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lished previously is 5.5 Å. In electron density maps in that resolution range, nucleic acid helices look like curved ribbons whose constituent nucleotides are often difficult to delineate, and protein density is hard to interpret at all. Nevertheless, a great deal was learned from those electron density maps because relevant structures that had been solved at higher resolution before could be fitted into them. The problem with the 70S model that emerged is that wherever its structure deviated from that of the structures being fit into its electron density maps, it was difficult to be sure what was going on. In 3.5 Å resolution electron density maps, such as those that led to the 70S *E. coli* structure reported by Schuwirth *et al.*, these ambiguities disappear because individual nucleotides are clearly visualized, and protein electron density is independently interpretable.

What has been learned? The structures presented by Schuwirth *et al.* are not the last word about the information contained in the particular crystals examined. Ribosomal proteins are not fully modeled at this point,

and the structures are not fully refined. In addition, the crystals analyzed by Schuwirth *et al.* lack transfer RNAs or any of the other proteins, nucleic acids, or small molecules that interact with the ribosome during protein synthesis. Nevertheless, several themes clearly emerge. The structures of the bridges that hold the two subunits together are clear, which is important because the bridges are critical functionally: The two subunits of the ribosome not only communicate during protein synthesis, they also engage in coordinated, relative motions (8). In addition, the two 70S structures reported by Schuwirth *et al.* differ in the orientation of the head domains of their small subunits, and in neither is the head domain position the same as it is in the *T. thermophilus* 70S ribosome structure now available (7). Movements of the small subunit's head domain like the ones reported by Schuwirth *et al.* occur during protein synthesis [e.g., (8)]. It is now possible to understand how these motions occur at the molecular level, and to propose models for

how they might be coupled to the events of protein synthesis. It remains to be seen what the small differences in conformation between the large ribosomal subunit of these *E. coli* ribosomes and the large ribosomal subunit structures of other organisms actually mean. Thus, the ribosome structures obtained by Schuwirth *et al.* really do advance our understanding of protein synthesis. Now that high-quality crystals are available for the *E. coli* 70S ribosome, the rate at which new information is obtained should increase.

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## ATMOSPHERIC SCIENCE

# Water Vapor Feedback in Climate Models

Robert D. Cess

General circulation models (GCMs) are the most detailed computer simulations available for projecting climate change caused by increasing greenhouse gases, as well as other anthropogenic changes. These numerical models contain numerous parameterizations of physical processes occurring within the climate system (that is, small-scale processes have to be described within the models). As a result, there is a need to devise ways of testing these parameterizations and processes within GCMs. On page 841 of this issue, Soden *et al.* (1) report an important reality check on one such process: the role of atmospheric water vapor in climate change.

It has long been known (2) that cloud-climate interactions constitute a major uncertainty in attempting to project future climate change with a GCM. As an illustrative example, if global cloud cover were to decrease because of climate warming, then this decrease reduces the infrared greenhouse effect due to clouds. Thus, the

