presolar grains and traditional astronomical observation." Clemson University's Donald Clayton agrees. Having shown how carbon grains form in supernovae,[3] Clayton believes that understanding how atoms combine under violent conditions, such as the AGB superwind, requires kinetic chemistry. "Thermodynamic equilibrium can predict what clusters are stable, but it is not a reliable guide to their rate of growth or their final sizes. This is a new challenge to chemistry."

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Two Satellites Observe Details of Ocean–Atmosphere Coupling

Winds drive ocean circulations, which, in turn, establish the sea surface temperature (SST) gradients that generate the atmospheric pressure to drive winds. Identifying and explaining the close coupling of ocean and atmosphere—its causes and effects, its feedback mechanisms—is a formidable challenge. In few locations is this goal more daunting than in the eastern tropical Pacific, the site of El Niño's and La Niña's biggest temperature anomalies. Here, the circulations of ocean and atmosphere are complicated by the coastal boundary, vigorous atmospheric convection, the convergence of northern and southern hemisphere trade winds, and the change of sign of the Coriolis force at the equator.

Ironically, as Dudley Chelton of Oregon State University and coworkers have shown recently,[1] the eastern tropical Pacific offers a favorable place to study ocean–atmosphere coupling. The researchers present a correlation of data gleaned by two satellites: QuikSCAT, which measures surface wind velocity; and the Tropical Rainfall Measuring Mission (TRMM), whose microwave imager (TMI) measures sea surface temperature. Their results show in unprecedented detail how quickly and strongly winds in the region respond to changes in SST.

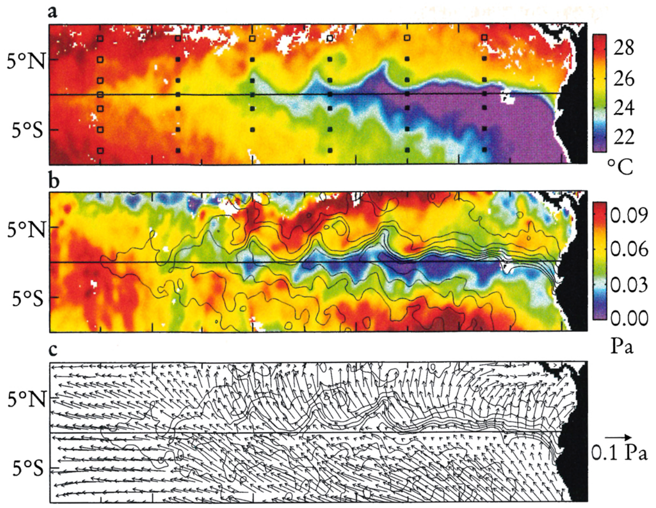
Cold tongue

Although QuikSCAT observes the entire globe and TMI's view spans 40° either side of the equator, Chelton and company chose to focus their study on a feature in the eastern tropical Pacific known as the cold tongue (see figure on next page). Especially prominent during La Niña years, the cold tongue arises from the wind-driven upwelling of cold subsurface water. When those winds weaken, as in El Niño years, the cold tongue disappears. (See David Neelin and Mojib Latif's article "El Niño Dynamics," PHYSICS TODAY, December 1998, page 32.) However, it's not clear exactly how the cold water is transported upward; nor have the cold tongue's detailed shape and off-equator location been accurately reproduced by computer models.

> Ocean winds respond rapidly to changes in the temperature of the underlying sea.

When the prevailing northwestward trade winds blow across the cold tongue, they weaken by a factor of two. To explain the weakening, Mike Wallace, Todd Mitchell (both at the University of Washington), and Clara Deser (now at the National Center for Atmospheric Research in Boulder, Colorado) proposed in 1989 that the atmospheric layer just above the sea becomes more stable over cooler water, thereby reducing its ability to grab momentum, via convection and turbulence, from the fast-moving winds higher in the atmosphere.[2]

Testing this particular ocean–atmosphere interaction requires measuring a range of values of SST and wind stress—that is, the force per unit area exerted by the wind on the sea surface. In 1989, Stanley Hayes, with his University of Washington colleague Wallace and Mike McPhaden of the Pacific Marine Environmental Laboratory, realized that nature obligingly serves up such a range of values in the form of tropical instability waves.[3] As evident in the figure, these cusp-shaped waves, which shape the boundary between the warm and cold water and whose restoring force originates in the conservation of vorticity, propagate westward along both the northern and southern flanks of the cold tongue with periods of 20–40 days, wavelengths of 1000–2000 km, and phase speeds of 0.5 m s^{-1}. Because the tropical instability waves, in effect, perturb the location of the edge of the cold tongue, they can be exploited to inves-



QuikSCAT and TRMM observations of wind stress and temperature of the eastern tropical Pacific in the period 2–4 September 1999. (a) Sea surface temperature (SST), as measured by TRMM's microwave imager, is shown in false color (the squares show the location of measuring buoys; the black area to the right is the west coast of central and south America). (b) Magnitude of wind stress, as measured by QuikSCAT, is shown in false color; the contours show SST. (c) Direction of wind stress, with contours of SST. (QuikSCAT data were provided by Michael Freilich of Oregon State University; TRMM SST data were provided by Frank Wentz and Chelle Gentemann of Remote Sensing Systems.)

tigate how quickly and by how much the wind-stress field responds to changes in SST.

