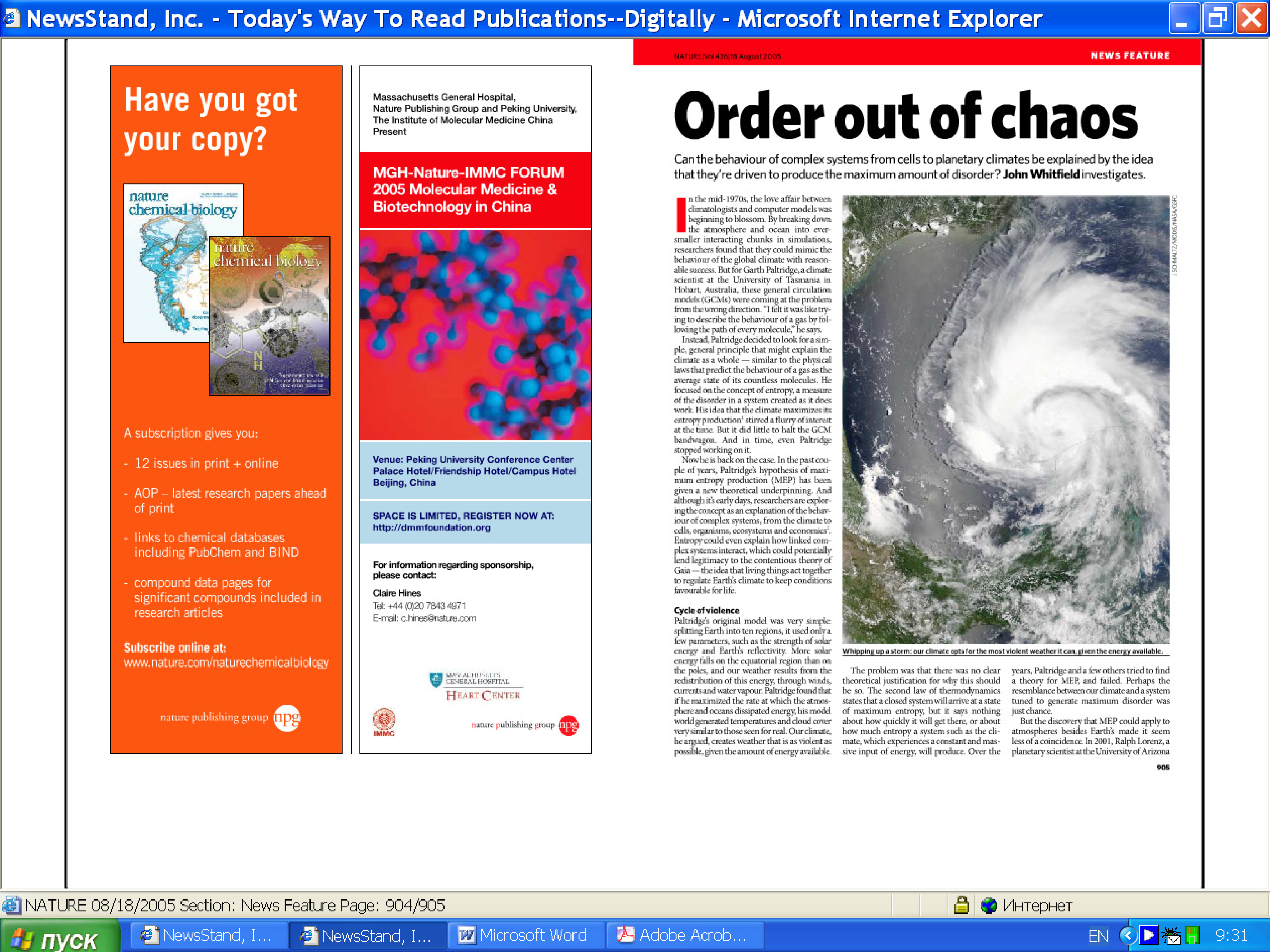

Order out of chaos

Can the behaviour of complex systems from cells to planetary climates be explained by the idea that they're driven to produce the maximum amount of disorder? **John Whitfield** investigates.

In the mid-1970s, the love affair between climatologists and computer models was beginning to blossom. By breaking down the atmosphere and ocean into ever-smaller interacting chunks in simulations, researchers found that they could mimic the behaviour of the global climate with reasonable success. But for Garth Paltridge, a climate scientist at the University of Tasmania in Hobart, Australia, these general circulation models (GCMs) were coming at the problem from the wrong direction. "I felt it was like trying to describe the behaviour of a gas by following the path of every molecule," he says.

Instead, Paltridge decided to look for a simple, general principle that might explain the climate as a whole — similar to the physical laws that predict the behaviour of a gas as the average state of its countless molecules. He focused on the concept of entropy, a measure of the disorder in a system created as it does work. His idea that the climate maximizes its entropy production[1] stirred a flurry of interest at the time. But it did little to halt the GCM bandwagon. And in time, even Paltridge stopped working on it.

