considerable advance — in principle, the way is open to continuous monitoring of inner-core rotation on periods as short as a year. ■

Henri-Claude Nataf is at the Observatoire des Sciences de l'Univers de Grenoble, CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble, France.

e-mail: henri-claude.nataf@ujf-grenoble.fr

1. Vidale, J. E., Dodge, D. A. & Earle, P. S. *Nature* **405,** 445–448 (2000).
2. Jault, D., Gire, C. & Le Mouel, J.-L. *Nature* **333,** 353–356 (1988).
3. Song, X. & Richards, P. G. *Nature* **382,** 221–224 (1996).
4. Poupinet, G., Souriau, A. & Coutant, O. *Phys. Earth Planet. Inter.* **118,** 77–88 (2000).
5. Vidale, J. E. & Earle, P. S. *Nature* **404,** 273–275 (2000).

Ocean science

Carbon fixation

Jim Gillon

"The total amount of data provided by ocean research is equivalent to that collected daily by meteorologists." That paraphrased comment, made some years ago, is fast getting out of date. As was evident at a conference* held last month, the upshot of merged research agendas from biology, chemistry and physical oceanography over the past decade is that the balance is being redressed. This is especially so where oceanic carbon is concerned — the central issue for research is of course how the oceans will respond to, and maybe accommodate, the human passion for CO_2 emission and the climate change it is likely to cause.

The greatest uncertainties seem to lie more with the biology than with the physics and chemistry of ocean processes. Maybe this is not surprising. Global-scale oceanography has its roots largely in the physical sciences, so we have a better picture of how physical and chemical parameters — pH, temperature, circulation and so on — can regulate carbon exchange between the ocean and the atmosphere. But it is marine organisms that can really tap into physicochemical carbon cycling and lock up carbon on geological timescales.

Equally, it is the biological response to climate change that seems to be the most difficult to predict. For example, the formation of calcium carbonate shells by certain algae — a process that counterintuitively releases CO_2 — appears to be reduced under conditions of higher levels of atmospheric CO_2 (I. Zondervan, Alfred Wegener Inst., Bremerhaven). So if the balance between carbonate chemistry and photosynthesis shifts in the future, these organisms might switch from being a carbon source to being a carbon sink.

As to the requirements for phytoplankton growth, limiting nutrients such as iron and silicon are known to govern biological productivity in certain oceanic regions. Nutrient supply, whether from the atmosphere or the deep oceans, is bound to change with climate perturbation. But contrary to the more rigid biological assumptions made so far, it seems that algae can modify their nutrient take-up capacity as nutrient availability changes (B. Quéguiner, CNRS, Marseille), with knock-on effects on primary productivity. Such observations call for a more dynamic biology to be incorporated into multi-element biogeochemical models.

Ecological responses further down the food chain also have to be considered. Sinking carbon escapes from surface waters primarily when blooms of larger algae, such as diatoms, outstrip the rate at which the larger grazers can crop the excess. But at the meeting it was clear that we have no answers as to how climate change will affect species assemblages, and hence operation of food chains and carbon export to the ocean depths. Can anything be learned from work on terrestrial systems? Most importantly, experience shows that early conclusions as to the CO_2 response of vegetation often provide little indication of the long-term response because they underestimate plants' ability to acclimatize. Long time-series of data (and the patience to acquire them) are required.

In the meantime there are plenty of other gaps to be filled in, especially in the 'middle ground'. Such areas include the mid-ocean depths, the 'twilight zone', where sinking carbon is processed (R. Armstrong, SUNY Stony Brook) and physical features at intermediate spatial scales (S. Doney, NCAR, Boulder). These features are on the 10–100-km scale, and are too large to be investigated with shipboard measurements but too fine to be resolved with global approaches such as satellite observation or modelling.

Ocean biogeochemistry models are likely to be in for a shake-up when all these considerations are taken into account. This is no academic matter — the next generation of models will produce the predictions that shape future policy on carbon usage. There are also data to come from the whole-Earth approach, linking up ocean, land and atmosphere, to help understand and quantify the carbon cycle, and from impending further experiments (with nutrient fertilization, for instance). Finally, the new Earth-observing satellites, such as Terra, can even provide information on the physiology of marine plankton as well as its abundance.

