PERSPECTIVES: OCEANOGRAPHY

Spice and the Demon

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One of the oldest problems in oceanography is the connection between salinity and temperature. In particular, there is a remarkably tight relation between the two in the stratified water beneath the more variable surface mixed layer of the ocean. This could be the result of either external atmospheric forcing and lateral stirring or internal vertical mixing processes. Some observations lend support to the first mechanism (*1*). However, it is not easy to distinguish between the two, as the substantial heat capacity of the ocean makes the atmosphere ineffective in changing water properties (*2*). Much progress has been made in the last few years, and results reported on page 526 of this issue by Rudnick and Ferrari (*3*), as well as others in press, serve to place the main issues in sharper focus.

Rudnick and Ferrari (*3*) find that over distances of tens of meters to 100 km, lateral changes in the temperature and salinity of the mixed layer are largely compensated in density. That is, despite substantial changes in temperature and salinity, horizontal density changes are usually negligible near the surface. This striking result contrasts with the stratified thermocline a few hundred meters deeper, where density differences due to temperature exceed density differences due to salinity by a factor of about two.

An exciting aspect of this work is that it provides support for recent ideas of William Young at Scripps about recent theoretical ideas about the action of lateral mixing processes on gradients in the mixed layer (*4*). That is, water motions must arise because of horizontal density gradients introduced by random atmospheric forcing. A simple slumping of the heavy fluid under the adjacent light fluid is an example. The action of many such events is to quickly remove any horizontal density differences while leaving behind those temperature and salinity differences that do not affect the density. Because density compensation involves a correlation between hot and salty water properties (versus cold and fresh), such temperature-salinity variability has come to be termed "spice." Young's models provide a mechanism for explaining the presence of spice in the mixed layer.

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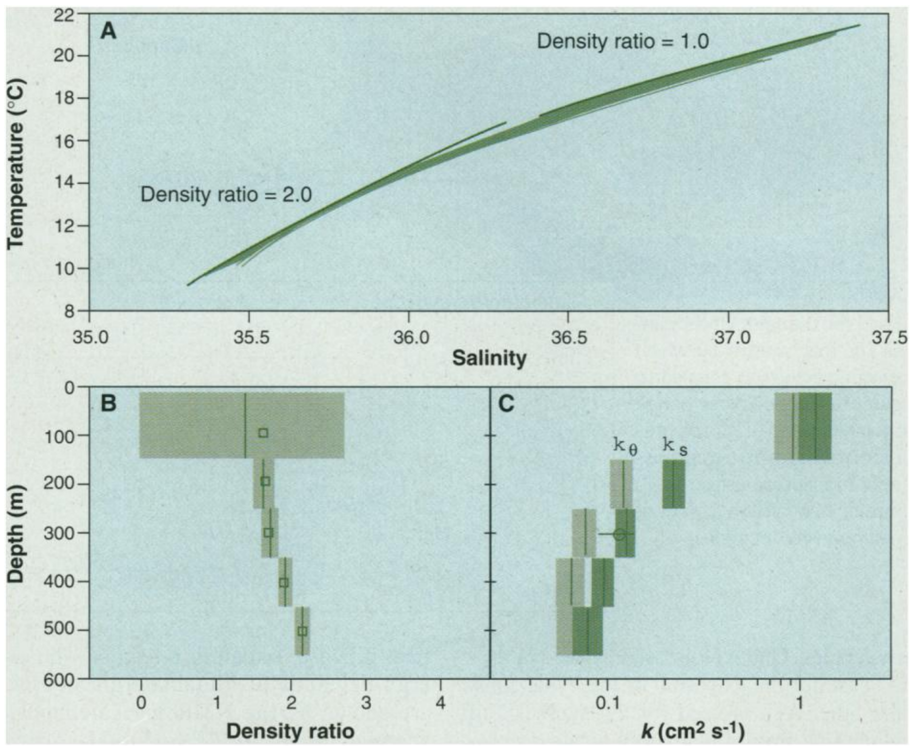
However, these new results raise problems for other ideas concerning the large-scale structure of the thermocline. In the water just below the mixed layer, such density-compensated variability is not observed. Rather, as mentioned above, the density variations due to temperature dominate those due to salinity. These are waters we expect to have been recently "subducted" by the wind-driven convergence of surface waters in midlatitude. Yet somehow the temperature-salinity relation is modified so that the the "density ratio" evolves from 1 to 2 and the spiciness is eliminated (see figure).



Salt and heat. **(A)** Temperature versus salinity for the upper 600 m of ocean in the eastern North Atlantic (green) (*7, 8, 10*). **(B)** Change in density ratio from surface to depth. Shaded box, the interquartile range computed from 5-m vertical differences; the vertical line is the median value. Open square, the large-scale average density ratio computed over 100 m. **(C)** Estimated vertical mixing rates for heat (k_θ) and salt (k_s) from microstructure measurements (*8, 10*).

The late Henry Stommel of Woods Hole proposed a lateral mixing process in the mixed layer that gave a horizontal density ratio of 2, as observed in the thermocline and over basin scales in the winter mixed layer (*5*). His "temperature-salinity regulator" relies on an imposed atmospheric temperature gradient and a mixing mechanism that responds to the random salinity anomalies generated by intermittent rainfall. One would certainly expect the regulator to operate on the scales sampled by Rudnick and Ferrari. Their results argue for the more recent models of Young and against Stommel's regulator. In any case, these mixed-layer mechanisms cannot explain the absence of spice in the thermocline. Nor do estimates of the large-scale patterns of atmospheric density forcing due to heat fluxes and water exchange suggest a means of externally imposing a density ratio of 2 on the ocean (*6*).