Now he is back on the case. In the past couple of years, Paltridge's hypothesis of maximum entropy production (MEP) has been given a new theoretical underpinning. And although it's early days, researchers are exploring the concept as an explanation of the behaviour of complex systems, from the climate to cells, organisms, ecosystems and economies[2]. Entropy could even explain how linked complex systems interact, which could potentially lend legitimacy to the contentious theory of Gaia — the idea that living things act together to regulate Earth's climate to keep conditions favourable for life.

Cycle of violence

Paltridge's original model was very simple: splitting Earth into ten regions, it used only a few parameters, such as the strength of solar energy and Earth's reflectivity. More solar energy falls on the equatorial region than on the poles, and our weather results from the redistribution of this energy, through winds, currents and water vapour. Paltridge found that if he maximized the rate at which the atmosphere and oceans dissipated energy, his model world generated temperatures and cloud cover very similar to those seen for real. Our climate, he argued, creates weather that is as violent as possible, given the amount of energy available.

J. SCHMALTZ/MODIS/NASA/GSFC

Whipping up a storm: our climate opts for the most violent weather it can, given the energy available.

The problem was that there was no clear theoretical justification for why this should be so. The second law of thermodynamics states that a closed system will arrive at a state of maximum entropy, but it says nothing about how quickly it will get there, or about how much entropy a system such as the climate, which experiences a constant and massive input of energy, will produce. Over the years, Paltridge and a few others tried to find a theory for MEP, and failed. Perhaps the resemblance between our climate and a system tuned to generate maximum disorder was just chance.

But the discovery that MEP could apply to atmospheres besides Earth's made it seem less of a coincidence. In 2001, Ralph Lorenz, a planetary scientist at the University of Arizona

Snow hope: Japanese researchers are using a model avalanche of styrene beads (inset) to see if entropy theory can describe the real thing.

in Tucson, was trying to model the climate on Saturn's moon Titan. Titan is smaller than Earth, has a thicker atmosphere, and turns more slowly. This ought to mean that heat moves quickly through its atmosphere, making polar and equatorial climates very similar. Yet Titan's equator is 4 °C warmer than its poles. Only when Lorenz applied an MEP model could he produce the right temperature difference[3]. The same approach also gave accurate predictions of the winds and carbon dioxide frosts on Mars, which has a much thinner atmosphere than Earth and whose weather had similarly stumped conventional climate models.

MEP is not the same as maximizing the rate of heat transport. A system's entropy production depends on its energy input, and — crucially — on the temperature difference between its interacting parts. Very rapid heat transport would level out the temperature gradient between Titan's equator and poles, and so reduce the amount of work that its atmosphere could do, as if a ball were rolling slowly down a very gentle slope. Very slow heat transport would create a large temperature gradient, but the system would be close to equilibrium, and little work would be done — like a ball trying to roll down a steep but sticky slope. MEP needs a climate somewhere between these two extremes. Lorenz became an entropy enthusiast. "I was evangelical about it — it made so much intrinsic sense," he says. But still the theoretical problem remained.

The breakthrough came in 2003, when Roderick Dewar, a theoretical physicist turned ecosystem modeller working for INRA, the French agricultural research agency, in Bordeaux, turned to information theory — a branch of mathematics dealing with communication and uncertainty. Thermodynamics can be expressed in terms of information theory: in the 1950s, it had been shown that the entropy of a system in equilibrium, such as a sealed container of gas, can be reformulated as a measure of missing information.

Out of order

Dewar extended the theory to non-equilibrium systems — such as the planetary climates modelled by Paltridge and Lorenz. In essence, he showed that what is true for a small container of gas molecules, with no energy input, should also apply if you put an astronomical number of gas and water molecules into an atmosphere-sized container and heat them up.

Dewar's theory says that for a large, complex system, the state of MEP is the most probable sum of its microscopic parts[4,5]. One need know only the constraints that influence the behaviour of the whole system, and nothing about the seething complexity of all its constituent parts because, at the large scale, all the different microscopic arrangements look the same. "What we see at the macroscopic scale is the most probable behaviour, because it can be realized in the greatest number of ways microscopically," Dewar says.

But the theory comes with strings attached. First, the system must also be free to 'choose' between different states. For the climate this should be no problem: it has myriad possible configurations, from the local changeability of wind and clouds, to switches between ice ages and interglacial periods. But the theory also applies only to systems in a steady state: that is, enough energy must be passing through to preserve large-scale structure, but not so much, or so little, that this structure is disrupted. For the climate, this might not always be the case: a world that was rotating very rapidly; had a very thin atmosphere; which was in a glaciated, 'snowball' state; or which was experiencing strong man-made climate change, might be prevented from settling into MEP.

