

were turbulent. A turbulent fluid can have a small particulate viscosity, yet behave in some ways as though it were viscous: correlations between different components of the fluid's velocity fluctuations cause both substantial energy dissipation and enhanced momentum transport.

The importance of viscosity in fluid flow is measured by a dimensionless quantity known as the Reynolds number; a high Reynolds number indicates a small viscosity. Shear flows (those with regions moving at different velocities) of high Reynolds number are generally exquisitely unstable to any small perturbation⁵. But astrophysical disks both shear and rotate; the rotation introduces Coriolis forces, which can sometimes stabilize an otherwise turbulent fluid.

Starting in the late nineteenth century, the British physicist Lord Rayleigh investigated fluids similar to the gas in an astrophysical disk that rotate differentially (at different speeds according to radial distance) and have a very small viscosity. He found that such fluids would become unstable (and possibly turbulent) only where the specific angular momentum of the flow decreases as one moves to greater radii. In a keplerian disk, however, the specific angular momentum increases with radius. According to the Rayleigh criterion, such a flow is stable.

Because the Rayleigh criterion applies only to infinitesimal disturbances, not those of finite amplitude, and only to perturbations that are symmetrical about the axis of rotation, the formal stability of keplerian disks did not immediately embarrass the theorists. Indeed, although Couette experiments⁶ persistently failed to reveal instability for keplerian profiles, it was widely believed that differentially rotating flows would ultimately prove to be unstable; it was simply a matter of reaching large enough Reynolds numbers in the laboratory⁷.

For many, this 'faith-based' approach to turbulent hydrodynamical accretion was less than satisfying. The discovery⁸ in 1991 that even very weak magnetic fields profoundly alter the stability of rotating gases improved matters. A rotating magnetized gas becomes unstable when its angular velocity decreases as one moves away from the centre, a condition nearly universally satisfied in astrophysical disks. Computer simulations have since shown that this 'magnetorotational instability' leads to precisely the sort of turbulence that disk theorists are seeking⁹.

Not all disks are ionized throughout to an extent that would allow magnetic fields the necessary influence to seed instability. Only a very small electron component is needed to couple the field and the gas, but accretion disks associated with the formation of stars, known as protostellar disks, seem to contain an extended region that is cold, dense and dusty. In such a region, free electrons are suppressed, and gas and field are decoupled. For this reason and others, many disk theorists continued to

believe that a fluid of large Reynolds number undergoing keplerian shear would ultimately prove to be turbulent. In 2001, a laboratory Couette-flow experiment at large Reynolds number seemed to find just that¹⁰.

One of the great difficulties in working with Couette flows is that the rotating cylinders have end-caps that rotate uniformly, whereas in the adjacent fluid the rotation is a function of distance from the rotation axis. This mismatch creates a boundary layer near the end-cap and a secondary axial velocity flow known as an Ekman circulation in addition to the purely rotational flow that one wishes to study. This effect can be controlled to some extent by making the cylinders very long, distancing the end-caps from the bulk of the flow.

Ji and colleagues, however, wish to use their apparatus¹ in investigations of the magnetorotational instability. These require a very uniform magnetic field that would be difficult to maintain over a long cylinder. So the authors overcame the Ekman circulation problem by splitting the end-caps into two parts that rotate at different speeds. This was sufficient to control the Ekman circulation and to attain an exceptionally high Reynolds number of around 2×10^6 .

The authors' finding that, at such a high Reynolds number, the rotation profile of a keplerian fluid is as stable as the rotation of a solid body should lay to rest the notion that any rotating flow (in general) or an accretion disk (in particular) is nonlinearly unstable

simply if its viscosity is sufficiently small. The implication, for which there is now growing astrophysical evidence¹¹, would seem to be that accretion is magnetically, not hydrodynamically, driven.

Ji and colleagues' primary goal for their apparatus was to find evidence for the magnetorotational instability in liquid gallium, and the results of these experiments are yet to come. The researchers might thus be poised for a double coup: tolling the death knell for hydrodynamical shear turbulence in accretion disks, and capturing magnetic instability in a cylindrical flow for the first time. ■

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1. Ji, H., Burin, M., Scharfman, E. & Goodman, J. *Nature* **444**, 343–346 (2006).
2. Novikov, I. D. & Thorne, K. S. in *Black Holes: Les Astres Occlus* (ed. De Witt, C.) 343 (Gordon & Breach, New York, 1973).
3. Prendergast, K. H. & Burbidge, G. R. *Astrophys. J.* **151**, L83–L88 (1968).
4. Lynden-Bell, D. *Nature* **223**, 690–694 (1969).
5. Drazin, P. G. & Reid, W. H. *Hydrodynamic Stability* (Cambridge Univ. Press, 1981).
6. Coles, D. J. *Fluid Mech.* **21**, 385 (1965).
7. Landau, L. D. & Lifshitz, E. M. *Fluid Mechanics* (Pergamon, Oxford, 1959).
8. Balbus, S. A. & Hawley, J. F. *Astrophys. J.* **376**, 214–222 (1991).
9. Hawley, J. F., Gammie, C. F. & Balbus, S. A. *Astrophys. J.* **440**, 742–763 (1995).
10. Richard, D. Thesis, Univ. Paris 7 (2001).
11. Miller, J. M. *et al. Nature* **441**, 953–955 (2006).

