (2017). Extraction of Microservices from Monolithic Software Architectures. *2017 IEEE International Conference on Web Services (ICWS)*, 524–531. https://doi.org/10.1109/ICWS.2017.61

Met Office. (2010 - 2015). *Cartopy: A cartographic python library with a Matplotlib interface*. https://scitools.org.uk/cartopy

Meyer, D., Grimmond, S., Dueben, P., Hogan, R., & Reeuwijk, M. van. (2022). Machine learning emulation of urban land surface processes. *Journal of Advances in Modeling Earth Systems*, *14*(3). https://doi.org/10.1029/2021ms002744

Molteni, F. (2003). Atmospheric Simulations Using a GCM with Simplified Physical Parametrizations. I: Model Climatology and Variability in Multi-Decadal Experiments. *Climate Dynamics*, *20*(2), 175–191. https://doi.org/10.1007/s00382-002-0268-2

Moses, W., & Churavy, V. (2020). Instead of Rewriting Foreign Code for Machine Learning, Automatically Synthesize Fast Gradients. *Advances in Neural Information Processing Systems*, *33*, 12472–12485. https://doi.org/10.48550/arXiv.2010.01709

Nakano, M., Yashiro, H., Kodama, C., & Tomita, H. (2018). Single Precision in the Dynamical Core of a Nonhydrostatic Global Atmospheric Model: Evaluation Using a Baroclinic Wave Test Case. *Monthly Weather Review*, *146*(2), 409–416. https://doi.org/10.1175/MWR-D-17-0257.1

Ramadhan, A., Wagner, G. L., Hill, C., Campin, J.-M., Churavy, V., Besard, T., Souza, A., Edelman, A., Ferrari, R., & Marshall, J. (2020). Oceananigans.jl: Fast and Friendly Geophysical Fluid Dynamics on GPUs. *Journal of Open Source Software*, *5*(53), 2018. https://doi.org/10.21105/joss.02018

Rasp, S., Pritchard, M. S., & Gentine, P. (2018). Deep Learning to Represent Subgrid Processes in Climate Models. *Proceedings of the National Academy of Sciences*, *115*(39), 9684–9689. https://doi.org/10.1073/pnas.1810286115

Reinecke, M., & Seljebotn, D. S. (2013). Libsharp - spherical harmonic transforms revisited. *Astronomy and Astrophysics*, *554*, A112. https://doi.org/10.1051/0004-6361/201321494

Rose, B. E. J. (2018). CLIMLAB: A Python Toolkit for Interactive, Process-Oriented Climate Modeling. *Journal of Open Source Software*, *3*(24), 659. https://doi.org/10.21105/joss.00659

Schneider, T., Behera, S., Boccaletti, G., Deser, C., Emanuel, K., Ferrari, R., Leung, L. R., Lin, N., Müller, T., Navarra, A., Ndiaye, O., Stuart, A., Tribbia, J., & Yamagata, T. (2023).

Harnessing AI and Computing to Advance Climate Modelling and Prediction. *Nature Climate Change*, *13*(9), 887–889. https://doi.org/10.1038/s41558-023-01769-3

Simmons, A. J., & Burridge, D. M. (1981). An Energy and Angular-Momentum Conserving Vertical Finite-Difference Scheme and Hybrid Vertical Coordinates. *Monthly Weather Review*, *109*(4), 758–766. https://doi.org/10.1175/1520-0493(1981)109%3C0758:AEAAMC%3E2.0.CO;2

Simmons, A. J., Hoskins, B. J., & Burridge, D. M. (1978). Stability of the Semi-Implicit Method of Time Integration. *Monthly Weather Review*, *106*(3), 405–412. https://doi.org/10.1175/1520-0493(1978)106%3C0405:SOTSIM%3E2.0.CO;2

Stompor, R. (2011). *S2HAT: Scalable Spherical Harmonic Transform Library*. https://ascl.net/1110.013.

Váňa, F., Düben, P., Lang, S., Palmer, T., Leutbecher, M., Salmond, D., & Carver, G. (2017). Single Precision in Weather Forecasting Models: An Evaluation with the IFS. *Monthly Weather Review*, *145*(2), 495–502. https://doi.org/10.1175/MWR-D-16-0228.1

Williams, P. D. (2011). The RAW Filter: An Improvement to the Robert–Asselin Filter in Semi-Implicit Integrations. *Monthly Weather Review*, *139*(6), 1996–2007. https://doi.org/10.1175/2010MWR3601.1

Willmert, J. (2020). *Blog Series: Notes on calculating the spherical harmonics*. https://justinwillmert.com/articles/2020/notes-on-calculating-the-spherical-harmonics/.