decades of intensive research. We need a broader array of molecular markers to dissect earlier and later steps of neural crest induction, as well as a better understanding of the signals seen by the neural plate that pave the way for participation by the surface ectoderm.

References

1. B. K. Hall, *The Neural Crest in Development and Evolution* (Springer-Verlag, New York, 1999).
2. A. K. Knecht, M. Bronner-Fraser, *Nature Rev. Genet.* **3**, 453 (2002).
3. N. Le Douarin, C. Kalcheim, *The Neural Crest*, J. Bard, P. Barlow, D. Kirk, Eds. (Cambridge Univ. Press, Cambridge, 1999).
4. M. I. García-Castro, C. Marcelle, M. Bronner-Fraser, *Science* **297**, 848 (2002); published online 13 June 2002 (10.1126/science.1070824).
5. C. D. Stern, *Nature Rev. Neurosci.* **2**, 92 (2001).
6. M. Manzanares, A. Locascio, M. A. Nieto, *Trends Genet.* **17**, 178 (2001).
7. M. Sefton, S. Sanchez, M. A. Nieto, *Development* **125**, 3111 (1998).
8. M. A. Nieto, M. G. Sargent, D. G. Wilkinson, J. Cooke, *Science* **264**, 835 (1994).
9. C. LaBonne, M. Bronner-Fraser, *J. Neurobiol.* **36**, 175 (1998).
10. M. A. Selleck, M. Bronner-Fraser, *Development* **121**, 525 (1995).
11. K. F. Liem Jr., G. Tremml, T. M. Jessell, *Cell* **91**, 127 (1997).
12. K. F. Liem Jr., G. Tremml, H. Roelink, T. M. Jessell, *Cell* **82**, 969 (1995).
13. M. E. Dickinson, M. A. Selleck, A. P. McMahon, M. Bronner-Fraser, *Development* **121**, 2099 (1995).
14. J. Vallin *et al.*, *J. Biol. Chem.* **276**, 30350 (2001).

PERSPECTIVES: GEOPHYSICS

Redistributing Earth's Mass

Anny Cazenave and R. Steven Nerem

Like a pumpkin, Earth is a bit wider around the equator than the meridian. This slight oblateness (by about 0.3%) results from axial rotation and large-scale mantle convection (*1*). If the dynamic oblateness J_2 decreases with time, then mass must have been redistributed from equatorial regions to the high latitudes, and inversely. But relative to the mass of Earth, any such mass distribution is likely to be very small.

Changes in J_2 were first measured 20 years ago by Yoder *et al.* (*2*), who used satellite laser ranging to show that it was decreasing linearly by 3×10^{-11} per year. Several investigators later confirmed his observation (*3*). Changes in J_2 with time have now been monitored for more than 25 years with satellite laser ranging. On page 831 of this issue, Cox and Chao (*4*) show that, contrary to expectation, in recent years J_2 has started to increase.

The earlier decreasing trend in J_2 meant that Earth was becoming less oblate. This observation can be largely explained by postglacial rebound—the viscous relaxation of Earth's mantle that began when polar ice caps started to melt at the end of the last glaciation 18,000 years ago. Postglacial rebound still continues today. Seasonal oscillations of J_2 have also been observed. They are caused by the redistribution of air mass in the atmosphere and of water mass among atmosphere, oceans, and continental water reservoirs (*5, 6*).

Cox and Chao (*4*) report satellite laser ranging data to numerous satellites from 1979 to 2001. For most of the past two decades, J_2 has been steadily decreasing. But in early 1998 it suddenly started to increase substantially [see figure 2 of (*4*)], indicating a large-scale mass redistribution from high latitudes to the equatorial regions.

