




FlowSieve: A Coarse-Graining Utility for Geophysical Flows on the Sphere

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Software

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Summary of Subject Area

Ocean and atmosphere dynamics span an incredibly wide range of spatial and temporal scales, with spatial scales ranging from the sub-millimetre viscous scales all the way up to planetary scales at tens of thousands of kilometres. Because of the strong non-linear nature of oceanic and atmospheric flows, not only do the behaviour and characteristics change significantly with scale, but important energetic interactions exist between different scales. As a result, an important step in understanding and predicting the behaviour of such complex flow systems is being able to disentangle the complex interactions across this wide range of scales. Coarse-graining is a physically-motivated and mathematically-rigorous technique for partitioning spatial flows as a function of a specified partitioning scale, allowing for a consistent and comprehensive scale-by-scale analysis.

Summary of Software

The core features of FlowSieve are: 1) computes coarse-grained scalar and vector fields for arbitrary filter scales, in both Cartesian and spherical coordinates, 2) built-in diagnostics for oceanographic settings, including kinetic energy (KE), KE cascades, vorticity, divergence, etc., 3) built-in post-processing tools compute region averages for an arbitrary number of custom user-specified regions [avoiding storage concerns when handling large datasets], and 4) includes Helmholtz-decomposition scripts to allow careful coarse-graining on the sphere [i.e. to maintain commutativity with derivatives].

FlowSieve is written in C++, with some user-friendly Python scripts included. Input and output files are netCDF. FlowSieve is designed with heavy parallelization in mind, as well as several context-based optimizations, in order to facilitate processing high-resolution datasets. In particular, MPI is used to divide time and depth [with minimal communication costs, since coarse-graining is applied at each time and depth independently], while OpenMP is used to parallelize latitude and longitude loops, taking advantage of shared memory to reduce communication overhead.

FlowSieve can currently only work on mesh grids (i.e. latitude grid is independent of longitude, and vice-versa), but those grids need not be uniform. This is not a restriction of the coarse-graining methodology, however, and future developments may extend this functionality (e.g. to include unstructured grids) if there is sufficient interest / need.

State of the Field

Coarse-graining is being increasingly used as an analytical method in oceanographic communities. While coarse-graining is similar to blurring / convolutions in image-processing, for which many software packages exist, those tools do not readily apply to oceanographic contexts: they often

rely on uniform, rectangular, Cartesian grids, which typically do not apply in Global Climate Model (GCM) data. An established package in the field, GCM-Filters (Grooms et al. (2021), Loose et al. (2022)), is designed to work on GCM data and grids. It uses a diffusion-type coarse-graining method that is made available to users through Python utilities. Another approach applies structure functions to Lagrangian trajectories to extract spectral diagnostics, such as power spectra and inter-scale energy transfers (Frisch (1995), Balwada et al. (2022)).

The unique contributions of FlowSieve to the field are: 1) analysis on full spherical geometries, allowing the processing of global data, 2) arbitrary filtering scales spanning from sub-grid to domain-size (e.g. Storer et al. (2022) extracts global power spectra for scales spanning 10s of km to 40000 km - the equatorial circumference of the Earth), 3) on-line diagnostic calculations [e.g. across-scale energy transfers, large-scale vorticity and divergence], 4) on-line post-processing to reduce output file sizes [e.g. averages over user-specified regions, zonal averages], 5) rigorous underlying mathematical framework of Aluie (2019) to preserve physical properties of the data (e.g. non-divergence of flow) to accurately filter realistic flows and ensure commutativity between filtering and differential operators, and 6) heavy parallelization to utilize HPC environments efficiently.

Statement of need

Aluie et al. (2018) demonstrated how, when applied appropriately, coarse-graining can not only be applied in a data-processing sense, but also to the governing equations. This provides a physically meaningful and mathematically coherent way to quantify not only how much energy is contained in different length scales, but also how much energy is being transferred to different scales.

FlowSieve is a heavily-parallelized coarse-graining codebase that provides tools for spatially filtering both scalar fields and vector fields in Cartesian and spherical geometries. Specifically, filtering velocity vector fields on a sphere provides a high-powered tool for scale-decomposing oceanic and atmospheric flows following the mathematical results in Aluie (2019).

FlowSieve is designed to work in high-performance computing (HPC) environments in order to efficiently analyse large oceanic and atmospheric datasets, and extract scientifically meaningful diagnostics, including scale-wise energy content and energy transfer.

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