The message from the meeting is that the future course of carbon-fuelled research is set fair. But should governments and grant-giving bodies ask where it is heading? Is there still the hope that scientists will show that the Earth may be able to save itself in some Gaia-esque feat of self-sustainability? As the error bars come down on predictions of how the carbon cycle will react to climate change, perhaps policy-makers and industry can move on and face the reality of a different world. Then again, with the prospect of carbon becoming a tradeable commodity, maybe the governmental push to track its every movement is just a sign of a very thorough market-research campaign. ■

Jim Gillon is an associate editor at Nature.

**Joint Global Ocean Flux Study (JGOFS) Open Science Conference. Bergen, Norway, 13–17 April 2000.*

Applied mathematics

The power of design

Mark Newman

The power law is a distinctive experimental signature seen in a wide variety of complex systems. In economics it goes by the name 'fat tails', in physics it is referred to as 'critical fluctuations', in computer science and biology it is 'the edge of chaos', and in demographics and linguistics it is called 'Zipf's law'.

Writing in *Physical Review Letters*[1] and elsewhere[2], Jean Carlson and John Doyle propose a theory that could help to explain the appearance of power laws in these many different areas. They suggest that power-law distributions, as well as several other features of many complex systems including robustness to perturbations and sensitivity to structural flaws, may be the result of the design or evolution of systems for optimal behaviour. They call their theory highly optimized tolerance.

A power law is any function of the form $f(x) \propto x^{\alpha}$, where x is some quantity you are interested in, and α is a constant, usually negative. Many distributions of observed quantities have this power-law form in their tails — that is, for large values of x. Thus, for example, the standardized price returns on individual stocks or stock indices in a stock market have a distribution that falls off approximately as x^{-3} for large returns[3]; the distribution of population sizes goes as x^{-2} for large cities[4]; the distribution of the sizes of meteor impacts on the Moon[5], of the numbers of species per genus of flowering plants[6], of the patterns of activity in J. H. Conway's famous Game of Life[7], and even of the frequency of citation of scientific papers[8], all follow power laws.

Is it possible that the common features of all these disparate phenomena could be explained by a single general theory? Some people, notably the proponents of the theory of self-organized criticality, have claimed that they can, but most scientists agree that power-law distributions are the result of many different processes. The distribution of meteor sizes, for example, is almost certainly the product of a random multiplicative or fragmentation process; the behaviour of the Game of Life is an ordinary critical phenomenon; and the distribution of the number of species per genus can be explained by a simple random-walk model. Other power-law-producing mechanisms include the thermal crossing of random energy barriers, systems driven by coherent noise, and the so-called record dynamics. To this toolkit, Carlson and Doyle have now added another, beautiful, idea, which could explain quite a variety of physical phenomena.

Carlson and Doyle first describe their highly optimized tolerance (HOT) theory in the context of a simple 'forest fire' model. This is an attempt to emphasize the similarities and differences between HOT and self-organized criticality, of which the self-organizing forest fire is one of the best-known examples[9]. Imagine then a forest that is managed by a forester who wants to grow as many trees as possible. The principal bane of this forester's life is fire; fires start in the forest with moderate frequency and can destroy large numbers of trees if left unchecked. So the forester cuts fire-breaks to prevent the spread of fire. What is the best way to place these fire-breaks to minimize the damage? If fires are started by sparks which land uniformly at random everywhere in the forest, then the solution is simple — cut the forest into equally sized chunks. However, if there are more sparks in some areas than others, it turns out that the average damage done by a fire is minimized by cutting the forest into chunks whose sizes vary in inverse proportion to the rate at which sparks land in that area.

Carlson and Doyle show that if you take this result and use it to work out the distribution of the sizes of fires, you get a distribution that follows a power law for a wide variety of choices of the distribution of sparks. Thus a power law is generated by the actions of an external agent (the forester) aiming to optimize the behaviour of a system (the forest).

But the HOT mechanism does more than this. If the forest is placed on a regular grid for simplicity, with trees positioned so as to minimize the average damage done by a fire, then the optimal configuration is one in which the trees are arranged in blocks with discrete fire-breaks between them. So the model tells you not only what the ideal arrangement of fire-breaks is, but also that the best way to control fires is to build breaks. This 'cellular' structure is one of the characteristic features of HOT systems.

