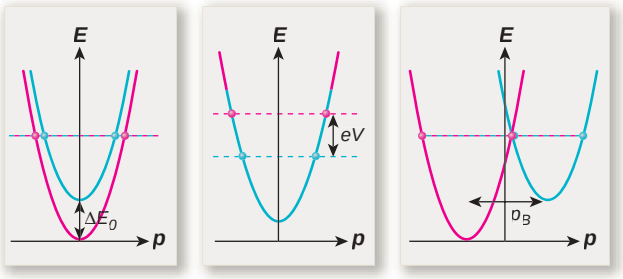
the horizontal momentum direction by p_B. Shifting of dispersion curves in momentum direction by tuning the magnetic field enables their crossing and concomitant current flow (second figure, right panel).

In the double-wire system, voltage bias and perpendicular magnetic field thus turn into convenient experimental knobs for shifting the dispersion curves of the wires in energy and momentum direction, respectively. By recording the voltage and magnetic field for resonant-tunneling conditions, one can obtain a direct image of the electronic excitation spectrum, even when electrons in the two wires interact. Similar momentum-selective tunneling studies were used earlier to investigate spectral properties of two-dimensional electron systems (*6*) and to image electronic wave functions in quantum dots (*7*).

For one-dimensional systems, theory predicts (*8*) drastic changes of the excitation spectrum due to electron-electron interactions. Auslaender *et al.* observe signatures of that. For example, a characteristic broadening of dispersion-curve images at low excitation energies may originate from a truly exotic interaction effect: spin-charge separation. Momentum-resolved tunneling is ideally suited for observing the expected fractionalization of electrons into independent charge and spin degrees of freedom, which, under ideal conditions, would reveal itself in a distinct doubling of tunneling resonances. Further investigations at lower temperature are needed to unambigously attribute the broadened feature to spin-charge separation.

As fabrication technology progresses at a breathtaking rate, we can expect many more intriguing applications of momentum-resolved tunneling techniques. We may look forward to seeing the results of a momentum-resolved spectral probe of quantum-Hall edge excitations (*9*) and the realization of a proposed spin-filtering device that operates without ferromagnets and magnetic fields (*10*). Momentum-resolved tunneling will continue to serve us in the future as a powerful spectroscopic tool. It may also become the basis for interesting device applications.



Tuning momentum-resolved tunneling. (**Left**) Parabolic dispersion curves giving energy E as function of momentum p for noninteracting electrons in the two wires making up the double-wire tunneling device. The highest energy at which electrons exist in the wires is indicated by broken lines. (**Middle**) A finite voltage bias V introduces a relative shift of the two parabolas in the E direction by an amount eV. Shown is the resonant situation $eV = \Delta E_0$, where both parabolas overlap, enabling electrons to tunnel and conserve energy and momentum simultaneously. (**Right**) Momentum-resolved tunneling can also be enabled by a magnetic field B, which shifts dispersion curves in the p direction by an amount p_B proportional to B.

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PERSPECTIVES: CLIMATE CHANGE

Tropical Surprises

Dennis L. Hartmann

Earth's climate fluctuates on various time scales, from interannual variations such as El Niño to glacial cycles with time scales of tens of thousands of years. In the global warming debate, knowledge of fluctuations on time scales of decades is particularly important for the detection of climate change and its attribution to natural or human causes. However, relatively little is known about the mechanisms that cause climate variations on these time scales.

Two reports in this issue demonstrate just how little we know. On pages 841 and 838, Wielicki *et al.* (*1*) and Chen *et al.* (*2*) report surprisingly large decadal variations in the energy budget of the tropics. The observations are not easily explained with existing climate models. They may be important for understanding climate stability and predicting the response of climate to human influences such as increasing carbon dioxide concentrations in the atmosphere.

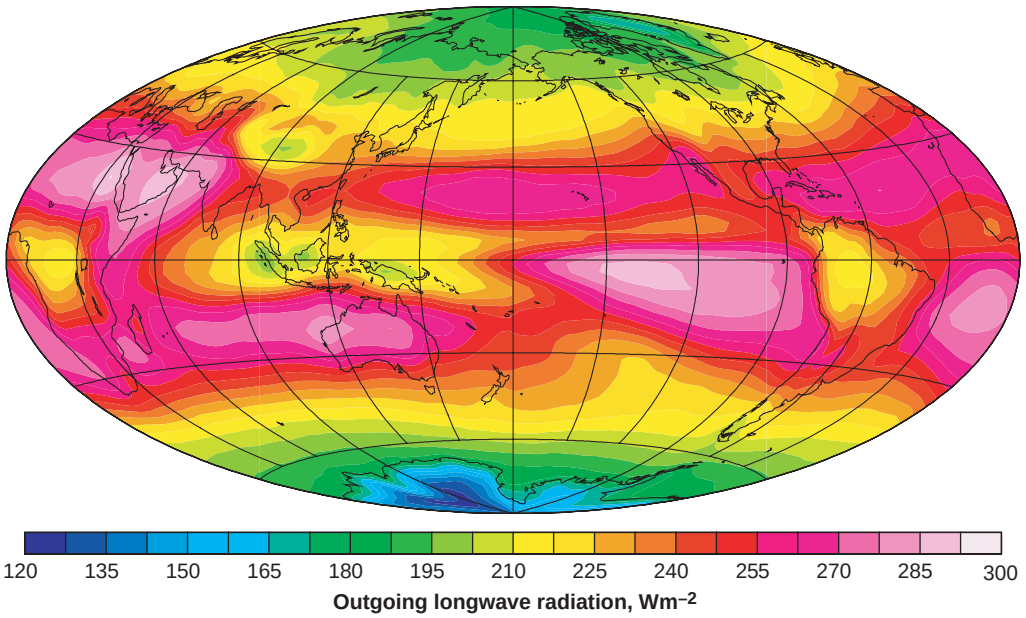
Earth's internal sources of energy are small compared with the energy provided by the Sun. The climate system is therefore in equilibrium when the solar energy absorbed by Earth is balanced by the thermal infrared energy emitted to space from Earth. The relationship between Earth's surface temperature and its energy exchange with space is controlled by the atmosphere. Greenhouse gases such as water vapor and carbon dioxide allow solar radiation to reach Earth's surface but inhibit the transmission of infrared emission from surface to space. Clouds increase the reflection of solar radiation, leading to a cooling of the surface, but also reduce infrared emission to space, thereby warming the surface (*3*). The effects of clouds on the solar and infrared energy fluxes thus tend to partially cancel each other. For tropical convective clouds, this cancellation is often nearly perfect (*4*, *5*).

