SATELLITE ALTIMETRY

Understanding ocean dynamics

Kurt Lambeck

SATELLITE altimetry has been one of the cornerstones of geodynamics research from space for a decade and a half, but the oceans have had to wait longer for their turn. A meeting in December* included symposia dedicated to the scientific results of two particularly promising missions: Topex/Poseidon, jointly run by the United States and France, and the European Space Agency ERS-1. What emerged, as illustrated here, was an exciting, if preliminary, insight into the dynamics of the world's oceans.

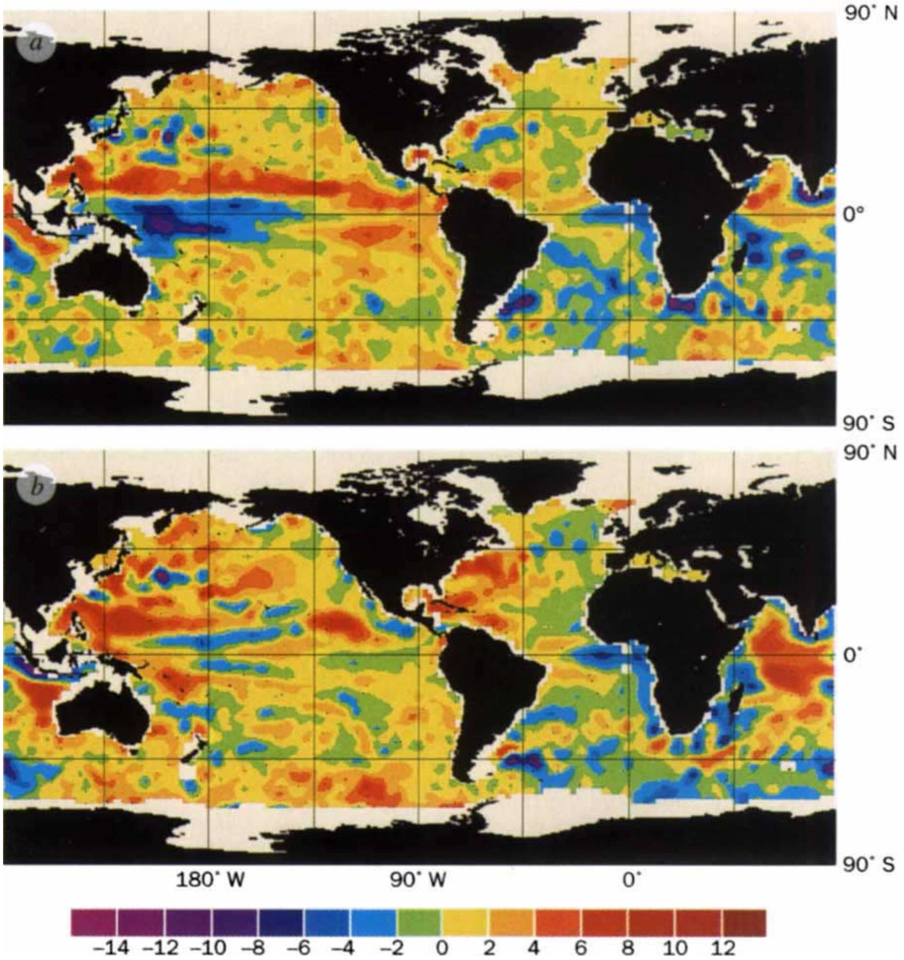
The satellite-borne altimeter measures the spacecraft height above the ocean surface. If the orbit of the spacecraft is accurately known then the shape of the ocean can be directly mapped. To a first approximation this shape is the geoid, an equipotential surface defined by the Earth's internal mass distribution, so the altimeter observations have provided valuable information on the physics of the solid Earth. Of greater interest to the oceanographic community is the departure of the sea surface from the geoid, the 'sea surface topography'. This topography and its changes provide the important information on the ocean currents. Earlier altimeter missions were hampered by either inadequate orbit control or a short spacecraft lifetime and consequently not much was learnt about the oceans. With the initial results from the Topex/Poseidon and ERS-1 missions, this has changed dramatically. The cause of this change has been progress in orbital dynamics and tracking accuracies which allow radial orbital accuracies to be maintained — and temporal variations in the ocean surface to be measured — to an accuracy of a few centimetres.