ENVIRONMENTAL CHEMISTRY

Browning the waters

Nigel Roulet and Tim R. Moore

Levels of dissolved organic carbon in British streams and lakes have risen over the past two decades. It might be a downstream effect of decreased acid rain — but isolating single factors is notoriously difficult.

It may be small, but dissolved organic carbon (DOC) — operationally defined as organic compounds in water that can pass through a 0.45- μm filter — is of great interest. The export of DOC from land to aquatic ecosystems and the oceans is a significant mover of carbon through continents and local landscapes (Fig. 1, overleaf). In some ecosystems, loss of DOC can be as great as long-term accumulation of carbon in the form of dead organic material, for example as peat in peatlands. Then there is its role in the metabolism of lake ecosystems and the protection of aquatic organisms: DOC-rich waters are light brown, and so absorb ultraviolet radiation. On the other hand, DOC-rich water can produce carcinogens when chlorinated. Last — but for the bibulous not least — DOC content is even believed to help determine differences

in the flavours of malt whiskies.

This is the context in which Evans *et al.*, writing in *Global Change Biology*¹, supply evidence that median DOC concentrations in eight streams and ten lakes in the United Kingdom have almost doubled from 1988 to 2003. It is important to distinguish between DOC export and concentration here: whereas increased export can result from an increase in runoff with no change in concentration, increased concentrations can occur with no change in hydrology, but with altered production or retention of DOC in the landscape. Increased export of DOC through streams and rivers in the Northern Hemisphere has been observed before, specifically in western Siberia as a result of increased release of DOC from peatlands². But decreased DOC export has also been observed, in the Yukon river system of

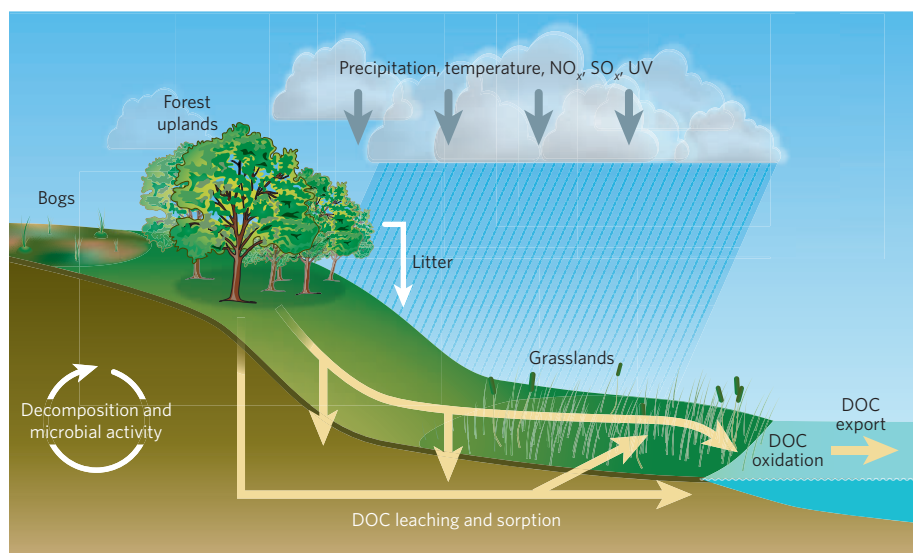


Figure 1 | Passage of dissolved organic carbon (DOC) through the landscape. The decomposition and subsequent leaching of organic litter in bogs, forests and wetlands are the principal sources of DOC in the terrestrial landscape. Production is mediated by several physical and biogeochemical factors, such as deposition of nitrates and sulphates from the atmosphere, moisture and temperature. The rate of export of terrestrial DOC is determined by the rate of production combined with the rate of sorption by mineral soils, and the availability of pathways for water through the landscape. Evans *et al.*¹ correlate an increase in hydrological DOC concentrations in the United Kingdom during 1988–2003 with the decreased deposition of sulphates in the form of acid rain in that period.

northwestern Canada and Alaska³. Although increased DOC concentrations in hydrological systems have been observed before^{4,5}, there has been no clear agreement on whether this constitutes a trend.

Where clear evidence of temporal changes in the concentration and/or export of DOC does exist, it is often difficult to provide convincing explanations. Many factors can influence its production and transport, and Evans and colleagues¹ review a range of hypotheses to explain their measured increases. First, they consider increased rates of decomposition in organic litter, and especially in peat soils, associated with changes in moisture and temperature⁶. This process could trigger an enzymatic 'latch' that would release more DOC⁷. Second, there is the possible stimulation of plant primary production by elevated atmospheric carbon dioxide⁸. Lastly, the authors examine the effect of changes in hydrological pathways.

