fusivities. 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 mollusk distribution point to a warmer mid-Holocene ocean, with modern conditions established only after 5800 yrs B.P. (*9*).

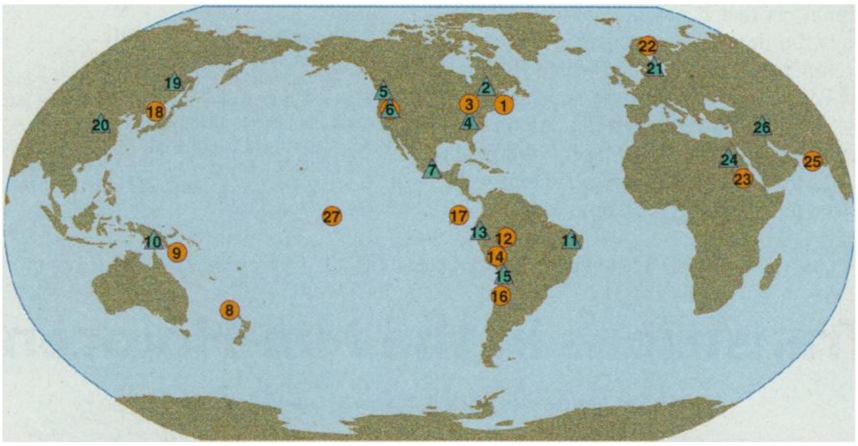
On the Peruvian coast, societies that relied almost exclusively on seafood for animal protein began construction of temples shortly after 5800 yrs B.P. (*10*). Marine resources have been used for 11,000 years in Peru (*11*), and highland agriculture is only a few millennia younger, but the use of both seafood and agricultural products by a single group occurred only after the apparent change in Pacific basin climate. Although we associate El Niño with disaster in Peru, it usually brings benefits rather than costs to the central coast where the above-mentioned first mounds were constructed: The lomas (fog meadows) bloom, rains are sufficient to enhance agricultural yields but are rarely destructive, populations of mollusks such as scallops explode, and fish may swim close to shore in great quantities before moving further south. The onset of El Niño and the associated flourishing of resources may therefore have facilitated the cultural transition evidenced by the temple mounds (*12*).

Elsewhere in the Pacific basin, from Chile to Japan, China, Korea, and the Russian Far East, the mid-Holocene was also a time of important cultural change in complex prehistoric societies. As in central Peru, after 5800 yrs B.P. the smaller populations on the north coast of Chile became culturally more complex, living in larger sites and adopting agriculture (*13*). In China, towns and cities appeared at this time (*14*). The Middle Jomon Period in Japan (roughly 5800 to 3200 yrs B.P.) is characterized by larger structures, increased use of shellfish, burial differentiation, and the appearance of high-status goods with restricted distributions (*15*). In Australia and New Guinea, where similar social complexity did not develop, increasing mid-Holocene populations were associated with new agricultural practices that were, however, not clearly correlated with climate change (*16*). In northwestern North America, major cultural change did not occur until about 4900 yrs B.P., when more sites and year-round settlement are evident (*17*).

In the Old World, ENSO does not dominate regional climates. Nevertheless, the mid-Holocene was a time of increased climate variability and cultural change. In the region west of the Nile Valley, which is now a desert, seasonally occupied villages of cattle herders expanded between about 9000 and 6300 yrs B.P., when stronger monsoons created wetter conditions than earlier in the Holocene. When the region became arid again after 6300 yrs B.P., again as a result of changes in the monsoon strength and areas of influence, it was depopulated. At the same time, peoples in the Nile Valley began to worship cattle and create monumental architecture (*18*). In northern Mesopotamia, a prolonged drought apparently began abruptly at about 4200 yrs B.P. Archaeological and documentary data indicate that the region was largely abandoned at that time, while human populations grew rapidly in southern Mesopotamia where irrigation-based agriculture remained feasible. An influx of refugees from the desiccated north likely added to this increase (*19*).

In Scandinavia at the end of the mid-Holocene, interior settlement increased, and pottery, farming, and long-barrow construction were introduced. Food species in coastal middens show greater emphasis on terrestrial mammals. These innovations may have resulted, in part, from changes in forest cover, particularly the decline in elm and the appearance of faster growing hardwoods such as hazel and birch (*20*).

The evidence presented above confirms that the mid-Holocene (8000 to 3000 yrs B.P.) was a time of increasing climate variability and cultural change in many parts of the world but that climatic and cultural events and trends were neither global nor synchronous. In general, climate was warmer and less variable for several millennia before 5800 yrs B.P. than in the immediately following period. Cultural complexity generally increased where climate change was most apparent. Faced with change, humans have the capacity to alternate behaviors, not all of which lead in the same direction or are equally successful. However, the connections between climate and culture remain largely unclear and require case-by-case study with high-temporal resolution and precise dating. Understanding the evolution of the ENSO system and its influence on prehistoric societies in the Pacific basin, for example, requires annually resolved paleoenvironmental records. Enhanced collaboration between paleoclimatologists and archaeologists will foster an integrated view of this crucial period in recent Earth history.



Clues to causality. Widespread evidence for climatic (○) and cultural (Δ) change during the mid-Holocene points to a possible causal connection between climate and culture, but the patterns are complex (*21*).

References and Notes

1. The "FERCO International Conference on Climate and Culture at 3000 B.C." was held at the University of Maine in October 1998. Data shown in the figure were presented at this conference by the conference participants. FERCO is the Canary Islands–based Foundation for Exploration and Research on Cultural Origins. The conference was organized by Daniel Sandweiss and Kirk Maasch; see the program at www.ferco.org/ferco_el_nino.html.
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