TMI measures SST by detecting the ocean's thermal emission. Although it peaks in the infrared, the spectrum can be characterized by observing in the microwave band, which, unlike the infrared, isn't muffled by cloud cover. TMI's spatial resolution and temperature precision are 46 km and 0.5 °C, respectively. Averaging the data over three days yields a good compromise between time resolution and accuracy.

To measure the wind stress, QuikSCAT bounces microwaves off the centimeter-sized ripples that are induced by wind blowing across water: the stronger the wind, the bigger the amplitude of the ripples, whose crests are perpendicular to the wind. Because the ripples and the microwaves have roughly the same wavelength, the signal returning to the satellite bears a diffraction-like signature, which is strongest when the ripples are perpendicular to the incident radar signal. By looking at the same patch of sea from several directions (when the radar looks forward and again, moments later, when it looks backward), QuikSCAT measures the wind-stress field with far greater spatial coverage than could have been accomplished with previous instruments. QuikSCAT's spatial resolution is 25 km and its velocity precision is 0.6 m s^{-1} in magnitude and 20° in direction.

The figure shows the SST and the wind-stress measurements for one three-day period last September. The presence of the cold tongue is obvious in the top panel, as are the tropical instability waves along its flanks. The middle panel shows how closely the magnitude of the wind matches the SST.

If, as Wallace, Mitchell, and Deser hypothesized, the wind slows over cooler water and speeds up over warmer water, the divergence of the wind-stress field should increase with the gradient of the temperature field, and the coupling should be strongest when the two vectors are aligned—that is, when the wind blows at right angles to the isotherms. Both effects are clearly seen in the data, with high statistical significance. The correlation also shows that the wind responds to changes in SST on time scales at least as short as three days.

Twist in the wind

Calculating divergence's orthogonal sibling, curl, for the wind-stress field provides an additional test of Wallace, Mitchell, and Deser's hypothesis. Where the wind happens to blow along the isotherms—that is, at right angles to the SST gradient—lateral gradients in wind stress should arise. The resulting wind-stress curl creates vorticity and tends to rotate the wind direction—just as your path would rotate if you took longer steps with your right foot than with your left foot. In general, the prevailing winds blow across, not along, the isotherms in the cold tongue region. However, in the cusps on the flanks of the cold tongue, the SST gradient parallels the wind (see the bottom panel). Here, as expected, the wind-stress curl is largest. Moreover, throughout the data set, the wind-stress curl is proportional to the SST gradient, and weakest when the wind and SST gradient are aligned.

Further testing this and other aspects of the ocean–atmosphere interaction in the eastern tropical Pacific requires *in situ* measurements to supplement the satellite data, which don't sample the vertical structure of the atmospheric boundary layer or the exchange of heat between air and sea. As part of a program known as the Eastern Pacific Investigations of Climate (EPIC), plans are under way to monitor the air–sea interaction in and around the cold tongue with buoys, ships, and aircraft. "If we don't have a huge El Niño warm event next year, we may get some useful data," says Chelton's Oregon State colleague Steve Esbensen.

The QuikSCAT–TRMM study has implications beyond the tropical Pacific. The conditions that give rise to the cold tongue and its tropical instability waves also occur in the eastern tropical Atlantic. Moreover, better quantifying the wind-stress–SST correlation will also help climate dynamicists improve their models of phenomena, such as the El Niño/Southern Oscillation (ENSO). "This result is significant," says UCLA's David Neelin, "because we want to model the transfer of momentum into the surface layer and then into the ocean as accurately as possible."

The work could also lead to a better explanation of the cold tongue phenomenon and ENSO. Chelton notes that the structure of the cold tongue is strikingly similar to the structure of the wind-stress curl field, and suspects that the two reinforce each other, causing the cold tongue to last longer than its warm-phase counterpart. "And because the La Niña phase of ENSO is essentially an amplification of the cold tongue season," speculates Chelton, "the cold tongue–curl relationship could have implications for the persistence of La Niña relative to El Niño and quiescent phases."

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