




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

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## Software

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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 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](#)).

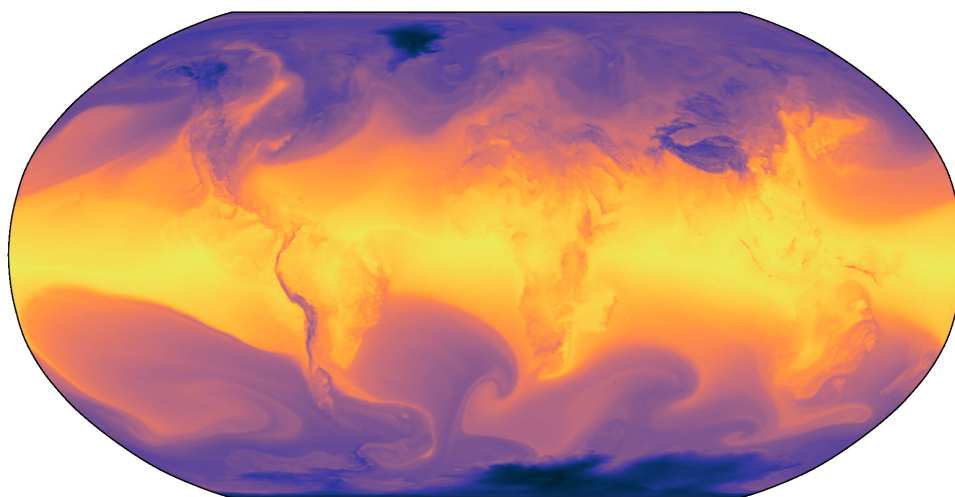
SpeedyWeather.jl internally uses three sub-modules RingGrids, LowerTriangularMatrices, and SpeedyTransforms. RingGrids is a module that discretizes the sphere on iso-latitude rings and implements interpolations between various grids. LowerTriangularMatrices is a module used to define the spectral space 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 analysing 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 to analyze the current variables, or individual terms of the equations. One can also adjust 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). 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 and composable 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)

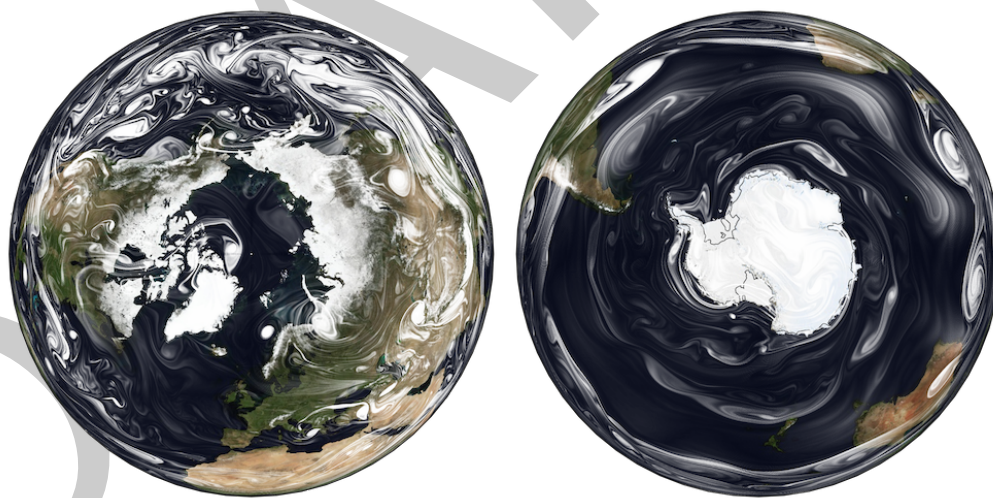
The dynamical core of SpeedyWeather.jl uses established numerics (Bourke, 1972; Hoskins & Simmons, 1975; Simmons et al., 1978; Simmons & Burridge, 1981), widely adopted in numerical weather prediction. It is based on the spherical harmonic transform with a leapfrog-based semi-implicit time integration (Hoskins & Simmons, 1975) and a Robert-Asselin-Williams filter (Amezcuca et al., 2011; Williams, 2011). The spherical harmonic transform is grid-flexible. 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 the number format, the grid,

75 and and other model components just-in-time. A simple parallelization across vertical layers is  
76 supported by Julia's multithreading. Output is stored as NetCDF files using [NCDatasets.jl](#).

## 77 Statement of need

78 SpeedyWeather.jl is a fresh approach to atmospheric models that have been very influential in  
79 many areas of scientific and high-performance computing as well as climate change mitigation  
80 and adaptation. Most weather, ocean and climate models are written in Fortran and have  
81 been developed over decades. From this tradition follows a specific programming style and  
82 associated user interface. SpeedyWeather.jl aims to overcome the constraints of traditional  
83 Fortran-based models. Running a simulation in Fortran and analyzing the data in Python makes  
84 it virtually impossible to interact with various model components directly. In SpeedyWeather.jl,  
85 interfaces to the model components are exposed to the user. Furthermore, data-driven climate  
86 modelling ([Rasp et al., 2018](#); [Schneider et al., 2023](#)), which replaces existing model components  
87 with machine learning, is difficult due to the lack of established machine learning frameworks  
88 in Fortran. In Julia, Flux.jl is available for machine learning ([Innes et al., 2019](#)) as well as  
89 automatic differentiation with Enzyme ([Moses & Churavy, 2020](#)), which calculates gradients,  
90 necessary to optimize network weights or parameters during training.

91 With SpeedyWeather.jl we hope to provide a first test platform for data-driven atmospheric  
92 modelling and in general an interactive model that makes difficult problems easy to simulate.  
93 Climate models that are user-friendly, trainable, but also easily extensible will suddenly make  
94 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.

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