What is being revealed by the satellites is the ocean at work in real time. Much of what is seen has been known in outline, inferred from sparse shipboard measurements, but the full dynamic nature of the ocean is now emerging with unprecedented resolution. The tides are readily seen, not only the main diurnal and semidiurnal components but also the longer-period tides such that at any time the global ocean tide is known to within 2 or 3 centimetres accuracy, a huge improvement over earlier results. It is encouraging that numerical models for the tides are also much improved and surely we can expect to see, for example, the definitive study of the mechanisms and distribution of the dissipation of tidal energy in the oceans. Intense, small-scale motions portray a complex instantaneous flow field which tends to swamp the weaker but larger-scale motions that are of greater significance to climate. Early results are indicating that the latter can be extracted from the higher-frequency signals.

Seasonal cycles, for example, are being mapped by the Topex/Poseidon team. Perhaps most striking of these results is the asymmetry between the two hemispheres. The highest and lowest sea levels occur in the Northern Hemisphere autumn and spring respectively, with amplitudes that are much greater than for the Southern Hemisphere. Perhaps, then, the heat storage in the smaller Northern Hemisphere ocean is much greater than in the Southern Hemisphere. The seasonal pattern has now been established for the years 1992–94 but the interannual variability appears almost as great as the seasonal change itself. For example, there are notable differences in the Pacific equatorial region for the summer and winter months which presumably relate to the El Niño/Southern Oscillation. This can be seen in the figure for sea surface heights in the summers of 1993 (*a*) and 1994 (*b*). But note also the differences for these two records in the western North Atlantic and in the Indian Ocean.

The complementarity of the two altimeter missions is important. The orbital configuration of the Topex mission is such that it provides mainly a global-scale picture of the oceans and the high spatial and temporal variability is less well observed. ERS-1, whose orbit is such that the satellite flies over the same part of the ocean more frequently, provides more information on such mesoscale signals and processes. At the moment, it seems that some orbital problems remain to be ironed out and the full potential of the mission is yet to be achieved. Post-event processing is improving matters, and much new information can be expected soon from the smaller but important shallow areas of the oceans.

Determination of the very long-term variations in the ocean dynamics remains a matter for the future. First, long time series of data are required. Topex/



Sea surface topography for the Northern Hemisphere summers of (*a*) 1993 and (*b*) 1994. Each result represents a three-month mean of the sea surface elevations with respect to the mean surface established for the two-year period. The scale is in centimetres. Results are from the Topex/Poseidon Science Team led by C. Wunsch, J.-F. Minster and C. Koblinsky.

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Poseidon is expected to live for at least three more years, and the space agencies should recognize the importance of providing continuity in order to study the longer-term interannual variability such as the Southern Oscillation and El Niño phenomena. Second, there remains a need for better information on the shape of the geoid. At present, this surface is less well-known than the measurement accuracy of the altimeter or the accuracy of the tracking data and it remains impossible to measure the absolute shape of the sea at the requisite level of accuracy. A dedicated mission to determine the planet's external gravity field, coupled with future altimeter missions like Topex and ERS, could revolutionize our understanding of the dynamics of the oceans and of their interaction with the atmosphere, as well as contributing to the deciphering of the Earth's sub-surface structure. ☐

