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# 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 fied, 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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