In Situ Segmentation of Turbulent Flow with Topology Data Analysis

F. Nauleau, B. Fovet, F. Vivodtzev

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PROBLEM

Study the areas of influence of the most important vortices on 2D turbulent hydrodynamic flows and 3D viscous flows.

Difficult to perform with traditional methods due to the complexity of the turbulent flows and the finer-grained mesh required.

Solving the compressible unsteady Navier-Stokes equation flows [7] with a massively parallel structured solver using immersed boundary conditions in a simulation code [2], with the TENO 5th order scheme [4] and the AUSM+-up Riemann solver [6].

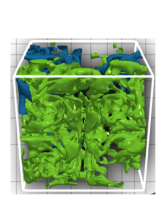
Running simulations at the exascale level means computing is getting cheaper while data transfer and storage is increasingly expensive.

METHOD

Adapt the simulation code to get ready for in-situ processing by mapping simulation data structures (mesh, scalar and vector fields) to Conduit [11] data model.

Define a ParaView pipeline segmenting the main vortices using the Topology Toolkit (TTK) [10] to be specified in a Python script.

Execute the Python script at each timestep with the Catalyst library, through a specific interface implemented for the simulation code.



In-situ analysis of the simulation runs based on the energy spectrum [5] of each topologically segmented vortex.

RESULTS

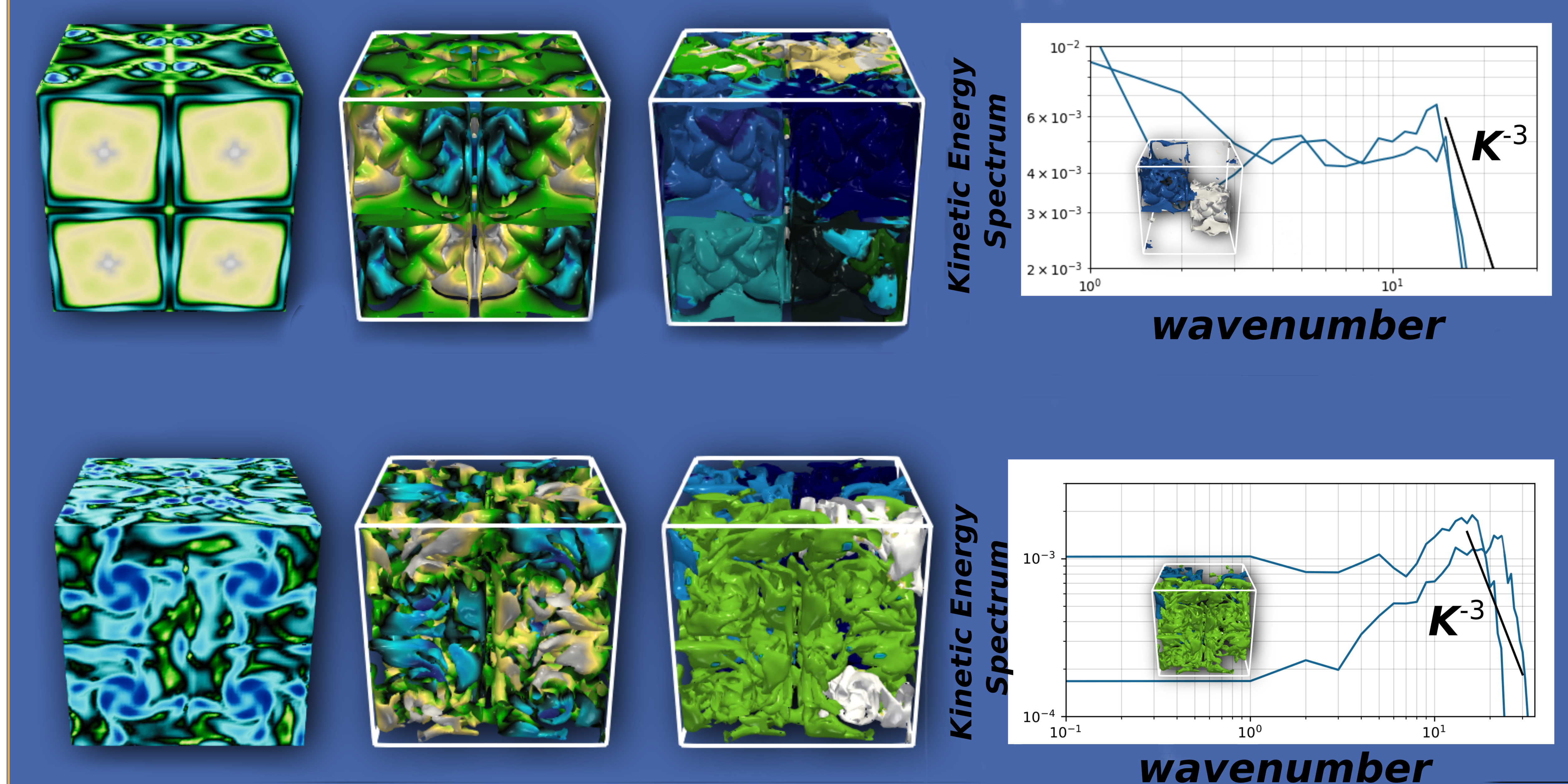
We show that the vortices describe a physical solution by looking at their energy spectrum.