Another feature of HOT systems is their sensitivity to unexpected perturbations and design flaws. For instance, if the distribution of positions at which fires start changes from the one for which the tree configuration is optimized, it can cause catastrophic damage; the average fires can be much larger in this case than if the trees were uniformly clumped. And if one of the fire-breaks has a flaw — a single fallen tree across the break, for example — this can result in much worse damage than such a small perturbation seems to warrant. Carlson and Doyle point out that these phenomena are well known to engineers who design systems for optimal performance. Highly tuned systems are often sensitive to small imperfections, so engineers commonly design them to be slightly suboptimal to avoid such problems.

This last point is crucial to the HOT picture. Carlson and Doyle have pitched HOT not only as a mechanism for generating power-law distributions, but also as a way of quantifying ideas about designed systems which are well known (anecdotally) in engineering, in a way that makes them comprehensible and useful to the scientific community. In this sense, Carlson and Doyle's paper[1] succeeds very well, constructing a theory of 'robust yet fragile' designs in a language that will be comfortably familiar to many of us. However, their general conceptual approach, and also the presentation of the idea in terms of abstract systems such as forest-fire models, is inevitably going to lead people to ask what real applications HOT has. Is HOT an answer looking for a question?

It seems not, and to prove it Carlson and Doyle have applied their ideas to a variety of real-world systems. In new work, as yet unpublished, they show how HOT can explain data on real forest fires, electrical power failures and Internet traffic. They claim that further examples are easy to find. We won't have to look hard. And if they are right, HOT could be one of the most important additions to the theory of complex systems in recent years. ■

Mark Newman is at the Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, New Mexico 87501, USA.
e-mail: mark@santafe.edu

1. Carlson, J. M. & Doyle, J. *Phys. Rev. Lett.* **84,** 2529–2532 (2000).
2. Carlson, J. M. & Doyle, J. *Phys. Rev. E* **60,** 1412–1427 (1999).
3. Mantegna, R. N. & Stanley, H. E. *Nature* **376,** 46–49 (1995).
4. Zipf, G. K. *Human Behavior and the Principle of Least Effort* (Addison-Wesley, Reading, 1949).
5. Neukum, G. & Ivanov, B. A. in *Hazards Due to Comets and Asteroids* (ed. Gehrels, T.) 359–416 (Univ. Arizona Press, Tucson, 1994).
6. Willis, J. C. *Age and Area* (Cambridge Univ. Press, 1922).
7. Bak, P., Chen, K. & Creutz, M. *Nature* **342,** 780 (1989).
8. Redner, S. *Eur. Phys. J. B* **4,** 131–134 (1998).
9. Drossel, B. & Schwabl, F. *Phys. Rev. Lett.* **69,** 1629–1632 (1992).

Neurobiology

Self-regulating synapses

Christine R. Rose and Arthur Konnerth

Information transfer between neurons is achieved mainly through chemical synapses. The presynaptic neuron releases a neurotransmitter into the synaptic cleft, and the transmitter binds to specific receptors on the postsynaptic cell. This generally leads to the opening of ion channels in the postsynaptic membrane and an alteration in the electrical properties of the postsynaptic neuron. The transmission properties of chemical synapses are controlled by neuronal activity. This activity-dependent regulation of synaptic plasticity is thought to represent the cellular basis for the development of neural circuitry and to underlie learning and memory. Hence the importance of the paper on page 454 of this issue[1], in which Liu and Cull-Candy reveal a mechanism for the regulation of synapses in the brain that are responsive to the neurotransmitter glutamate.

Over the past decade, several mechanisms have been described by which neuronal activity alters the transmission properties of synapses that use glutamate (see ref. 2 for a review). Most of these mechanisms are based on an activity-induced alteration in the number and/or functional properties of one type of glutamate receptor — the so-called AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionate) receptor. AMPA receptors are the main contributors to the excitatory postsynaptic current that can be generated at low frequencies of stimulation. Increased neuronal activity can induce the phosphorylation of AMPA receptors, leading to an increase in the flow of ions through AMPA channels[3], or it can induce AMPA-receptor-type activity at synapses that were not previously responsive[4]. The latter process is likely to be mediated by activity-regulated insertion of AMPA receptors at the synapse[5,6].

The activity-induced alteration of AMPA-