A Frontal Challenge for Climate Models

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These edge states always propagate in one direction (and for that, they are called "chiral") as a result of combination of the Lorentz force and the confining potential in the edge of the sample. Chirality allows currents to propagate large distances coherently. However, this is not the case in the experiments of Abanin *et al*. because the magnetic fields used are not large enough to produce coherent quantized levels. Nonlocal transport can also occur in systems with long-range order due to electron-electron interactions, such as charge density waves and superconductors. In those cases, the state of the many-body system is coherent over macroscopic scales and the electrons behave cooperatively. However, no such long-range order has ever been detected in graphene.

What Abanin *et al*. advocate as the reason for this anomalous behavior is the unusual physics that occurs at the so-called Dirac point [the point where the cones meet (see the figure, lower inset)] in the presence of a magnetic field. At this particular point, graphene is electrically neutral and its electrical resistance is high. However, small magnetic fields can produce charges with well-defined spin that points either up or down relative to the applied field. As a consequence, the Hall resistance of graphene (the ratio of the Hall voltage to the applied current) close to the Dirac point suffers a large change, and spin-up and spin-down currents are produced in opposite directions (see the figure). Thus, we are faced with a very unusual situation in which the charge of the electron still behaves incoherently (and hence, classically) but its spin behaves coherently (and thus, quantum mechanically). A similar effect occurs in metals and semiconductors with strong coupling between the spin and orbital degrees of freedom of the electrons (*6*). However, in ideal, flat graphene (as the ones supported in boron nitride), the spin-orbit coupling is too weak. In the presence of ferromagnetic contacts (*7*), one would be able to use this effect at room temperature and macroscopic distances for new graphene-based spintronics in 2D, with the electron spin as the quantum degree of freedom. This discovery adds a new chapter to the rich history of graphene.

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OCEAN SCIENCE

A Frontal Challenge for Climate Models

An unusually detailed portrait of an ocean front off Japan could help improve climate predictions.

Raffaele Ferrari

The ocean surface is filled with a convoluted web of "fronts" that separate waters of different temperatures and salinities (see the figure). Just as thin ducts in the lung called alveoli facilitate the rapid exchange of gases when breathing, fronts are the ducts through which heat, carbon, oxygen, and other climatically important gases enter into the deep ocean. A lack of observations, however, has hampered progress in understanding the dynamics of fronts, which can be as narrow as hundreds of meters and as wide as tens of kilometers. Global satellite measurements of ocean-surface velocities and air-sea fluxes, for instance, are only available at resolutions of a few hundred kilometers. Although shipboard researchers can sample vertical ocean profiles down to centimeter scales, only rarely do they collect profiles that are less than 100 km apart. On page 318 of this issue, D'Asaro *et al*. (*1*) present a breakthrough in observing ocean fronts, providing direct observations of the workings of the Kuroshio front off Japan on scales from kilometers to millimeters. This detailed and wide-ranging portrait was made possible by the development of towed instruments that continuously sample the waters behind a steaming ship, the deployment of freely drifting instruments that follow ocean currents, and the exercising of a great deal of ingenuity in keeping all these tools along the front for a few weeks in 2007.

The convergence of waters at an ocean front can result in water masses sinking rapidly, at rates of 10 to 100 m/day, compared to typical rates of 1 to 10 m/day in the rest of the ocean. These rapid vertical velocities may be key in determining the exchange rate of heat, carbon dioxide, and other gases between the atmosphere and the deep ocean. Fronts, however, are an important element of the ocean-atmosphere coupled climate system, and in efforts to predict the response of climate to anthropogenic activities, such as the burning of fossil fuels. Currently, however, ocean models used for climate studies are based on grids that are coarser than the typical widths of fronts because of computer speed limitations. Although these models can be tuned to reproduce the collective effect of fronts in the present climate, their capability to predict the impact of fronts on future climate is unknown. We are essentially running models of the ocean lungs that do not include alveoli.