We easily identify the areas of influence of large vortices thanks to the topological tools of TTK such as persistence curves.

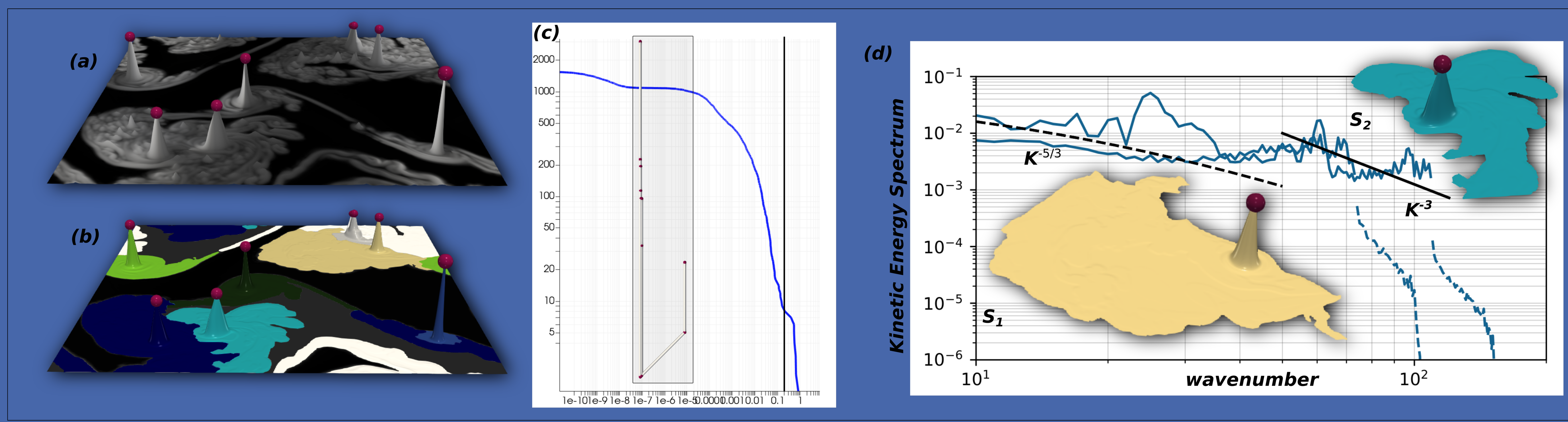
We verify the segmentation of the vortices on the enstrophy scalar field, with the energy spectrum of each vortex ensemble.

We notice that the energy transfer of vortex ensembles evolves in $K^{5/3}$ for 2D Kelvin-Helmholtz instability simulations and in K^{-3} for 3D Taylor Green Vortex simulations, as expected [8].

Topological segmentation of turbulent flow simulation is made faster and more accurate with respect to the kinetic energy of each vortex.

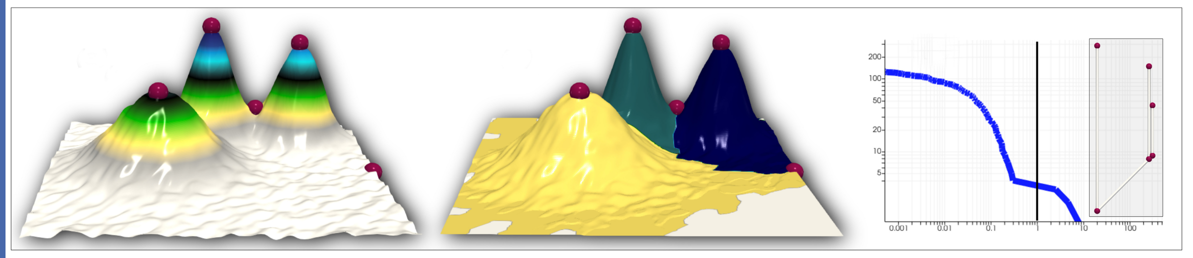


(a) Surface visualization of a Kelvin-Helmholtz instability. (b) iso-contour of the segmented enstrophy scalar field. (c) Persistence diagram and persistence curve used for the segmentation. (d) Energy spectrum for two different vortices in order to control the segmentation during run time.



OUR APPROACH

Our segmentation uses several Topological Data Analysis techniques [9] to face extensive computations of numerical approaches.



Critical points : variation in the topology of input scalar fields only change at special locations called critical points that are used to describe features of the flow.

Persistence : assesses the importance of a critical point based on the lifetime of the topological feature manipulated with persistence diagrams and persitence curves to filter noise and main vortices.

Morse-Smale Complex : partitions the domain according to the flow behavior of the gradient of the function.

RELATED WORK

Topological Data Analysis (TDA) provides a set of techniques [9] which focus on structural features such as the turbulence in a flow.

The concept of persistent homology [3] introduces tools for the multi-scale representation of the structural features of interest.

In-situ visualization methods [12] allow to analyze simulation data as it is generated. This is a processing paradigm in response to recent challenges in the High Performance Computing (HPC) domain.

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Florent Nauleau, CEA, florent.nauleau@cea.fr
Benjamin Fovet, CEA, benjamin.fovet@cea.fr
Fabien Vivodtzev, CEA, fabien.vivodtzev@cea.fr

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