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

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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 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 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 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 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).

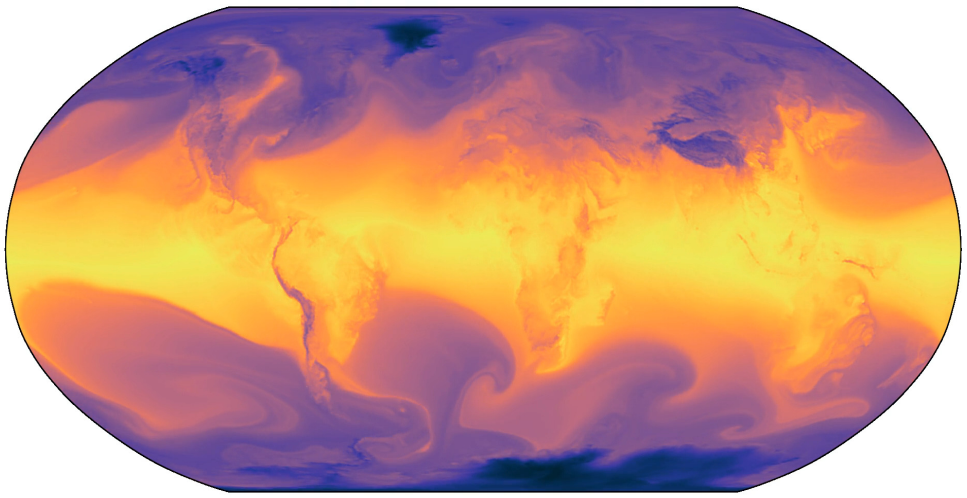

Figure 1: Surface temperature simulated with the primitive equation model in SpeedyWeather.jl. (Figure will be updated)

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 (Amezcua 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, 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. Running a simulation in Fortran and analyzing the data in Python makes 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 difficult due to the lack of established machine learning frameworks in Fortran. 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.

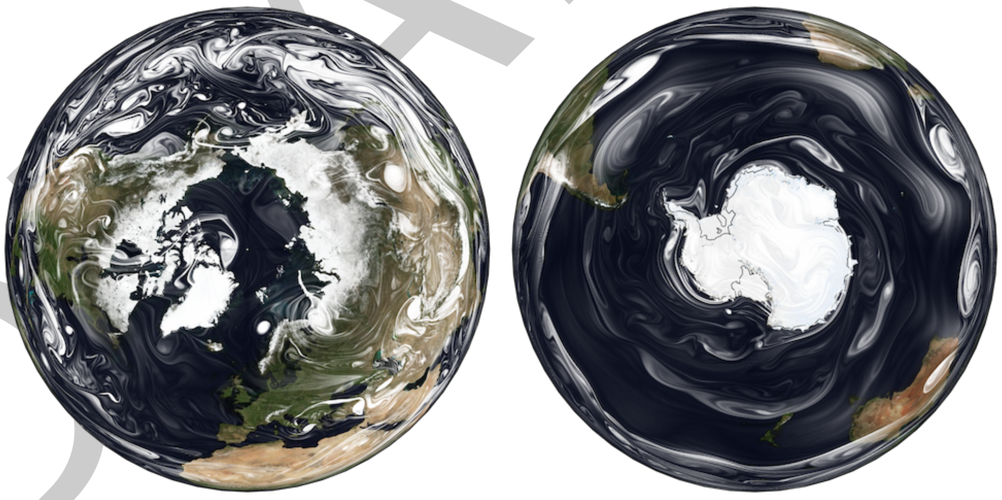
Figure 2: Relative vorticity simulated with the shallow water model in SpeedyWeather.jl. The simulation used a spectral resolution of T1023 (about 20 km) and Float32 arithmetic on an octahedral Clenshaw-Curtis grid (Hotta & Ujiie, 2018). Relative vorticity is visualized with Matplotlib (Hunter, 2007)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

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