Recent work on the stability of fronts seems to indicate that air-sea exchange at fronts is short-lived. The evidence suggests that the exchange is strong when the front first forms, but is suppressed a short time later, when the front becomes unstable. In satellite images, the instability appears as a meander in the front (see the bottom left of the figure); it pushes waters from the light (warm) side of the front over waters on the dense (cold) side (*2*, *3*). The resulting buoyant layer of warmer, lighter water on top of the front is very stable and suppresses any vertical transport, effectively closing the exchange pathway with the atmosphere. This scenario is observed when the atmospheric forces that influence ocean fronts (atmospheric forcing), such as winds, heat loss, or evaporation, are weak. In contrast, D'Asaro *et al*. show that when the atmospheric forces are strong, the exchange pathway remains open. This is because small-scale turbulence develops that mixes heat and gases across the buoyant surface

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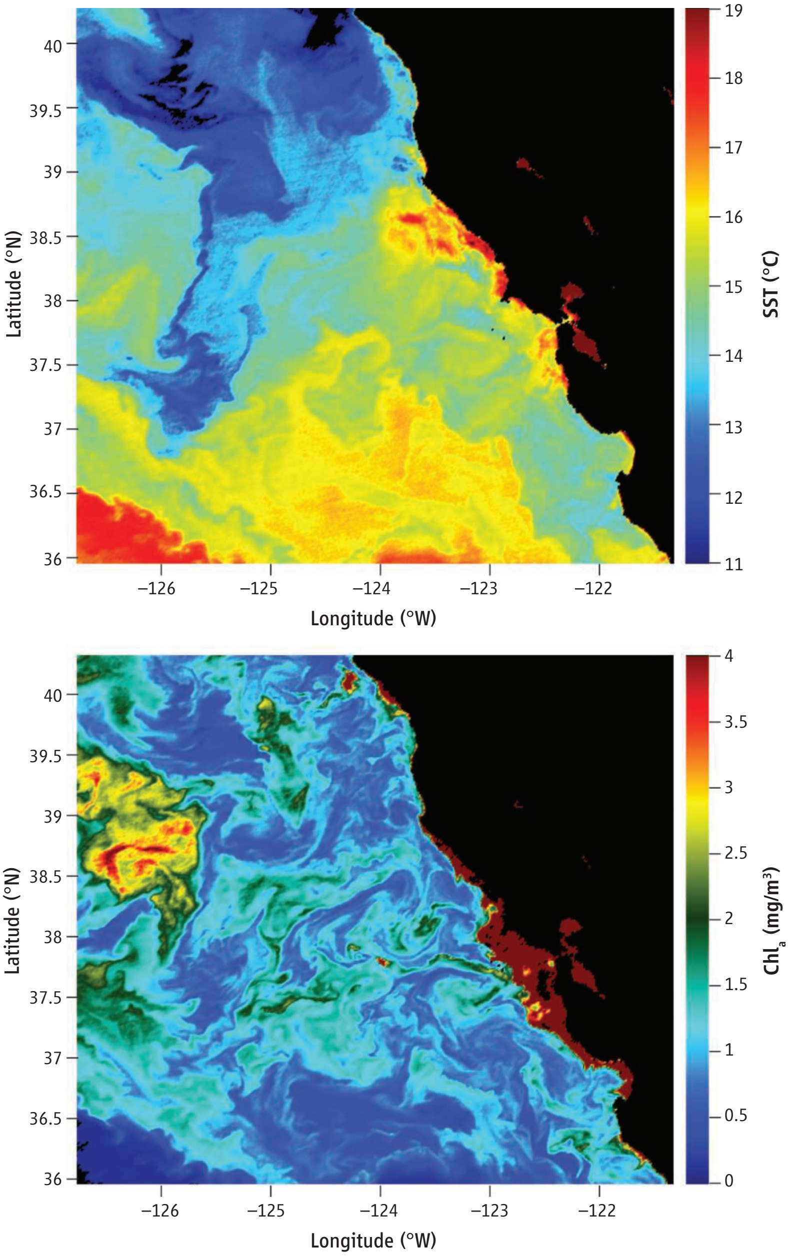
layer. The onset of strong small-scale turbulence at forced fronts has also been observed in numerical simulations (*4*). So, in a sense, the ocean takes a deep breath every time the winds or surface heat losses are strong.

