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SENATE COMMERCE COMMITTEE MEETING ON ROLE OF CLOUDS IN CLIMATE CHANGE

October 7, 1991

Statement by:

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Subject: **GLOBAL WARMING AND THE TROPICAL WATER BUDGET**

1. Background

I was born and educated in England, with a BA (and MA) in Natural Sciences (Theoretical Physics) from the University of Cambridge in 1967, and a PhD in Meteorology from Imperial College, of the University of London, in 1970. I came to the Department of Atmospheric Science at Colorado State University in 1970 to work on the analysis of a tropical field experiment in Venezuela (VIMHEX: the Venezuelan International Meteorological and Hydrological Experiment), in which I had participated in 1969. I remained on the academic faculty at CSU until 1978, when I moved to Vermont to continue my research work independently. For the past 13 years, I have lived and worked in Vermont, supported by direct grants and contracts from the National Science Foundation and the National Aeronautics and Space Administration.

My research has dealt with atmospheric convection and clouds; their description by observations and theory, and the representation of their energy and water transports in global models, both numerical weather prediction and climate models. In the 1970s my research concentrated on convection in the tropics, and I helped plan and execute the Global Atmospheric Research Program Atlantic Tropical Experiment in 1974 (GATE) (Betts, 1974, Houze and Betts, 1978), as well as a second VIMHEX Experiment in 1972. For this research, I was awarded the Richardson Prize of the Royal Meteorological Society in 1974, the Meisinger Award in 1977 and a Special Award in 1978 by the American Meteorological Society. I co-ordinated the convection research for GATE for the National Academy of Science panel. In the past decade my research has broadened to cover as well the analysis of clouds and convective boundary layer processes over land and the oceans, both in the tropics and mid-latitudes, and the representation of convective processes in global models. I am currently a member of the National Academy panel for the International Satellite Cloud Climatology Project.

2. Water vapour and the climate system

The earth's climate system, which involves not only the atmosphere, but the ocean circulations and the biosphere, is exceedingly complex. As a result of theoretical studies, a global observing system, and the development of computers fast enough to model the global atmosphere at sufficiently high resolution, we have made remarkable progress in our understanding in the past 20 years. Yet our present models are still extremely simple, when compared with the complexity of the real climate system of the earth. As a result our global climate models are only as good as the conceptual components of which they are made.

I wish to discuss the links in the chain between the known global increase of the gases such as CO_2, CH_4 and the CFC's, which are due to anthropogenic activity, and the changes of temperature, water vapour and clouds in the tropics; which in turn primarily control the surface equilibrium temperature of the earth. I will focus my discussion on water vapour: others here will discuss the radiative effects of the clouds themselves. Water vapour is the major absorber in the infrared contributing to the greenhouse effect. Unlike the other greenhouse gases, whose global concentrations are slowly increasing because of anthropogenic activity, the concentration of water vapour is controlled by the transport and precipitation processes in clouds. Generally the water vapour content increases with temperature, because the saturation vapour pressure increases with temperature. In the tropics, water evaporates primarily from the oceans, which are heated directly by incoming solar energy, rises in cumulonimbus clouds (thunderstorms), where it condenses, releasing the latent heat of condensation and freezing. This latent heat release both drives the vertical circulation and balances the net infrared cooling of the atmosphere. The air which flows out of these storms in the upper troposphere is full of ice, which forms the extensive picturesque anvils so characteristic of thunderstorms. In the tropics, clusters of thunderstorms produce extensive anvil clouds, which are readily visible on satellite pictures. These anvils, which are often 400 mb thick, last for many hours, sometimes even a day, since they are maintained by dynamical, convective and radiative processes. As they decay and their ice crystals evaporate, they are responsible for most of the water vapour input to the upper troposphere. Estimates from GATE (Gamache and Houze, 1983) have suggested that up to 10% of the water which is evaporated at the ocean surface is injected into these thick anvils. Away from convective disturbances where air sinks as it slowly cools radiatively, the relative humidity in the tropical upper troposphere is around 30 - 40% up to about 350 mb, where routine rawinsonde measurements become unreliable. At higher levels, the data from the Stratospheric Aerosol and Gas Experiment (SAGE-II) suggest that the relative humidity (away from deep convection) is about 20-25% at 200 mb. The annual variation is small, with higher values on the summer side of the equator.

? Up to 350 mb have rawinsonde above have SAGE data

3. Lindzen's argument

Lindzen (1990) has argued that there is a possibility that deep convection might dry the upper troposphere. This is important because absolute decreases of water vapour at high levels can offset the effect of increases at low levels in their greenhouse effect.

