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► **To cite this version:**

Hamid Kellay. Thick puddle made thin. Nature Physics, 2011, 7, pp.279-280. 10.1038/nphys1948 . hal-00608684

HAL Id: hal-00608684

<https://hal.science/hal-00608684>

Submitted on 15 Dec 2017

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TURBULENCE

Thick puddle made thin

For turbulent flows, the energy transfer between large and small whirls depends on the dimension of the fluid. Imposing large-scale shear on a three-dimensional system can unexpectedly induce two-dimensional behaviour.

Hamid Kellay

Fluid flows come in a variety of states, from slow and perfectly predictable to fast and horribly complex. Turbulent flows represent this last category, which is actually the most common type of flow on the surface of the Earth, and on other planets for that matter. Such a complex and unpredictable state has been depicted in a variety of ways but the most common representation is that of swirls and eddies mingling with each other to give the impression of something uncontrollable. But this inherent complexity has not prevented scientists from all sides from trying to confront this problem. It is somehow a cliché now to describe turbulent flows as the last unsolved problem of classical mechanics.

Several attempts have been undertaken to identify the problem so as to be able to craft a solution. In this respect, the work of L. F. Richardson¹ comes to mind, as he noted that turbulent flows disperse and mix (pollutants, dust, smoke and so forth)

fast and well. He then devised experiments to measure such dispersions by tracking the separation of weather balloons in the atmosphere. His work showed that ‘turbulent dispersion’ is much more efficient and much faster than, say, thermal diffusion, and allowed him to put numbers to the process now known as Richardson dispersion. This quantitative aspect has not prevented Richardson from using a qualitative representation as well, stating that “big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity...” in an attempt to represent ‘turbulence’ as an assembly of interacting swirls exchanging energy with each other.

Such an approach is still being used today to teach students of turbulence how eddies transport energy injected at some large scale in the system all the way to the smallest scales where viscosity will transform it into heat^{2,3}. At this point of the story another character enters the set: A. N. Komogorov⁴. His theory of turbulent flow is still around, despite its limitations, and brings a quantitative explanation of what Richardson measured with his floating balloons. The idea is still the same: big whirls break into smaller ones down to viscosity. In turbulence speak one says that energy cascades from the large to the small scale, at a constant injection rate (or dissipation rate)^{2,3}. The direct cascade of energy of three-dimensional (3D) turbulence was born along with an expression for it²⁻⁴: the $-4/5$ law.

I explicitly mention three dimensions because this picture of small eddies feeding on larger ones breaks down if the spatial dimension is changed from three to two^{3,5,6} (Fig. 1). This concept was put forth in the late 1960s⁷ and early 1970s⁸ where the cascade is said to be an inverse cascade of energy: big eddies or whirls now feed on smaller ones, up to infinity (so to speak, as the container size will cut such transfers). Two-dimensional turbulence — that is, turbulence in flat space — changes the character of energy transfers between scales for fundamental reasons. Eddies in three dimensions stretch but in flat space all they can do is deform and eventually merge. This picture of turbulence in flat land has



Figure 2 | Image from a soap film showing upscale transfers as small vortices detach from the teeth of a comb and grow as they travel downstream from the grid.

been made quantitative through numerical simulations at first, and through different experiments that either use soap films (see Fig. 2) or very thin layers of fluid^{5,6}. Upscale energy transfers have therefore been predicted and found. Such a picture favours the presence over long timescales of large vortices dominating the flow and has been used to explain the robustness and long lifetime of such objects as Jupiter’s red spot⁹. Notice that the word thin comes back and for good reason: eddy or vortex stretching has to be suppressed to obtain such upscale energy transfers, and to suppress it, the thickness of the layer has to be very small. This limits the validity of such an upside-down turbulent picture to a small category: very thin layers.

But whether this picture is applicable in other situations such as atmospheric flows and at what scales remains a question with many answers. This is where the Letter by

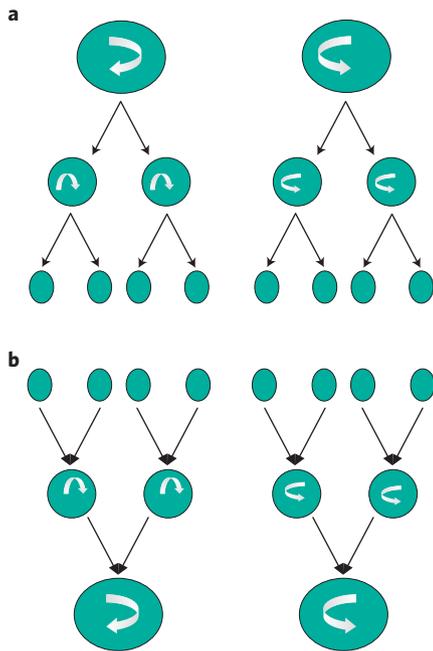


Figure 1 | Downscale and upscale energy transfers. **a**, In three dimensions, big eddies break up into smaller and smaller eddies. **b**, In two dimensions the small eddies give rise to larger and larger eddies.

Hua Xia and collaborators¹⁰ comes into play because it shows that this picture can be obtained in even thicker layers, which extends the importance of such inverse transfers to a much wider category of flows of importance for geophysics and oceanography. How did they do this? Well the answer comes from the use of an extra-large-scale flow imposed on the thick layer. This layer, an electrolyte solution, was first driven by a so-called electromagnetic forcing scheme (small magnets below the cell cause deviations in the motion generated by an imposed current in the solution). The flow observed in this thick layer (several millimetres) shows much movement in the direction perpendicular to the plane of the layer, or in the third dimension.

By imposing a large-scale vortex through the use of an additional layer of magnets placed near the upper surface of the layer, a large vortex was superimposed on the flow. The presence of this large vortex slowly suppressed the velocity variations in the third dimension and rendered the behaviour of the flow in the thick layer similar to that in very thin layers: all the flow features were confined

to the plane of the layer. The consequences of such an operation is the recovery of features common to turbulence in very thin layers, upscale energy transfers, for a thick pool of fluid for which previous work ruled out any two-dimensional behaviour.

The authors argue that the shear engendered by the large-scale vortex is responsible for the suppression of 3D movements. This discovery is important for a variety of phenomena for which if the flow were rather 2D instead of 3D several curious features can be explained. The authors invoke two major examples: atmospheric turbulence in the range between 10 and 500 km and turbulence in the tachocline layer beneath the surface of the Sun. Strong shear between the outer convective layer of the Sun and its radiative interior make turbulence in the tachocline layer a candidate for a two-dimensional phenomenology. As many questions, such as its stability and its role in the Solar dynamo, are still open, an understanding of the nature of the turbulence in the tachocline layer is highly important. Also, the shear engendered by planetary-scale motions may

render turbulence in the atmosphere two dimensional. This will help in modelling such systems, partially explaining features of their wave-number spectra, and reveal how energy is exchanged between the widely different scales that enter the problem. Although the argument about atmospheric turbulence or turbulence in the tachocline layer is certainly not closed by this study, an important step towards settling it has been achieved through this work.

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