Fluid control, Information processing

Information flow in turbulence

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Abstract

It has been conjectured that fluid turbulence exhibits universal statistical laws. Despite numerous theoretical attempts, proving this conjecture has long been challenging due to the strong nonlinearity and nonequilibrium nature of turbulent fluctuations. On the other hand, the recent establishment of the field of information thermodynamics has made it possible to elucidate the universal statistical properties of nonequilibrium fluctuating systems. In our study, we applied information thermodynamics to turbulence and clarified some aspects of the universal statistical properties of turbulent fluctuations.

Background & Results

Turbulence is a chaotic flow consisting of eddies of various spatial scales, appearing ubiquitously in natural environments, engineering applications, and everyday life. Although turbulence seems hopelessly complicated, it has been conjectured that universal statistical laws are hidden in the disordered fluid motion. Revealing these laws is a longstanding challenge, often dubbed the "graveyard of theories". This difficulty stems from nonlinear interactions spanning a wide range of scales. These nonlinear interactions cause interference of fluctuations between disparate space-time scales, rendering the traditional theoretical approach based on scale separation ineffective.

On the other hand, thermodynamics has been extended to systems where fluctuations are significant, such as colloidal particles and molecular motors in living cells. In particular, information thermodynamics was established in the 2010s, revealing that the concept of information is essential for understanding the universal statistical laws governing fluctuating systems (Fig. 1). While information thermodynamics has begun to find broad application from quantum systems to biological systems, it was unclear whether it could yield useful insights into fluid phenomena.

This research aimed to elucidate the universal properties governing turbulent fluctuations by applying information thermodynamics to turbulence. We proved that information about fluctuations propagates from macroscopic to microscopic scales, like a game of telephone (Fig. 2). This is a universal and rigorous result that holds regardless of the details of mathematical models. Furthermore, it was found that the magnitude of this scale-to-scale information propagation determines the lower bound of turbulent fluctuations. That is, turbulent fluctuations at any given scale can be amplified by receiving information of fluctuations at larger scales. These results not only elucidate a new property of turbulent fluctuations but also demonstrate that the information thermodynamic perspective can provide useful insights into turbulence research.

Significance of the research and Future perspective

In this study, we applied information thermodynamics to fluid phenomena for the first time. By further advancing this novel interdisciplinary approach, it may be possible to establish a new theoretical framework called "information hydrodynamics" that would provide a perspective on the fundamental constraints of prediction and control for various fluid phenomena. Combining this approach with conventional data assimilation and machine learning is expected to improve the accuracy of weather forecasting and control.

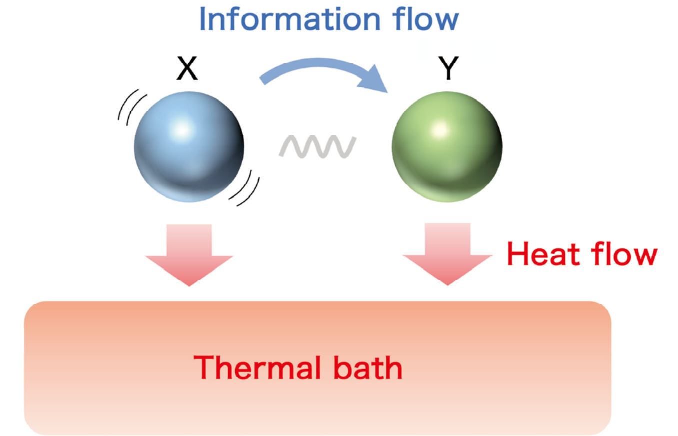

Fig. 1: A typical setting in information thermodynamics. The statistical properties of subsystems X and Y, which are in contact with an equilibrium heat bath, are universally constrained by the information flow between the subsystems.

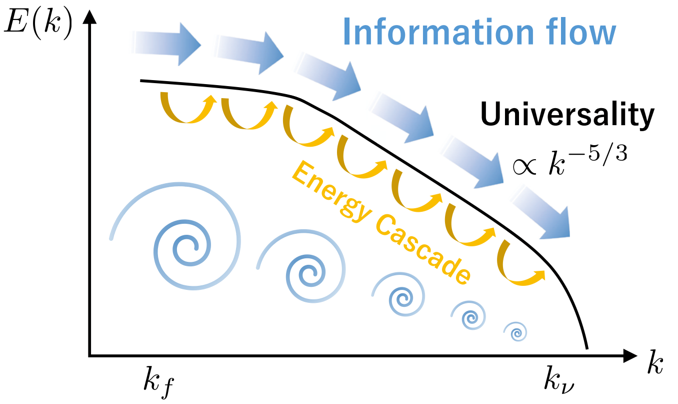

Fig. 2: Schematic of the wavenumber dependence of the turbulent energy spectrum and the scale-to-scale information flow.

Patent

Treatise
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