A possible answer to these puzzles may lie in the unique nature of the mixing processes active in the upper thermocline. The contrast between the mixed layer and the thermocline is tremendous when one considers the levels of turbulence in each depth interval. Whereas the mixed layer is generally very turbulent, the thermocline is rarely so. Evidence from the North Atlantic Tracer Release Experiment (NATRE) shows conclusively that vertical mixing in the thermocline is weak (*7*), as has long been suspected from microstructure measurements (*8*). The low levels of turbulence raise the likelihood that the mixing of heat and salt in the thermocline will be influenced by their very different molecular diffusivities. Specifically, the "double-diffusive" process of salt fingering becomes strong when the density ratio is near 1 (*9*). Moreover, microstructure observations from NATRE reveal solid evidence for salt fingering in the upper thermocline (*10*). At the level of the tracer release (300 m), about half the tracer dispersion can be accounted for by salt fingers. Also, the mean tracer depth was observed to drift downward across density surfaces with time, a result quantitatively consistent with salt fingers but of the wrong sign for ordinary turbulence. Of particular interest for the Rudnick and Ferrari observations in the Pacific, the NATRE microstructure data, from the same latitude band and equivalent circulation regime in the Atlantic, display increasing amounts of fingering approaching the base of the mixed layer.

Salt fingers are convective cells a few centimeters wide that transport heat and salt at different rates. They are particularly active when the vertical density ratio is near 1 (that is, when the water is spicy) but are ineffective at density ratios above 2. This observed dependence, plus the fact that fingers transport more salt than heat, led me to propose a salt fingering process to explain the pervasive "twoness" of the density ratio in the thermocline (*11*). In addition, the action of salt fingers on spice anomalies is to cause warm salty anomalies to rise across density surfaces, because they lose more salt than heat, and cold fresh anomalies to sink across density surfaces, because they gain more salt than heat (*12*). The mixing continues until the anomalies disappear. This idea, attributable to Melvin Stern of Florida State University, the discoverer of salt fingers, is an attractive way to explain the tightness of the temperature-salinity relation. Whereas Young's mixed-layer mechanism is a generator of spice, Stern's is a strong spice consumer that contributes to the postwinter restratification process. Double diffusion is rarely incorporated into oceanic models, and recent coupled climate model runs without it show problematic growth of spiciness (*13*). It will be important to improve our quantitative understanding of the role of fingers in oceanic mixing to develop confidence in long-term models for climate prediction, as numerical simulations have revealed a distinct sensitivity of the ocean circulation to double diffusion (*14*).

Thus, mixing may yet win out over atmospheric forcing as the primary explanation for the temperature-salinity relation. Young's lateral mixing mechanisms can explain the "density ratio = 1" result for the surface mixed layer, in the presence of random atmospheric forcing and strong vertical mixing. Similarly, the action of salt fingers in the weakly turbulent, strongly stratified thermocline provides a rationale for the "density ratio = 2" result found there. The interesting transition between these regimes involves a seasonal cycle of atmospheric forcing whereby only the wintertime mixed-layer properties are allowed into the thermocline below. Stommel likened this selective mechanism to Maxwell's Demon, as it admits only water with the correct density into the thermocline (*15*). The problem with "Stommel's Demon" is that it has no way of knowing about the density-compensated variations in temperature and salinity, which Rudnick and Ferrari now show to be substantial. A key issue is to what extent the demon uses salt fingers to handle its spicy diet; this question will require some new approaches to microstructure measurements as well as tracer experiments in stronger salt finger zones.

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PERSPECTIVES: CLIMATE AND CULTURE

Transitions in the Mid-Holocene

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The period between about 8000 and 3000 years before present (yrs B.P.) was a time of profound cultural transitions: The first temple mounds were constructed in Peru, the first pyramids were built in Egypt, settled agrarian societies were established worldwide, civilizations rose and collapsed in the ancient Near East, and a multitude of other changes with long-term consequences for the development of complex societies occurred throughout the world. During this period—the mid-Holocene—Earth's climate was highly variable in comparison with the immediately preceding and succeeding millennia. Both archeologists and paleoclimatologists are now confronting this correlation and possible causal connections among changes in mid-Holocene climate and culture around the globe. A wealth of new data is becoming available, as evidenced at a recent meeting "FERCO International Conference on Climate and Culture at 3000 B.C." at the University of Maine, and a complex picture of cultural response to climate change is emerging (see figure) (*1*).

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An important region, both culturally and climatically, is the Pacific basin, extending from the western Americas across to Australia, New Zealand, and northeast Asia. The tropical Pacific climate oscillates with a period of 3 to 7 years between an El Niño phase with warm tropical waters and a La Niña phase with cold tropical waters. This oscillation, called the El Niño–Southern Oscillation (ENSO), creates the periodic weather patterns that dominate the Pacific basin today. Geoarchaeological evidence from the Peruvian coast suggests that ENSO, as currently defined, did not operate between 8900 and 5800 yrs B.P. and perhaps earlier (*2*). Other paleoclimatic records from the Pacific basin support this suggestion (*3*). Faunal records (shells and fish) from sites in northern Peru indicate warmer mean sea-surface temperature from about 8900 to 5800 yrs B.P. than today (*2*). Andean ice cores indicate a warmer and more humid atmosphere during that period (*4*). Coral records from the western Pacific show higher sea-surface temperatures and reduced variability around 6600 yrs B.P. (*3*). Lake-sediment records from Ecuador (*5*), northern Chile (*6*), and the Galapagos (*7*) suggest increased interannual climate variability after about 5800 yrs B.P. Pollen data from northern Australia indicate a gradual onset of ENSO conditions during the mid-Holocene, with a transition at around 5800 yrs B.P. to an ENSO-dominated climate marked by greater variability (*8*). In the northwest Pacific, changes in