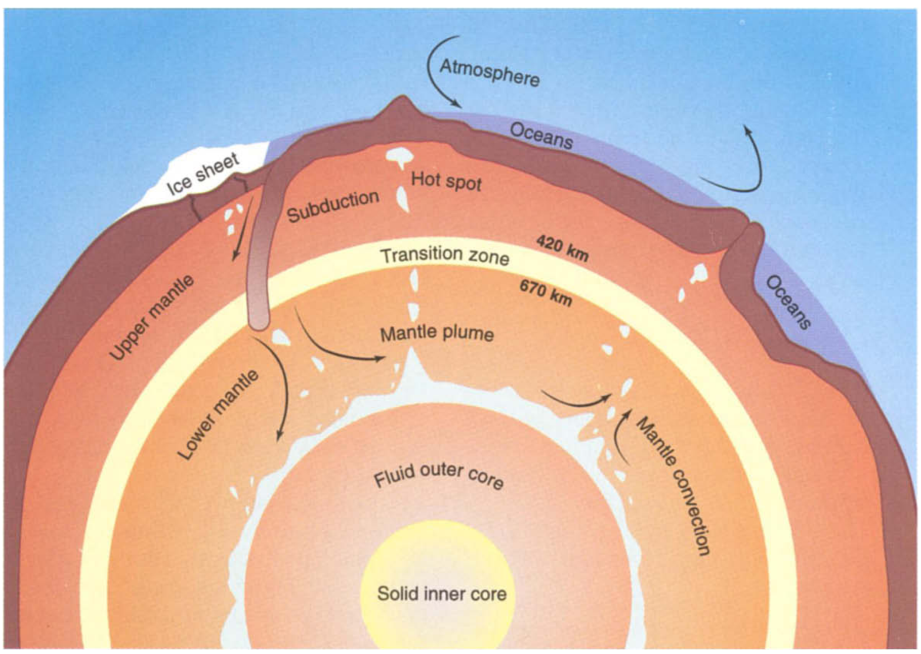
Cox and Chao discuss several mechanisms that might explain these observations: melting of the polar ice caps, melting of the Alpine glaciers, or melting of Arctic sea ice. According to current knowledge (*7*), however, none of these can explain the observations. Ice cap melting should indeed lead to a rise in the global mean sea level, but the observed sea level rise since 1992 (*8*) is incompatible with the amount of ice melting required to explain the observed J_2 change (*4*) [even if the observed rise is attributed entirely to ice melting, which is not the case (*9*)].

What, then, is causing the change? Cox and Chao apparently rule out the atmosphere as a possible source. There remain two potential candidates: Earth's fluid outer core and the oceans (see the figure).

A sudden change in material flow at the top of the fluid outer core, as evidenced by geomagnetic "jerks" (changes in the trend of the secular variation of the geomagnetic field), could produce a nonnegligible change in J_2. As pointed out by Cox and Chao (*4*), a jerk around 1999 suspected from geomagnetic observations (*10*) was recently confirmed from updated data (*11*). Thus, one cannot rule out that redistribution of mass inside the core before the observed jerk may have contributed to the observed change in J_2.

Large-scale mass redistribution in the oceans remains a serious candidate. Figure 2 of (*4*) shows other fluctuations in J_2 (for example, from 1980 to 1983 and from 1989 to 1992), although they are smaller than the fluctuation that began in 1998. Hence, what may at first appear to be a sudden single event (or a change in the trend direction) may rather be a recurrent interannual or decadal fluctuation of varying intensity.

The recent J_2 change occurred in late 1997 to early 1998, at the time of the strongest El Niño event this century. The El Niño–Southern Oscillation and its decadal modulation are primarily associated with



Schematic representation of the Earth system inside which mass redistribution may occur.

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mass transport in the tropical Pacific parallel to the equator, but transport perpendicular to the equator (meridional transport) also occurs. Interannual and decadal J_2 variations, visible after the linear decreasing trend is removed, appear to be correlated with the Pacific Decadal Oscillation index. The dynamics of this oscillation are not well understood, but model studies indicate water mass transport from the subtropics to the tropics (*12*), which may produce a change in J_2.

It may be tempting to search for an oceanic (and hence climatic) origin for the observed change in J_2, but as yet there is no evidence. Whatever the cause, the results of Cox and Chao emphasize the importance of gravity variations as a barometer of integrated mass changes in the Earth system. Monitoring these variations with improved spatial and temporal resolution would provide an important tool for studying Earth system changes.

Future insights into the causes of the unexpected J_2 change should come from at least two sources. State-of-the-art ocean general circulation models should be able to determine whether large-scale water mass redistribution occurred in the ocean in recent years. And the recently launched GRACE (Gravity Recovery and Climate Experiment) satellite mission will measure mass redistribution in the surface fluid envelopes with unprecedented spatial resolution (300 km) and precision (1 cm water equivalent), on time scales ranging from a month to several years (*13*).

If events like the mass redistribution of 1998 to 2001 occur again, they will be easily detectable by GRACE. Unlike the observations of Cox and Chao (*4*), who can only give information integrated over the whole Earth, GRACE will identify the geographical location of the source, providing strong constraints on the cause of the mass redistribution. This would provide unprecedented insight into the ongoing changes in the Earth system.