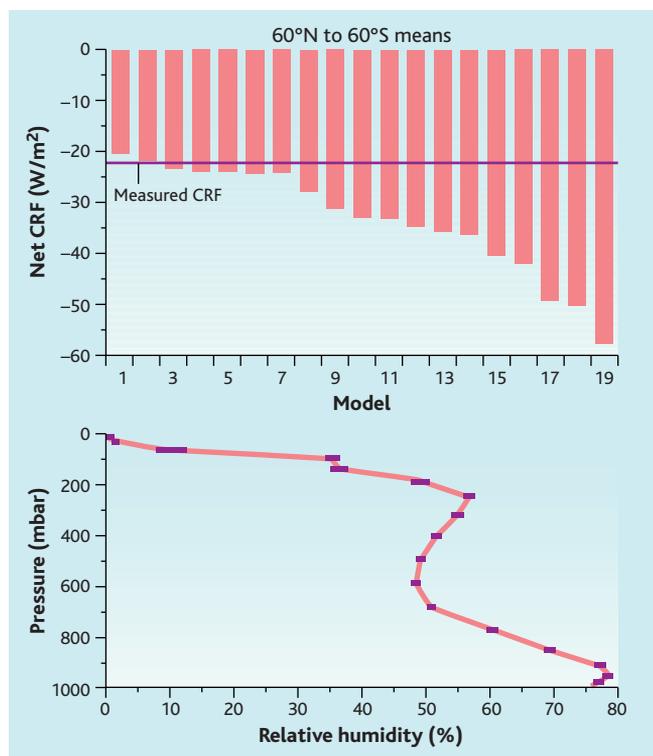
climate system is able to emit infrared radiation more efficiently, moderating the warming and so acting as a negative feedback mechanism. But there is a related positive feedback in this example that would increase the warming: The solar radiation absorbed by the climate system increases because the diminished cloud cover causes a reduction of reflected solar radiation by the atmosphere.

The situation is actually far more complicated than in this simple example, because changes in cloud cover will undoubtedly depend on cloud type and geographical location. Moreover, there would likely be associated changes in cloud altitude and cloud optical depth. One test of cloud-climate interactions within a GCM is to determine, relative to satellite observations, how well a GCM represents the radiative impact of clouds on the model's climate during the 5 years encompassing 1985 to 1989, and the top panel of the figure demonstrates that many models do rather poorly in this respect. And with regard to those models that do agree well with Earth Radiation Budget Satellite observations, it must be emphasized that this test is a necessary, but not sufficient, test of a model.

Another feedback mechanism is water vapor feedback. Water vapor is the atmosphere's dominant greenhouse gas, and a change in its concentration associated with a change in climate would alter the greenhouse effect of the atmosphere, thus producing a feedback mechanism. In 1967 it was proposed (3) that the atmosphere might conserve its relative humidity, and if so, this would lead to a positive feedback because a warmer atmosphere would contain more water vapor, thus amplifying the warming. And indeed, GCMs do tend to conserve global mean atmospheric relative humidity, as is shown for one such model in the bottom panel of the figure. But for more than a decade there has been considerable debate on this issue, with suggestions that water vapor feedback might actually be a negative feedback mechanism.

Soden *et al.* (1) present a very clever way of testing one aspect of water vapor feedback. As they point out, observed moistening trends in the lower troposphere have been linked to corresponding changes in surface temperature. But attempts to observe a moistening trend in the upper troposphere have proven to be unsuccessful, and this is the issue that Soden *et al.* address. They accomplish this by using clear-sky satellite radiance measurements from the High Resolution Infrared Radiometer Sounder channel centered at 6.7 μm (channel 12), which measures a portion of the 6.3-μm water vapor absorption band and therefore is sensitive to water vapor in the upper troposphere. They then compare the channel 12 observations of global mean blackbody temperature, for the

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period January 1982 to December 2004, to those computed from the temperature and moisture profiles of the Geophysical Fluid Dynamics Laboratory atmospheric GCM, which uses prescribed sea surface temperatures. The temporal trends of the observed and modeled channel 12 observations are in very good agreement, and this agreement

persists when the GCM results are repeated with the assumption of constant atmospheric relative humidity. On the other hand, there is considerable disagreement with the channel 12 observations when the GCM results are repeated by assuming no change in the water vapor content of the

upper troposphere. Soden *et al.* then use additional satellite observations to emphasize that global mean relative humidity is being conserved by the upper troposphere in response to atmospheric warming. This work by Soden *et al.* provides the clearest evidence yet that GCMs are properly representing water vapor feedback.