His argument is as follows. *Boundary layer temperature and moisture increase with increasing sea surface temperature, so that the tops of the deep convective clouds in the tropics will go higher.* This is correct. If the temperature at the tropopause falls, then the highest outflows from these clouds will be at colder temperatures. Since the saturation mixing ratio over ice decreases with temperature, Lindzen argues *that the cumulonimbus outflow will therefore inject drier air at the highest outflow level; and then the subsidence of this dry air between clouds will produce a drier upper troposphere.*

X This idea is wrong (Betts, 1990), because deep convective clouds inject water (as ice and vapour) into the upper troposphere at all levels above their freezing level (this is near the middle troposphere in the tropics; about 550 mb), not just at their tops. Near their highest outflow levels, most of this water is in the form of ice (the anvil clouds), so that the comparatively small value of the saturation mixing ratio plays a relatively insignificant role in the water budget at the highest levels. If Lindzen's model were right, the present upper troposphere would be very dry. In fact, the relative humidity near the freezing level in the deep tropics is about 40%. This is consistent with a subsidence of order 20 mb/day (which is roughly in thermal balance with the radiative cooling rate), and the injection of 10% of the surface evaporation as ice into the upper troposphere (mentioned above).

Lindzen's model is implausible on more general grounds. If the sea surface temperature rises in the tropics, the troposphere as a whole is warmed to a higher temperature, so that, at any given pressure, the saturation mixing ratio increases significantly. For the absolute mixing ratio to decrease at any level, the relative humidity must therefore decrease significantly (by 12 - 15% for a 2°C rise in sea surface temperature). The theoretical evidence is to the contrary. If the temperature warms (towards a warmer "moist adiabat") the stability of the atmosphere increases proportionally more than the increase in the radiative cooling rate, so that the mean sinking motion between the convective systems decreases (Betts and Ridgway, 1989). This reduced subsidence would tend to increase (not decrease) the relative humidity at any level (Betts and Albrecht, 1987). In this simple coupled model of Betts and Ridgway (1989), doubling CO_2 increased the tropical surface temperature by 2 to 3°C, consistent with the increase shown by global circulation models.

Clearly, we need better observations of water vapour in the tropical upper troposphere, but the evidence we have is consistent with a relatively tight coupling of water vapour to temperature in which the relative humidity changes rather little.

4. Conclusion

I have concentrated on the role of water vapour in the tropics on the greenhouse effect. It is probable that water vapour, because it is coupled thermodynamically to the temperature, will increase as the temperature of the troposphere increases. This coupling leads to an important amplification of the greenhouse effect, as is shown by both global climatc models (e.g. Cess et al., 1990) energy balance models (e.g. Betts and Ridgway, 1989) and observational studies (e.g. Raval and Ramanathan, 1989). The radiative role of clouds is more complex, and others here will discuss this in more detail.

As a society we have many choices, but one basic dilemma concerning climate change. The waste products of our civilization are significantly modifying the atmosphere, making it more opaque to infrared radiation.* The coupling of temperature and water vapour amplify this effect, while the effects of changes in cloudiness are more complex. Modelling studies suggest that a warming of the atmosphere of several degrees will result if present trends continue. Because of the natural fluctuations of the climate system, it may be a decade or more before we can have confidence that the recent climate warming reflects a long-term trend. Because of the complexity of the earth system, our relatively simple models might mislead us, but again the improvement of our models is a steady incremental process which also takes decades.

* If we wait a decade or two for increased certainty, the climate impact will be much larger, harder to reverse, and the impact on the earth's natural ecosystem may be severe. A wise society would take action now to reduce emissions to the atmosphere, in order to limit and delay the long-term impact on our climate. Much can be done at little incremental cost. The scientific community can present the evidence, but political resolve and global co-operation are clearly needed. 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.

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To give you an indication of Dr. Betts competence and reputation within the meteorological community, I have extracted the following from peer reviews of a recent proposal (now funded) by Dr. Betts, to continue his research into the coupling of the climate with the atmospheric boundary layer.

- In my opinion this work is quite important and should be funded. Betts is well known as a bright and innovative scientist and he is one of the few theoreticians/modelers making contributions in this area.

- The PI has considerably advanced our understanding of the boundary layer and of the coupling of the boundary layer to the upper atmosphere, and his work had given rise to a great deal of the research done by others on these systems.

- The accomplishments of the PI under this grant have been phenomenal. More than 10 papers, covering a wide range of topics from atmospheric convection to coupled oceanic and coupled land processes, were published in the past three year period under this grant. These papers have a major impact in enhancing our fundamental understanding of atmospheric convective processes as well as parameterization in GCMs.

- Dr. Betts is an extremely competent scientist and a world expert on tropical convection. He is an unique individual in his approach to science and management. He interacts widely with a large number of scientists in different research institutions and universities and has been a source of valuable scientific advice and inspiration to all his co-workers.

John Ball