The generation of small-scale turbulence at oceanic fronts has important implications for global ocean circulation and how the ocean dissipates energy. The ocean is set into motion at global scales by atmospheric winds. The large-scale ocean currents then break into eddies with scales of hundreds of kilometers. If the ocean is to achieve equilibrium, the energy must be converted into heat and radiated back to space (*5*). Ocean eddies are strongly constrained by Earth's rotation, however, and they transfer little energy to smaller-scale motions. Energy dissipation is confined either to the eddy's top, where fronts develop and become unstable, or to the eddy's bottom boundary, where dissipation is generated by topographic corrugations (*6*).



To the front. Sea-surface temperatures (SST) (**top**) and chlorophyll concentrations (**bottom**) highlight ocean fronts off the California coast as measured by the MODIS instrument operating on the NASA Aqua spacecraft on 6 October 2002.

CREDIT: JOHN TAYLOR/DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCES, MASSACHUSETTS INSTITUTE OF TECHNOLOGY FROM MEASUREMENTS COLLECTED 6 OCTOBER 2002 BY THE MODIS INSTRUMENT OPERATING ON THE NASA AQUA SPACECRAFT

D'Asaro *et al.*'s observations may help solve this puzzle of where energy is dissipated. They report that at the Kuroshio front, the energy dissipation resulting from frontal instabilities peak at 10 times the mean work done by the winds to maintain the front. These high dissipation rates are, however, of short duration and occur probably 1% of the time. The implication is that only 10% of the energy input into the ocean over a year is lost through frontal instabilities—more quantitative estimates confirm this result. Extrapolating to the global ocean suggests that most dissipation occurs when eddies rub against topographic features on the sea floor, and that these areas become the graveyard of ocean energy. This extrapolation is uncertain and is offered mostly to challenge readers to improve it.

Biogeochemically, fronts shape the physical and chemical environment for ocean ecology and carbon uptake on scales of kilometers. Phytoplankton are at the base of the ocean ecosystem and can grow only in the euphotic layer, the upper 10 to 100 m of the ocean that receive sufficient light for photosynthesis. However, phytoplankton also need nutrients (nitrogen, phosphorus, inorganic carbon), which are abundant only a few hundred meters below the surface. Fronts, with their strong vertical velocities (*7*), can lift nutrients into the euphotic layer and enhance the productivity of the ocean. They can also increase light exposure by modulating the rate at which phytoplankton is mixed below the euphotic layer. Satellite images of phytoplankton abundance, inferred from ocean color, show that fronts are regions of enhanced growth (see the figure).

Given the importance of frontal physics for ocean dynamics and biogeochemistry, how are we going to make substantial progress in understanding and quantifying the effect of fronts on the global climate system? Two upcoming observational programs provide hope. The first campaign is funded by the U.S. Office of Naval Research. Over the next 2 years, it will deploy an impressive array of instruments along the Gulf Stream front off the east coast of the United States and will make detailed physical measurements on scales ranging from hundreds of kilometers down to millimeters. The second campaign, the Surface Water Ocean Topography mission planned by NASA, is more ambitious and involves measuring sea-surface height from space, using techniques that will provide a 1-cm accuracy over a distance of 10 km. Klein *et al.* (*8*) suggest that, at this resolution, sea-surface height can be used to reconstruct global maps of the vertical velocities associated with major fronts and to provide the first global assessment of frontal physics in the ocean.

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