study whether REV-ERBα–dependent regulation contributes to the transcriptional regulation of phosphoenolpyruvate carboxykinase and glucose 6-phosphatase genes in *Rev-erbα*–deficient mice.

At first glance, the studies by Dodd *et al*. and Yin *et al*. appear unrelated. However, they propose that both plant and animal clocks possess a mechanism for implementing cellular signaling or redox status in the fine-tuning of daily transcriptional regulation. Thus, a common theme emerges in which small molecules provide feedback mechanisms between the circadian clock network and clock-controlled metabolic pathways to maintain metabolic homeostasis.

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ATMOSPHERIC SCIENCE

Resolving an Atmospheric Enigma

Data and modeling are helping to explain what drives an important atmospheric oscillation in the tropics.

Dennis L. Hartmann and Harry H. Hendon

In 1971, meteorologists Roland Madden and Paul Julian studied weather data from near-equatorial Pacific islands. To their surprise, tropospheric winds, pressure, and rainfall oscillated with a period of about 40 to 50 days (*1*). The oscillation in clouds and precipitation tends to be confined to the tropical Indian and Pacific oceans, but the oscillation in winds and pressure is felt throughout the tropics (see the figure). The search for a single robust theory for this Madden-Julian Oscillation (MJO) continues today.

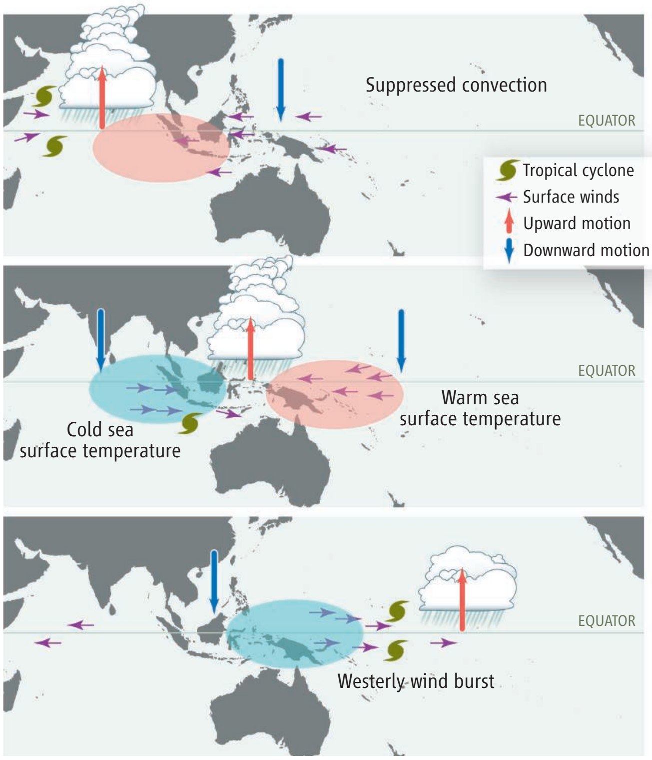
The MJO is not a true oscillation, in the sense that its period varies and its appearance is episodic, but it is the largest source of tropical weather variability on subseasonal time scales, especially in the Indian and Pacific oceans. On page 1765 of this issue, Matthews *et al.* (*2*) use observations from the new Argos system of profiling floats to reveal the deep-ocean response to the MJO. Also in this issue, Miura *et al*. on page 1763 report an advance in modeling the MJO (*3*).

Because of its large amplitude and long period, the MJO affects many people. It causes prolonged dry and wet episodes during the Asian Summer Monsoon and modulates the intensity, frequency, and location of tropical storms in the Indian, Pacific, and Atlantic oceans (*4*, *5*). The strong and persistent surface winds associated with the MJO drive a large response in the upper ocean (*6*). Matthews *et al.* have measured the deep ocean response to wind surges associated with the oscillation. It is as yet unclear what effect this has on the deep ocean. The MJO also influences the onset and intensity of El Niño events and may underlie the very existence of the El Niño–Southern Oscillation (*7*).

In climate models, the MJO is typically weaker and moves faster than is observed. Weather prediction models cannot sustain the MJO. Coupled ocean-atmosphere models tend to produce more realistic simulations, because the MJO interacts strongly with the upper ocean, but this coupling is not essential for the existence of the oscillation (*8*, *9*).

Observations show that a wide range of scales interact within the MJO, ranging from the scale of individual convective cells a few kilometers across and a few hours in duration to the 10,000-km planetary scale of the 40- to 50-day variation (*10*). Similar to a hurricane but on a much larger scale, the release of latent heat in moist convection drives the planetary-scale wind variations of the MJO. The planetary wind variations in turn provide organization to the convective-scale phenomena, suppressing convection in some regions and enhancing it in others.

Because the MJO arises from the interaction of convective and planetary scales, it serves as a probe into our ability to understand and model the interaction of convection and clouds with climate. This interaction remains one of the largest uncertainties in climate projections (*11*). The inability to properly simulate the MJO indicates inaccurate treatment of the interaction between the scale of convection—perhaps 1 km or



The Madden-Julian Oscillation. Precipitation first develops in the Indian Ocean and moves eastward with a speed of about 5 m s^{-1}. Surface winds converge under the convection, and a burst of eastward surface winds follows the passage of the heaviest rainfall. This burst is an important driver for ocean dynamics. Each panel is separated by ~15 days.

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less—and the resolved scales of global models, which currently have grid points separated by ~25 km for global weather forecasting models and ~100 km for climate models.