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MATERIALS SCIENCE

Multiple Kauzmann paradoxes

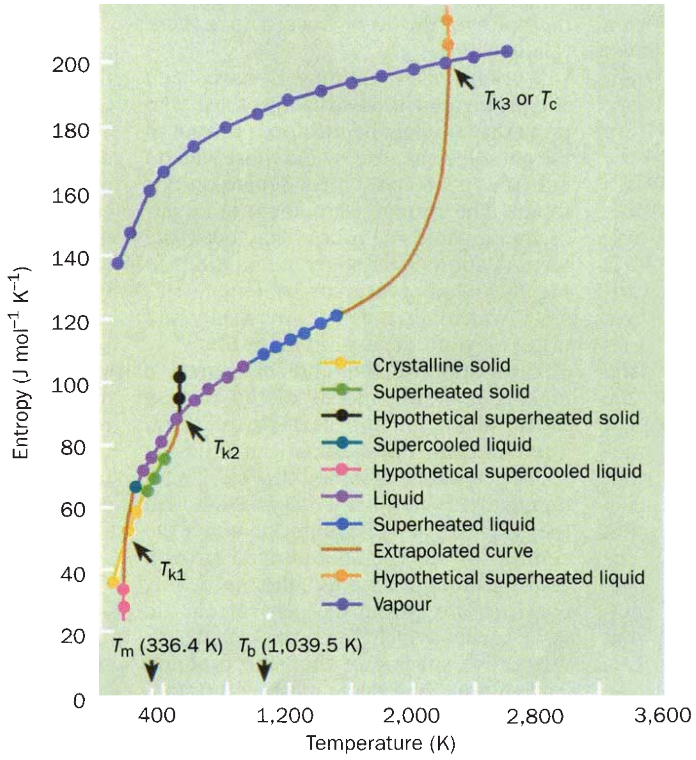
Robert W. Cahn

THE Kauzmann paradox, beloved of physical chemists (and chemical physicists) has featured in these pages before[1]. The concept has been gradually broadened, and a recent paper from Bangalore, India, in the *Journal of Chemical Physics*[2], has broadened it further still.

Kauzmann's original paper[3] first drew attention to the fact that the entropy difference between the crystalline phase and the (extrapolated) liquid phase of a substance can vanish at a temperature well above absolute zero; below that temperature, the crystal would have a higher entropy than the liquid. As this would violate the Third Law of Thermodynamics, Kauzmann termed his conclusion a paradox. A good concise introduction to this paradox appears in Elliott's book on amorphous solids[4], and a shorter one in my News and Views piece in 1988. The usual escape from the paradox is to claim that the 'ideal glassy state', which is the *equilibrium* configuration of the liquid at the Kauzmann temperature, can never be attained because the diffusion rate becomes negligible before the temperature has sunk to that level. In other words, the amount of supercooling a liquid can accept while remaining in metastable equilibrium is limited.

Fecht and Johnson[5] and Fecht[6] extended Kauzmann's ideas to high temperatures: the question they examined is whether a crystal can be superheated to (or beyond) the temperature at which the liquid and the superheated (extrapolated) crystalline phase have the same entropy. Their arguments lean heavily on the very high vacancy concentrations that are to be expected at this high 'isentropic temperature'; the crystal collapses at this temperature because the vacancies destabilize the lattice. Such a collapse is termed an 'entropy catastrophe'.

Kishore and Shobha[2] now raise the stakes by considering the relationship between a superheated liquid and its vapour. The figure, for potassium, one of the specific examples treated in their paper, shows the entropies of solid, liquid (shading into glass at low temperatures) and vapour. T_{k1} and T_{k2} are the original Kauzmann temperature and the upper Kauzmann temperature as previously analysed by Fecht and Johnson. T_{k1} is the absolute lower temperature limit for the existence of a supercooled liquid (*alias* glass) rather than the crystalline solid. T_{k2} is the absolute upper temperature limit for the superheated crystalline solid, vis-á-vis the liquid. The innovation is T_{k3}, the absolute upper temperature limit for a superheated liquid vis-á-vis the vapour phase. Kishore and Shobha explicitly remark that T_{k3} "could be considered as the critical temperature, T_c".



They compute values of T_{k3} for water and for various alkali and other metals. Agreement is mostly only moderate, within about 15 per cent in terms of absolute temperatures. For the example of potassium in the figure, $(T_{k3})_{calc}$ = 1,932 K whereas $(T_c)_{exp}$ = 2,220 K. For water, agreement is much better: T_{k3} = 636 K, T_c = 643 K. No attempt is made in the paper to bring in pressure as a variable, and it would have been better to have attempted a calculation of T_{k3} at the critical pressure, for comparison with T_c. In spite of this reservation, the ghost of Van der Waals will be pleased with this new approach to his famous criticality concept that goes back all the way to his 1873 doctoral thesis (which, as Maxwell remarked at the time, "at once put his name among the foremost in science").

As John Cahn has reminded us[7], it was van der Waals who first recognized that a liquid at the critical point has negative compressibility which renders it unstable, and it was he who coined the word 'spinodal' for this condition: after a gap of almost a century, the relevance of the spinodal concept for certain solid-state transitions, now known as spinodal transformations, came to be perceived. I wonder whether, one day, spinodal transformations and the Kauzmann paradox will be linked up.

Quite generally, Kishore and Shobha find that $2T_{k1} \approx T_m \approx T_{k2}/2$, where T_m is the melting temperature. They go on to estimate T_{k1} and T_{k2} by an alternative approach: they advance arguments as to why the configurational part of entropy is much more important here than the vibrational part, and use indirect (nonthermal) input, for instance viscosity measurements via the well-known Vogel–Tammann–Fulcher equation for the viscosity of liquids (which is focused on configurational features), to estimate configurational entropies and hence the Kauzmann temperatures. They achieve reasonable agreement with values