EGU21-7894
https://doi.org/10.5194/egusphere-egu21-7894
EGU General Assembly 2021

Lagrangian betweenness: detecting fluid transport bottlenecks in oceanic flows

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The study of connectivity patterns in networks has brought novel insights across diverse fields ranging from neurosciences to epidemic spreading or climate. In this context, betweenness centrality has demonstrated to be a very effective measure to identify nodes that act as focus of congestion, or bottlenecks, in the network. However, there is not a way to define betweenness outside the network framework. Here we introduce the “Lagrangian betweenness”, an analogous quantity which relies only on the information provided by trajectories sampled across a generic dynamical system in the form of Finite Time Lyapunov Exponents, a widely used metric in Dynamical Systems Theory and Lagrangian oceanography. Our theoretical framework reveals a link between regions of high betweenness and the hyperbolic behavior of trajectories in the system. For example, it identifies bottlenecks in fluid flows where particles are first brought together and then widely dispersed. This has many potential applications including marine ecology and pollutant dispersal. We first test our definition of betweenness in an idealized double-gyre flow system. We then apply it in the characterization of transport by real geophysical flows in the semi-enclosed Adriatic Sea and the Kerguelen region of the highly turbulent Antarctic Circumpolar Current. In both cases, patterns of Lagrangian betweenness identify hidden bottlenecks of tracer transport that are surprisingly persistent across different spatio-temporal scales. In the marine context, high Lagrangian betweenness regions represent the optimal compromise between the heterogeneity of water origins and destinations, suggesting that they may be associated with relevant diversity reservoirs and hot-spots in marine ecosystems. Our new metric could also provide a novel approach useful for the management of environmental resources, informing strategies for marine spatial planning, and for designing observational networks to control pollutants or early-warning signals of climatic risks.