The carbon dioxide concentration in the atmosphere is expected to double before the end of the 21st century, primarily as a result of coal, oil, and natural gas burning. Surface temperatures are likely to rise as a result, but projections of future climate remain highly uncertain, not least because it is unclear how water vapor and clouds will respond to changes in climate (*6*).

Water vapor is the most important greenhouse gas in the atmosphere and is likely to increase global warming. Its saturation vapor pressure increases exponentially with temperature, resulting in a strong positive feedback between surface warming and a stronger water vapor greenhouse effect.

When water vapor condenses to form cloud droplets, it releases latent heat. This heat drives tropical convection and carries liquid water and ice into the upper troposphere. Evaporation of the cloud water humidifies the atmosphere at high altitudes. Water vapor in the upper tropical troposphere reduces Earth's energy emission

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Energy emission to space. The annual average infrared emission from Earth, also known as the outgoing longwave radiation (OLR), shows large variations in the tropics. Over Indonesia, persistent high clouds with cold tops result in a mean OLR of less than 200 W m^{-2}. In some subtropical regions, the OLR is nearly 300 W m^{-2} because downward motion in the atmosphere suppresses cloudiness and water vapor, thus allowing the emission from the warm surface to escape to space. The Intertropical Convergence Zone is marked by the line of reduced OLR north of the equator in the eastern Pacific. This figure was created with data from the Earth Radiation Budget Experiment for 1986–87.

and has the effect of warming the surface (*7*, *8*). The latent energy of water vapor in surface air increases rapidly with surface temperature, and it is therefore likely that convection will be more intense in a warmer climate.

These climate feedback processes involving clouds and water vapor are potentially stronger in the tropics, where surface temperature is already high. A closer look at the tropical energy budget of recent decades is therefore of particular interest.

Wielicki *et al.*'s measurements indicate (*1*) that the energy budget of the tropics (20ºN to 20ºS) has varied substantially in the past two decades, in association with the eruption of Mount Pinatubo and with warm (El Niño) and cold (La Niña) events in the tropical Pacific Ocean. In addition, they find that during the 1990s, the energy emitted from the tropics increased substantially. The reflected solar radiation decreased by a smaller amount, resulting in a net loss of energy from the tropics relative to earlier years in the record. It is unclear whether these changes represent a long-term trend or are part of a natural fluctuation that will soon reverse itself.

Chen *et al.* (*2*) show that the change in the observed tropical energy budget in the 1990s was associated with a shift in the position and intensity of convection, clouds, and large-scale tropical circulation. Convection, cloudiness, and upward motion decreased in the vicinity of the Indonesian Islands. At other longitudes, convection increased along the Intertropical Convergence Zone, where the trade winds from the Southern Hemisphere meet those from the Northern Hemisphere and intense convection, rainfall, and cloudiness occur. This reorganization of convection was associated with stronger upward motion of air masses near the equator and stronger sinking motion in the subtropics (10º to 30ºN and 10º to 30ºS). Because sinking motion suppresses cloud cover and humidity, the subtropics also experienced increased escape of thermal energy to space and reduced reflection of solar radiation.

Further evidence of changes in the tropics in the 1990s was recently given by Cess *et al.*, whose observations suggest that during the 1998 El Niño, convective clouds produced a negative effect on the energy balance, rather than the neutral effect that had been expected (*9*). Other studies have indicated that the tropical circulation and its relation to global climate have changed on decadal time scales, with El Niño events becoming more frequent and persistent in recent years (*10*).

What causes these changes remains unclear. Some modeling studies suggest that the warm/cold cycle in the Pacific may be intensified by global warming (*11*). On the other hand, observations suggest that decadal variations in the strength and frequency of El Niño events are part of the natural climate variability (*12*).

The decadal shifts in the tropical energy balance observed in (*1*, *2*) may provide insights into how sensitive the climate system is to perturbations. Wielicki *et al.* deduce a change of about 5 W m^{-2} in tropical Earth emission and solar radiation reflection. This change is of the same magnitude as the change in radiative energy balance expected from an instantaneous doubling of atmospheric carbon dioxide. Yet only very small changes in average tropical surface temperature were observed during this time.

The observations also affect our confidence in global climate models. Wielicki *et al.* show that when observed sea surface temperature changes during the last few decades are used as a boundary condition in state-of-the-art atmospheric models, the models do not produce the observed average changes in absorbed and emitted energy in the tropics. It may be that these changes are not directly related to tropical sea surface temperatures, but it seems more likely that the models are deficient.

It is of great interest that the tropics can undergo substantial changes of emitted radiation over the course of a decade, apparently as a result of a reorganization of the spatial distribution of circulation and clouds in the tropics, while average surface temperature changed little. If the energy budget can vary substantially in the absence of obvious forcing, then the climate of Earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models.

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