[Reprinted from BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, Vol. 71, No. 10, October 1990]
Printed in U. S. A.

Greenhouse warming and the tropical water budget

In "Some Coolness Concerning Global Warming" (March 1990), Lindzen has raised an important climate issue: how well do we understand the water budget of the tropics? Water vapor is the major absorber in the infrared contributing to the greenhouse effect. It is not always considered a "greenhouse gas" because its concentration is controlled on timescales of order a week by convective, radiative and dynamical processes in the atmosphere; while the other greenhouse gases (such as CO_2, CH_4, and the CFCs) have longer timescales in the troposphere, and their concentration is steadily increasing from anthropogenic activity.

Most theoretical and modeling studies couple the water vapor content of the atmosphere to the temperature, so that atmospheric water vapor increases with increasing global temperature: this gives a major amplification of the warming produced by the more inert greenhouse gases (Ramanathan 1981). Unless there is a major decrease in the relative humidity with increasing temperature, which has not been documented at any level in the troposphere, then the Clausius-Clapyron equation dictates that water vapor increases with temperature. Lindzen (1990) argues that we should explore the possibility that deep convection might dry the upper troposphere. His argument is that as boundary layer temperature and moisture increase with increasing sea surface temperature, the tops of the deep convective clouds in the tropics will go higher to levels that are colder. If then the mean outflow is at colder temperatures, and the clouds precipitate all their cloud and ice water, then the outflow of moisture into the upper troposphere will decrease, because of the decrease of (ice) saturation mixing ratio with temperature. This is important to the greenhouse effect because decreases of moisture at high levels can offset the effect of increases at lower levels.

Clearly we must understand the processes by which water is distributed from the ocean surface into the tropical atmosphere by deep convection. Lindzen's model is a highly over-simplified one of a deep single cell circulation which transports mass between the cloud base near the surface and the upper troposphere. This model was originally proposed by Riehl and Malkus (1958) for the mean Hadley circulation, and incorporated into the simple cumulus parameterization scheme of Arakawa and Schubert (1974), which Lindzen cites. However, we have known since the GATE and MONEX experiments (Yanai 1972; Betts 1978; Houze and Betts 1981; Gamache and Houze 1983), which were designed to study convective systems in the tropics, that this mean picture is incomplete. Tropical convective mesosystems (the so-called "cloud clusters") go through a complex life cycle. They start with a single cell circulation from low to high levels, associated with the growth of cumulonimbi, but then they develop a double cell circulation with ascent above the freezing level in a large mesoscale anvil, and with descent underneath the anvil. This double cell structure is driven by condensation and freezing above, and melting and evaporation of falling precipitation below the freezing level (which in the tropics is near 550 mb in the middle troposphere). The decay of these thick upper-level anvil ice clouds (between 550 and 150 mb) leaves large amounts of water in the upper atmosphere, so that deep convection is the major source of the upper tropospheric moisture. Gamache and Houze (1983) estimated that the water input from the anvil is roughly 10% of the precipitation. This is a water input vastly greater than ice saturation at levels close to the tropopause. Lindzen's model concept of deep tropical clouds, which detrain only near the troposphere at very cold temperatures, after precipitating virtually all their water substance, is an unrealistic oversimplification. It does not consider the life cycle of these deep mesoscale anvil clouds, which are the characteristic feature of satellite pictures of the tropics.

Another clue that the historical single cell model of the tropics is not a complete picture came from the boundary layer studies of Betts and Albrecht (1987), and Betts and Ridgeway (1988). They found that the air sinking back into the top of the CBL over wide regions of the Pacific had *not* sunk unmodified from the upper troposphere, but only from near the freezing level. With radiatively driven subsidence rates of order 40 mb day^{-1}, the air sinking into the top of the CBL (near 800 mb) takes five to six days to sink from the middle troposphere. This is consistent with an advection distance of order 3500 km at 7 ms^{-1}, typical of the wavelength of disturbances in the tropics (Reed and Recker 1971; Thompson et al. 1979). At radiatively driven sinking rates of 30-40 mb day^{-1}, there is insufficient time between disturbances for air to sink unmodified from the upper troposphere. The single cell model may describe the mean Hadley circulation, but it does not describe the trajectories of air parcels, and of moisture associated with the transient cloud clusters.

A further important issue touched on by Lindzen (1990) is the mass and energy circulation in the mean Hadley and Walker circulations, which are primarily coupled to the vertical mass flux in deep convection. How does this change with increasing temperature? Lindzen asserts that the mass flux in the tropical convective clouds increases with warming. It is not obvious that this is correct. Indeed Betts and Ridgway (1989) in a simple model of a closed tropical circulation in energy balance found that the mass circulation *decreases* with increasing temperature. The reason for this is simple. In this model, and probably the real atmosphere, the surface evaporation (plus the much smaller sensible heat flux), which balances the net radiative cooling of the troposphere, increases with the surface temperature at roughly the slope of the Planck function: 6 W m^{-2} K^{-1}. However, the low-level moisture, which is loosely coupled to temperature through the Clausius-Clapyron equation (relative humidity near the surface changes little), increases more rapidly with surface temperature, so that the tropospheric subsidence and the corresponding ascending mass flux actually *decrease* with increasing temperature, although the upward vapor flux at cloud base increases!

Clearly we need studies in many areas. Observational studies of the dependence of upper tropospheric moisture on SST for the different ocean basins and for interannual variations could give us observational insight into the coupling of moisture to temperature. Raval and Ramanathan (1989) have shown a direct link between SST and infrared emisions to space, and by inference column moisture. However we lack good observations of upper tropospheric moisture in the tropics, as Lindzen (1990) points out. This is a key area; perhaps surface-based Raman lidar (Melfi et al, 1989) from a few stations in the tropics could give us this much needed climatology.

The link between water vapor input to the troposphere and cloud cluster lifecycle needs further study. As mentioned above, Gamache and Houze (1983) estimated that about 10% of the surface evaporation is transported into the upper troposphere by deep convection. Does this percentage increase or decrease with temperature? How might cloud precipitation efficiency and life cycle processes change with a small increase of temperature, and the height of the freezing level? Betts & Harshvardhan (1987) showed that the liquid and ice water content of *adiabatic* clouds increases with temperature, also through a link with the Clausius-Clapyron equation. However it is unclear how cloud amount or thickness will change if the climate warms. This remains a major uncertainty where the possibility of feedbacks of either sign exists.

The issue of global climate change is too important for us to wait for this experiment to be played out. There is a great deal of observational and modelling work urgently needed. However, the impact of atmospheric pollution on regional scales and the biosphere is becoming more serious annually. We will not be able to predict with any certainty for decades the impact on a global scale, because of the complexity of the whole earth system. Yet, changing the direction of our industrial society towards one which is more respectful of its impact on our global environment will take time, probably decades, even if we begin now.

Acknowledgments. A. K. Betts wishes to acknowledge the support of the National Science Foundation under Grant ATM90-01960 and the NASA Goddard Space Flight Center under Contract NAS5-30524.

ALAN K. BETTS
RD 2, BOX 3300
MIDDLEBURY, VT 05753

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