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FluidSF: A Python package for calculating turbulent fluid statistics

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Summary

Fluid systems are everywhere, from small-scale engineering problems to planetary-and-larger-scale systems (atmosphere, ocean, galactic gas clouds). These systems are often turbulent, where motion is chaotic, unpredictable, and can only be characterized through statistical analyses. Spatial structure functions (SFs) are one such statistical analysis technique for turbulence, that require calculation of spatial differences in properties as a function of their separation distance. By combining and then averaging these spatial differences, various types of SF can be constructed to measure physical properties of fluid flow, such as heat and energy transfers, energy density, intermittency etc. However, calculating SFs is often a cumbersome and computationally-intensive task tailored to the specific format of a given fluid dataset.

Statement of need

FluidSF is a flexible `Python` package for calculating spatial structure functions (SFs) in one, two, or three spatial dimensions from diverse fluid data sets. The package can construct user-defined SFs that utilize any fluid properties (e.g., velocity, vorticity, temperature, magnetic field etc.), including combinations of these properties and structure functions of arbitrary order. The flexibility of this package enables geophysical, astrophysical, and engineering applications…. ADD EXAMPLES OF SF UTILITY BREADTH: e.g., quantifying the energy cycles within Earth's ocean (Balwada et al., 2022; J. Pearson et al., 2019), Earth's atmosphere (Lindborg, 1999), and Jupiter's atmosphere (Young & Read, 2017), the intermittency of magnetohydrodynamic plasma turbulence (Wan et al., 2016), the anistropy of flow over rough beds (Coscarella et al., 2020), the characteristics of ocean surface temperature (Schloesser et al., 2016), and the scaling laws of idealized 3D turbulence (Iyer et al., 2020).

Paragraph on package capabilities & limitations. Regularly-gridded data, Lat-lon gridded data, track/directional sampling, 1D-data, evenly-spaced, iregularly-spaced (what are limitations), binning, bootstrapping(?), local advection terms (B. C. Pearson et al., 2021), Bessel function examples(?) (Xie & Bühler, 2018) examples of time-averaging, SWOT application. What are limitations (can it take 2D data in a vector rather than array format? Can it calculate 2D or 3D maps of SF rather than just a function of $|r|$ magnitude?). Perhaps these don't need to be mentioned, or can be stated as future developments.

State of the field

There are a small number of open source software available that calculate structure functions. `fastSF` is a parallelized C++ code designed to compute structure functions from Cartesian grids of data (Sadhukhan et al., 2021). Fuchs et al. (2022) created an open source `MATLAB` toolkit that performs a variety of turbulence analysis, including structure functions. An complimentary and alternative method to structure functions for analyzing turbulence data is

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coarse-graining. `FlowSieve` is a primarily C++ package that uses coarse-graining to estimate ocean and atmospheric turbulence properties from Global Climate Model data (Storer & Aluie, 2023).

Features

FluidSF uniquely contributes to the field through expanded data support, an increased variety of SF calculations, and tools for analyzing spatial variations in SFs.

FluidSF calculates SFs from 1D, 2D, and 3D data with periodic and non-periodic boundary conditions. Regular Cartesian (1D, 2D, 3D) and non-uniform latitude-longitude gridding (1D, 2D) are supported. Since FluidSF is written in `Python`, any data intialized and loaded as `NumPy` arrays can be used.

FluidSF is the first software pacakage that calculates novel advective SFs, a type of SF that depends on velocity advection and does not assume an isotropic flow field (B. C. Pearson et al., 2021). Therefor FluidSF also computes advection for 2D and 3D data. It supports blended SFs, i.e. a combination of longitudinal and transverse velocity SFs, whereas other software only supports purely longitudinal or transverse SFs.

To explore spatial variations in SFs, FluidSF computes 2D polar maps of SFs that vary in separation distance and separation direction.

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