**Cloudy predictions.** (Top) Actual effect of clouds on climate (measured CRF) compared to the effect predicted by 19 global climate models. Some of the models significantly overestimate cloud-induced cooling. Clouds can potentially cool climate (by reflecting solar radiation) and simultaneously heat the system (by increasing the atmospheric greenhouse effect). The net effect illustrated in the figure is cooling, as indicated by the negative values of CRF. Actual net CRF (cloud-radiative forcing), measured by the Earth Radiation Budget Satellite (4) and averaged from 60°N to 60°S, is  $-22 \text{ W/m}^2$ . (Bottom) Average relation between atmospheric pressure and humidity for a 120-year (1870 to 1989) simulation of global warming. The profile is an average of 120 annual mean profiles; the bars represent two standard deviations, indicating that global mean atmospheric relative humidity is conserved over the entire 120-year period. The simulation is from the National Center for Atmospheric Research Community Climate System Model Version 1 (6).

persists when the GCM results are repeated with the assumption of constant atmospheric relative humidity. On the other hand, there is considerable disagreement with the channel 12 observations when the GCM results are repeated by assuming no change in the water vapor content of the

This is an important contribution because it eliminates one potential uncertainty within these climate models. There remains, however, an uncertainty in other climate feedback mechanisms, the most notable of which is cloud feedback as described above. The reduction of these uncertainties will require a suite of cleverly designed necessary, but not sufficient, tests of the models.

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## CHEMISTRY

# Building a Quintuple Bond

Gernot Frenking

**B**ond order and the division of chemical bonding into single or multiple bonds are among the most fundamental concepts in molecular chemistry. Elements in the main group of the periodic table may have up to three bonds to the same bonding partner (that is, the maximum bond order can only be three). It was long believed that this is the highest bond order that can be achieved in a stable molecule. Because of this conventional wisdom, the 1964 report by Cotton *et al.* (1) on the synthesis of a molecule with bond order four caused a sensation. The analysis of transition metal salt compounds containing the anion  $[\text{Re}_2\text{Cl}_8]^{2-}$  revealed a quadruple bond

between the rhenium atoms. This finding opened the door to a new field of chemistry and led to the synthesis of a large number of hitherto unknown molecules with multiple bonds having bond orders up to four between transition metal atoms (2). It has been speculated that a further extension to bond order five should in principle be possible, but attempts to make a compound with a quintuple bond have been unsuccessful until now. On page 844 of this issue, Nguyen *et al.* (3) report the synthesis of a stable compound with fivefold bonding between two chromium atoms (see first figure on the following page).

Chemical bonding between two atoms is usually discussed in terms of bonding and antibonding combinations of the valence atomic orbitals (AOs) that yield molecular orbitals (MOs). The pivotal AOs of the transition metal atoms are the five d

orbitals. The figure shows schematically the combination of the d-AOs that give five components for the bonding MOs ( $\sigma$ ,  $\pi$ ,  $\delta$ ) and five components for the antibonding MOs ( $\sigma^*$ ,  $\pi^*$ ,  $\delta^*$ ). The diagram also qualitatively indicates the expected ordering for the energy levels of the orbitals. A quintuple bond between two transition metals requires that 10 electrons occupy the lowest lying MOs. This yields one  $\sigma$  bond, one degenerate  $\pi$  bond, and one degenerate  $\delta$  bond (that is, the  $\pi$  and  $\sigma$  bonds each have two levels with the same energy). Transition metal compounds like  $[\text{Re}_2\text{Cl}_8]^{2-}$  with a quadruple bond have only one (not degenerate)  $\delta$  bond. Theoretical analysis (1) showed that the  $d_{x^2-y^2}$  AOs that form the second component of the  $\delta$  bond (see the figure) interact primarily with ligand orbitals such as the chlorine AOs in  $[\text{Re}_2\text{Cl}_8]^{2-}$ . All previous attempts to synthesize a molecule with the general formula  $L_n\text{TM-TML}_n$  (where L is ligand, TM is transition metal) in which the  $d_{x^2-y^2}$  AOs of TM engage in the "missing" fifth metal-metal bonding rather than in TM-L bonding have failed.

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