These constraints may limit the utility of MEP for climate modelling. Although the climate might be in a steady state on a planetary scale, and over long time-frames, at other scales things are always changing. What's more, ice, clouds and the ocean at different depths and latitudes respond to the same forces at vastly different rates. "It's not just the end result that's important, it's how you get there," says Kevin Trenberth of the National Center for Atmospheric Research in Boulder, Colorado.

Lorenz agrees that MEP is unlikely to revolutionize the way we model the climate — but he believes the idea could also be used to gauge the trustworthiness of GCMs. If a model's output is very far from MEP, it should throw up a warning flag, he suggests. Where MEP theory will be most useful, he adds, is as a means of getting a broad-brush picture of climates about which we know very little, such as those of extrasolar planets, or in Earth's distant history. MEP models allow surface temperatures across a planet to be calculated from knowing only how much of its star's light falls on it, how much is reflected back into space, the tilt of the world's axis, and its absorbance of infrared radiation. All these parameters can in principle be measured with a telescope[6].

Natural disarray

Now researchers are looking for other systems that might be amenable to modelling using Dewar's theory. Plate tectonics, in which rock dissipates heat generated by radioactivity as it flows, might be complex enough to attain MEP[2]; so might the growth of crystals[7]. And Hisashi Ozawa, a climatologist at Hiroshima University in Japan, who has previously studied the entropy production of ocean currents[8], is now staging small avalanches of powder in his laboratory, to see if MEP can explain the patterns that form at the front of the sliding mass. "There are many natural phenomena to which the MEP hypothesis can be applied," Ozawa says. "It's attractive because it's very general: it doesn't depend on specific physical and chemical properties."

Lorenz wonders about applications in economics. Money and goods flow between people in a similar way to heat in the atmosphere, he says: "I see a direct analogy between temperature gradients and price gradients." But economists aren't getting carried away just yet. "The deliberate nature of human actions makes economic systems qualitatively different from the climate, and adds an extra layer of complexity," says economist Matthias Ruth, of the University of Maryland in College Park.

Dewar is now working to apply MEP theory to biological systems ranging from cells to the planet. At a small scale, he is trying to see whether the theory can explain when plants open and close their stomata, tiny pores in the leaves that regulate the flow of gases and water vapour in and out. This has traditionally been explained in terms of the plant's efforts to maximize its photosynthesis and minimize its water loss; perhaps it might be reinterpreted as the leaf maximizing the entropy produced by gas exchange. If so, this would indicate that the biologically optimal state is also, in physical terms, the most probable state.

The opening and closing of a leaf's pores (pictured) may be governed by entropy.

At the ecosystem level, ecologists have long used a metric called the Shannon diversity index, based on the number of species in a given place and their relative numbers. This index is mathematically identical to a measure of entropy. Dewar suspects that MEP theory might be able to predict the number of species in a place based on its energy input, and possibly explain why the places with most energy, the tropics, are also the most diverse — or, in other words, entropic.

At the global scale, Dewar and his colleagues are trying to put numbers on the fluxes of solar energy, heat, water vapour and carbon dioxide between plants and the atmosphere. Previously, these have been added to climate models as ad hoc fudge factors: MEP might allow them to be calculated from fundamental principles.

Total anarchy

By linking vegetation and the climate, MEP also offers a new twist on the Gaia hypothesis. The problem for Gaia theorists has been explaining why Earth's organisms should en masse 'want' to maintain a stable climate. MEP might offer a way out, says Axel Kleidon, a biogeophysicist at the University of Maryland. According to his models, provided a planet is suitable for life in the first place, biological activity increases the entropy production of the entire planetary system, both living and non-living. It also increases the number of states that the system can adopt, he says, so making MEP more likely[9]. This would give a version of Gaia in which life isn't manipulating the climate to its own ends. Instead, if both climate and ecosystems tend to a state of MEP, the stability of the climate becomes a by-product of this state, towards which the system will return when perturbed.

"Maximum entropy production is an organizational principle that potentially unifies biological and physical processes."
— Roderick Dewar

Yet the concerns voiced regarding other applications of MEP theory still apply. Is life, at the planetary scale, in a steady state? And is it free to enter maximum entropy production? Based on his modelling, Tim Lenton of the University of East Anglia in Norwich, UK, one of the leading lights of Gaia research, is sceptical. "Gaia would benefit from a sound theoretical footing, but there's still a gap between Dewar's very elegant theoretical treatment and many of the systems we're interested in," he says.

Ecosystem modeller Marcel van Oijen of the Centre for Ecology and Hydrology in Edinburgh is is also unsure whether MEP is compatible with what we know about evolution: natural selection might be a force strong enough to prevent life from attaining maximum entropy production. "The problem of reconciling MEP and natural selection will be a focus of debate in coming years," he says. "I see adaptation and constraints everywhere in biology, and these aren't accounted for in the derivation of MEP."

Dewar is undaunted, and predicts that a new order will arise from the current chaos, as theorists wrestle with the various potential applications of MEP. "The underlying theory suggests that it's entirely general," he says. "It's an organizational principle that potentially unifies biological and physical processes." ■

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