References and Notes

1. K. Lambeck, *Geophysical Geodesy, the Slow Deformations of the Earth* (Clarendon, Oxford, 1988).
2. C. F. Yoder *et al.*, *Nature* **303**, 757 (1983).
3. W. R. Peltier, *Rev. Geophys.* **36**, 603 (1998).
4. C. M. Cox, B. F. Chao, *Science* **297**, 831 (2002).
5. R. S. Nerem, R. J. Eanes, P. F. Thompson, J. L. Chen, *Geophys. Res. Lett.* **27**, 1783 (2000).
6. A. Cazenave, F. Mercier, F. Bouille, J. M. Lemoine, *Earth Planet. Sci. Lett.* **171**, 549 (1999).
7. J. Church *et al.*, in *Climate Change 2001, the Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 639–693.
8. R. S. Nerem, G. T. Mitchum, in *Satellite Altimetry and Earth Sciences, a Handbook of Techniques and Applications*, L. L. Fu, A. Cazenave, Eds., vol. 69 of *International Geophysics Series* (Academic Press, San Diego, CA, 2001), pp. 329–349.
9. C. Cabanes, A. Cazenave, C. Le Provost, *Science* **294**, 840 (2001).
10. M. Mandea, E. Bellanger, J.-L. Le Mouel, *Earth Planet. Sci. Lett.* **183**, 369 (2000).
11. M. Mandea, personal communication.
12. M. J. McPhaden, D. Zhang, *Nature* **415**, 603 (2002).
13. J. O. Dickey *et al.*, *Satellite Gravity and the Geosphere* (National Research Council, Washington, DC, 1997).

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PERSPECTIVES: COMPUTER SCIENCE

Satisfied with Physics

Carla P. Gomes and Bart Selman

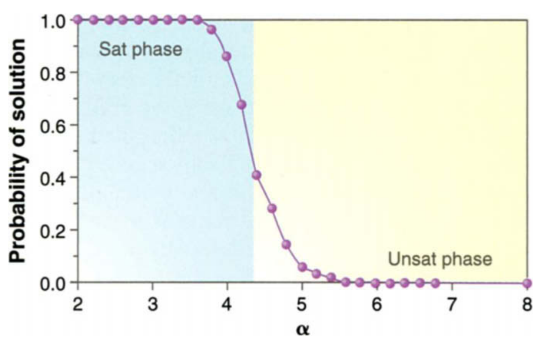
Statistical physics is one of the pillars of modern physics, explaining the macroscopic world on the basis of the dynamics of its microscopic components. But methods from statistical physics can also foster a deeper understanding of computational phenomena. On page 812 of this issue, Mézard *et al.* (*1*) use this approach to characterize the properties of random instances of the satisfiability problem in unprecedented detail. They also introduce a novel strategy for finding solutions to this problem.

Satisfiability (SAT) is a logical reasoning problem defined in terms of Boolean variables (*a*, *b*, *c*, and so forth) and logical constraints describing the relation between these variables. Each variable can be either "True" or "False." An example of a constraint is

$$a \text{ OR } (\text{NOT } b) \qquad (1)$$

A SAT problem is solved by assigning truth values to the variables such that all constraints are satisfied simultaneously. For example, the constraint in Eq. 1 is satisfied if *a* is "True" or *b* is "False."

The SAT problem plays a central role in the quest for more efficient ways of solving large-scale computational problems, such as planning and scheduling, finding the folded state of a protein, and determining whether a computer chip design meets its specification. These problems are called "NP-complete." Thousands of NP-complete problems are known; all can be encoded as SAT problems (see the second figure).



Phase change in 3-SAT. Plotted is the probability that a 3-SAT problem has at least one satisfying assignment as a function of α, the ratio of logical constraints to variables. Satisfiable phase on the left; unsatisfiable phase on the right. We considered problems with 50 variables.

It is widely believed that there does not exist an efficient algorithm for solving NP-complete problems. Formally proving that no such algorithm exists is one of the main open problems in modern computer science (*2*). NP-completeness is, however, a worst-case notion, capturing the computational cost of the very hardest possible instances of the problem. In practical applications, one may not encounter instances that are quite that hard. What, then, is the computational cost of "typical" instances? One can obtain important insights into typical case complexity by considering randomly generated SAT problems.

Mézard *et al.* (*1*) consider random instances of a particular case of SAT, the K-satisfiability problem (K-SAT), in which each constraint contains exactly *k* variables. Such randomly generated instances exhibit a "phase transition" as a function of the ratio α of constraints to variables (*3*). K-SAT problems with a small α value almost all have one or more satisfying assignments, whereas problems with a large α value have too many constraints and become unsatisfiable (that is, no setting of the variables simultaneously satisfies all constraints). As the number of variables grows, the transition from almost always satisfiable to almost always unsatisfiable becomes very sudden (see the first figure). For 3-SAT (that is, $k = 3$), the transition occurs at $\alpha \approx 4.25$. The exact location of the phase transition threshold has not yet been derived rigorously (*4*–*8*).

Many of the computationally hardest problem instances appear to lie in this phase transition area. Hence, a better understanding of the phase change in the K-SAT problem may also provide new insights into its computational properties and strategies for solving it.

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