Seismology

Inner core takes another turn

Henri-Claude Nataf

Biologists have developed amazing tools to image blood flow in the human body. Is it possible to map motions in the deepest parts of the Earth using similar techniques? This is more or less what Vidale *et al.*[1] (page 445 of this issue) have done. By measuring minute changes in seismic waves that are back-scattered by small heterogeneities in the inner core, the authors find that it rotates some 0.15° per year faster than the mantle. This is the latest, and most refined, estimate of relative core rotation.

The inner core is a ball of solid iron, 1,200 km in radius, at the centre of the Earth. It is surrounded by the outer core, an ocean of liquid iron 2,300 km thick. Convective motions in this electrically conducting ocean produce Earth's magnetic field through the so-called dynamo mechanism. Large-scale eddies at the surface of the outer core have been identified from the analysis of the slow drift of patches of magnetic field, with typical flow velocities of the order of 0.1° per year. These motions could be the surface expression of cylindrical structures extending across the bulk of the outer core because, in a rapidly rotating system, structures tend to be aligned with the axis of rotation.

In 1988, Jault *et al.*[2] realized that the variation of angular momentum of the outer core, derived from reconstructed core motions between 1970 and 1988, matches that deduced from the variations of the length of the day; these variations are only a matter of milliseconds, but they contained crucial information about the physics of the core. Nevertheless, pinning down motions deep inside the core by measuring the rotation of the solid inner core could provide valuable information about the dynamo's operation.

How can such measurements be made? The idea is to choose a fixed geometry of emitters and receivers of seismic waves, to record waves that 'see' the inner core, and to look for some variation over a certain period in the characteristics (say, travel times) of those waves.

The first tests along these lines were performed by Souriau in 1989. The emitters were French nuclear explosions in Polynesia and the receiver was the Warramunga seismic array in Australia. The path corresponded to seismic waves that are reflected from the surface of the inner core (Fig. 1a). Hypothetical wide and deep bumps could affect the travel time of these waves, but no definite variations were found.

The second test was the impressive study of Song and Richards[3], who analysed the travel time of waves passing through the inner core (Fig. 1b). The emitters were earthquakes in the South Sandwich islands and the receiver a seismograph in Alaska. Song and Richards found that waves travelling between these two points were 0.3 of a second faster in 1996 than in 1968. The interpretation is subtle and rests on the observation that propagation of seismic waves is anisotropic in the inner core; that is, it varies according to the direction of propagation. Using a model of the distribution of anisotropy, the authors inferred a total inner-core rotation of 30° between 1968 and 1996, giving a rotation rate of about 1° per year. Earlier this year, however, much of the recorded delay was shown to be due to misestimates of the positions of the emitter earthquakes, putting an upper bound on inner-core rotation of 0.2° per year for that period[4].

Clearly, a higher-resolution technique was needed. This is precisely what Vidale *et al.*[1] provide. The emitters were two nuclear tests in northern Siberia, the devices being exploded in 1971 and 1974. The receiver was LASA, the Large Aperture Seismic Array, a constellation of hundreds of seismic stations in Montana in the United States (the array was dismantled more than 20 years ago but the data it collected remain available). The key ingredient of this new method, however, is the use of waves that are scattered in the inner core rather than transmitted through it (Fig. 1c).

In a previous study[5], Vidale and Earle discovered that the inner core is not transparent to seismic waves but is somewhat 'fuzzy', a far-reaching result in its own right. Thanks to the high angular resolving power of the LASA array, they obtained a sort of 'angular speckle' of waves scattered by the inner core. They next wondered whether there was any change of this speckle with time. If the inner core rotates with respect to the mantle, waves scattered by heterogeneities located in the side that is getting closer will arrive earlier, whereas waves coming from the retreating side will arrive later.

This is precisely what Vidale *et al.*[1] found when comparing seismic waves from the Siberian nuclear explosions of 1971 and 1974. The observed ±0.1-second 'butterfly' pattern is explained by a rotation of only 0.45°, yielding an average eastward rotation rate of 0.15° per year. By looking at scattered rather than transmitted seismic waves, Vidale *et al.* have improved the resolution of these kinds of investigations by almost two orders of magnitude.

Nonetheless, several issues have to be addressed before the measurements of Vidale *et al.* can be seen as definitive. First, theoretical developments are needed to go beyond one element of the analysis — the Born approximation — used in this study. Second, the effect of possibly inexact estimates of emitter location and of heterogeneities near the source requires further work. Finally, the pattern obtained by Vidale *et al.* seems to imply that the axis of rotation of the inner core is different from the Earth's rotation axis. This result is difficult to reconcile with our understanding of core dynamics and will require careful appraisal. Nonetheless, it looks as if here we have a

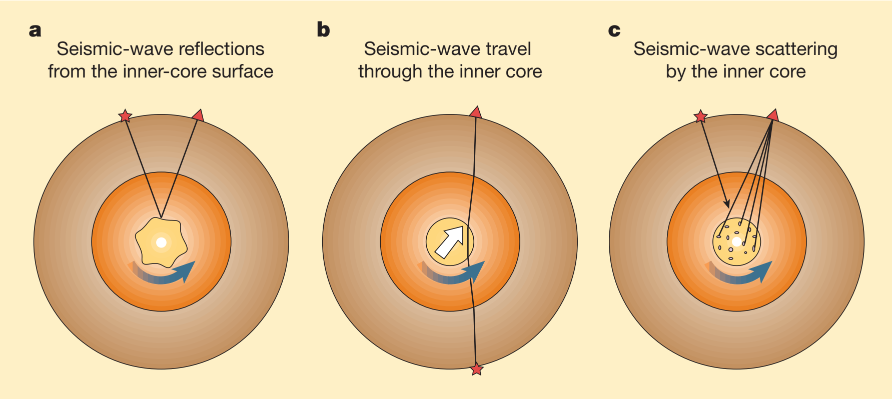

Figure 1 **Three ways of detecting differential rotation of the inner core (yellow) with respect to the mantle (brown). Triangles denote a station or array for detecting seismic waves (the receiver); stars indicate an earthquake or a nuclear explosion (the emitter). When an observation is repeated after some time interval, keeping the same geometry, the travel time of the waves may change by a few tenths of a second because the inner core has rotated during that time.** a, **Souriau analysed waves that bounce off the surface of the inner core.** b, **Song and Richards[3] investigated waves that propagate through the inner core, using its anisotropic axis (white arrow) as a marker.** c, **The method proposed by Vidale *et al.*[1] relies on waves that are scattered in the inner core. This approach increases the resolution over previous studies by almost two orders of magnitude, and gives an estimate of differential rotation of 0.15° per year.**

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

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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. ■

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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],