After concluding that no proposed hypothesis is particularly convincing, Evans *et al.* posit a new one¹: that the increase in DOC concentration has been caused by the decrease in sulphur deposition that has occurred in northern Europe and North America over the past 20 years, as clean-air legislation has taken effect. The anthropogenic sulphur deposition is estimated to have declined by 41% between 1998 and 2003 in the stream and lake catchments that Evans and colleagues have studied⁹.

The mechanisms through which sulphur might influence DOC concentrations in this scheme are primarily chemical, rather than biological. Increased sulphate concentrations and raised pH in soil pore water have been

shown experimentally to decrease the mobilization of DOC in soils. To test this sulphur hypothesis, the authors present a correlation analysis of the relationship between the temporal trends in DOC concentrations and sulphate deposition.

But the origin and interactions of DOC in an entire landscape is a complex issue, and what is observed at the outflow of hydrological catchment areas is the combined result of many processes that occur upstream. In nine small boreal lakes in Canada, for example, variations in ice-free DOC concentrations were found to be most strongly correlated with solar radiation and winter precipitation⁵. Increases in sulphate deposition and lake acidity were not correlated with DOC concentration.

The problem is that in these types of analysis there is very little control on the experiments that nature is providing. Studies are plagued by the influence of extraneous variables, and the cause of changes in some of these variables is unknown. What is certain is that, at the heart of any DOC increase, there has to be an increase either in net DOC production in terrestrial ecosystems or in the leaching of DOC from them. Evans *et al.* demonstrate that in their catchment areas there has been no increase in runoff, thus focusing attention on the second option.

It is true that, during the period of their study, temperatures were increasing and sulphate deposition was decreasing, both in North America¹⁰ and in western Europe¹¹. But the same sources show that deposition of nitrates was increasing at the same time. This point is significant because nitrogen production can improve ecosystem productivity, resulting in

increased litter production, and can at the same time influence the rate of carbon mineralization in litter and soil. Elevated DOC concentrations in the Hudson River in the northeastern United States have been attributed to increased DOC production from forest soils subjected to higher nitrogen deposition, as well as to decreased degradability of DOC once in the river system¹². Similarly, it has been estimated that soils in England and Wales have lost 4 million tonnes of carbon each year from 1978 to 2003 because of climate change¹³. At least part of this loss might be as increased DOC transport to aquatic ecosystems.

The sulphur hypothesis could be tested. There are several regions in the developing world where sulphate deposition is rapidly increasing. If Evans and colleagues' hypothesis is correct, this should lead to a decrease in DOC stream concentration, once changes in the volume and pathways of water flow are taken into account.

Although the increase in DOC export in some regions is clear, studies showing that the trend is universal, and establishing its causes, are still wanting. Chemical analyses of the DOC in rivers and lakes or analysis of its ¹⁴C and ¹³C isotopic signatures might help in pinpointing its age and origin. An issue of more global import is whether there will be large changes in the concentration and export of DOC in rivers undergoing major changes as a result of the changing climate, such as the melting of permafrost. This might release large amounts of DOC², or alternatively allow greater water movement through mineral soils, and thus increase DOC retention through sorption³. Studies such as that of Evans and colleagues¹ are valuable contributions to the debate on rising DOC, but we are far from reaching definitive answers.

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- Evans, C. D., Chapman, P. J., Clark, J. M., Monteith, D. T. & Cresser, M. S. *Glob. Change Biol.* **12**, 2044–2053 (2006).
- Frey, K. E. & Smith, L. *Geophys. Res. Lett.* **32**, L09401 (2005).
- Striegl, R., Aiken, G., Dornblaser, M., Raymond, P. & Wickland, K. *Geophys. Res. Lett.* **32**, L21413 (2005).
- Evans, C., Monteith, D. & Copper, D. *Environ. Pollut.* **137**, 55–71 (2005).
- Hudson, J., Dillon, P. & Somers, K. *Hydrol. Earth Syst. Sci.* **7**, 390–398 (2003).
- Freeman, C., Evans, C. & Monteith, D. *Nature* **412**, 785 (2001).
- Freeman, C., Ostle, N. & Kang, H. *Nature* **409**, 149 (2001).
- Freeman, C. *et al.* *Nature* **430**, 195–198 (2004).
- Davies, J. J. L., Jenkins, A., Monteith, D. T., Evans, C. D. & Cooper, D. M. *Environ. Pollut.* **137**, 27–39 (2005).
- Meteorological Service of Canada Canadian National Atmospheric Chemistry (NAtChem) Precipitation Chemistry Database www.msc-smc.ec.gc.ca/natchem/precip/index_e.html (2006).
- Norwegian Pollution Control Authority State of the Environment Norway www.environment.no/templates/TopPage_3142.aspx (2006).
- Findlay, S. *Front. Ecol. Environ.* **3**, 133–137 (2005).
- Bellamy, P. H. *et al.* *Nature* **437**, 245–248 (2005).