Miura *et al.* use a global model in which the horizontal grid spacing is 7 km. To perform their simulation they used the Earth Simulator, a Japanese supercomputer developed for running more realistic global simulations (*12*). In the simulation, the MJO appears to be sustained with realistic structure over a period of 1 month. This result suggests that a transition to more realistic behavior may occur for grid spacing as large as 7 km, rather than 1 km.

Increasing the resolution of weather prediction models to 7 km would require an increase in computing power of about a factor of 100, which might be achieved in less than a decade. Thus, increasing the spatial resolution of operational models may provide a brute-force solution to a critical problem in weather and climate research. In the near term, tools such as the Earth Simulator should be used to better understand the scale interactions that underlie the MJO.

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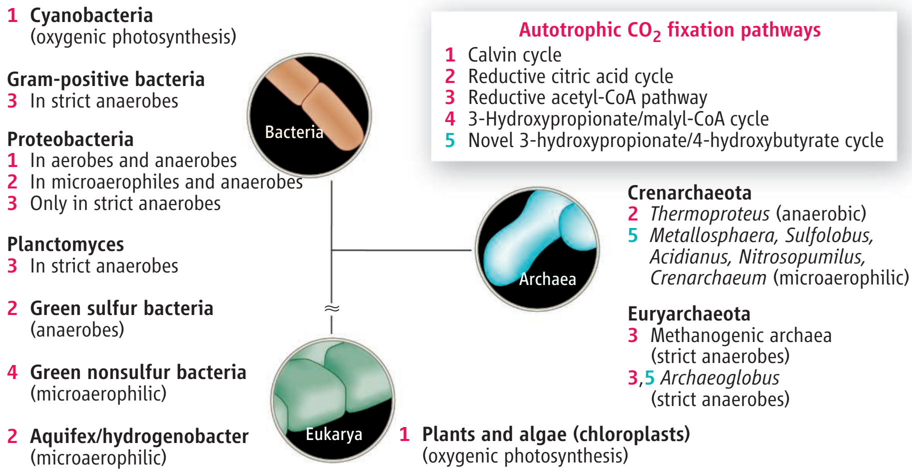
MICROBIOLOGY

A Fifth Pathway of Carbon Fixation

Genome sequence analyses and enzymatic studies reveal a novel CO_2 fixation cycle in some autotrophic archaea.

Rudolf K. Thauer

Autotrophs are organisms that can grow using carbon dioxide (CO_2) as their sole source of carbon. Among them are plants, algae, cyanobacteria, purple and green bacteria, and also some bacteria and archaea that do not obtain energy from light. Autotrophs generate the biomass on which all other organisms—including humans—thrive. They also play an important role in Earth's nitrogen and sulfur cycles. Four mechanisms are known by which autotrophic organisms fix carbon (see the figure). On page 1782 of this issue, Berg *et al.* (*1*) describe a fifth autotrophic CO_2 fixation pathway in archaea that may have been used by some of the earliest organisms on Earth.



A novel pathway of CO_2 fixation found by Berg *et al.* (*1*) in Archaea. Four other pathways are known by which autotrophic representatives of Bacteria, Archaea, and Eukarya fix carbon.

The first autotrophic CO_2 fixation pathway was elucidated by Calvin about 50 years ago (*2*). In this pathway, CO_2 reacts with a five-carbon sugar, yielding two carboxylic acids, from which the sugar is regenerated in a cyclic process. The Calvin cycle operates in plants, algae, and cyanobacteria (which all perform oxygenic photosynthesis) and in autotrophic proteobacteria, some of which do not tolerate oxygen (anaerobes). The key enzyme of the cycle—RuBisCO (*3*)—is also found in several other bacteria and some archaea, but these either lack another enzyme crucial for the cycle and/or there is no evidence for autotrophic growth.

In 1966, Evans *et al.* proposed that the green sulfur bacterium *Chlorobium* uses a second cycle for autotrophic CO_2 fixation (*4*). It took until 1990 until all the details of this reductive citric acid cycle were worked out (*5*). The cycle also operates in several other groups of bacteria and archaea. Because it involves enzymes that are sensitive to oxygen, this cycle is only found in anaerobes or in organisms that tolerate oxygen only at levels below those found in air (microaerophiles). At the beginning of the 1980s, a third pathway of autotrophic CO_2 fixation was found in certain Gram-positive bacteria and methane-forming archaea. In these organisms, one CO_2 molecule is reduced to CO and one to methanol (bound to a carrier); subsequently, acetyl–coenzyme A (CoA) is synthesized from CO and methanol (*6*). This reductive acetyl-CoA pathway is also found in several other bacteria and archaea. It involves one of the most oxygen-sensitive enzymes known and is thus only found in strict anaerobes.

The fourth pathway was discovered in the green nonsulfur bacterium *Chloroflexus*. Here, CO_2 fixation starts with the carboxylation of acetyl-CoA; the CO_2 acceptor is then regenerated in a cyclic process, with 3-hydroxypropionate and malyl-CoA as characteristic intermediates (*7*). The 3-hydroxypropionate/malyl-CoA cycle appears to be restricted to *Chloroflexus* species. None of the enzymes involved in this cycle are inherently sensitive toward oxygen; one of them is sensitive to ultraviolet-A light, which, however, does not reach the ecological niches in which the green bacteria thrive.

The novel autotrophic CO_2 fixation pathway described by Berg *et al.* has some of the same intermediates as the 3-hydroxypropionate/malyl-CoA cycle. Succinyl-CoA is also formed from acetate and 2 CO_2 mol-

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