CLIMATE-CONVECTION FEEDBACKS: SOME FURTHER ISSUES

An Editorial Comment

The editorial essay by Shaw et al. (1998) discusses the possible role of deep convective transports of sulfate particles in regulating climate. They suggest that a 30% increase in the biogenic sulfate aerosol, cycled through enhanced deep convection in a warmer climate, upon sinking back into the convective boundary layer (BL), could increase the albedo of BL clouds by 1.6% by providing additional cloud condensation nuclei and increasing the droplet number concentration (Charlson et al., 1987). Given a 30% BL cloud fraction, this would increase the global albedo by 0.5%, and provide a significant negative feedback on climate change. There are many links in the convective components of this argument, where we need a better understanding of the processes and the climatic equilibrium involved (Betts, 1990). I will discuss some of them.

The first is whether there will be more transport of air (carrying biogenic sulfur) out of the BL in a warmer climate. This is not proven, and indeed the reverse could be true. While it is true that deep convection is more intense when fueled by a higher BL equivalent potential temperature (as evidenced by lightning: Williams, 1994), this depends equally on the cooler overlying vertical atmospheric structure, which provides the convective available potential energy (CAPE). In a warmer climate, where the *entire* tropical tropospheric temperature will be warmer (with an equilibrium structure which is only slightly unstable to a warmer moist adiabat), there is no certainty that the mean CAPE will increase much. Certainly any increase in mean CAPE is a distinct issue from the spatial variation in mean CAPE, which we see in our present climate, associated with spatial variations in sea surface temperature and in the land surface boundary. Furthermore, the global vertical transport of BL air with biogenic sulfur depends on a global vertical mass transport out of the BL by deep convection, not on the intensity of individual convective systems. The upward mass transport depends on the frequency of deep convection as well as the intensity of typical system. For example fewer more intense convective systems or a greater number of less intense ones could carry the same mass transport.

Do we know whether the net vertical mass transport by convection would increase in a warmer climate? One study of the climatic equilibrium of the tropics (Betts and Ridgway, 1989) in fact says the net mass circulation in the tropics will *decrease* in a climate with a warmer sea surface temperature (SST). In this radiation-convective equilibrium model, the upward mass flux in the ascending branch of the tropical circulation is balanced by the subsidence into the convective BL in the descending branch. Figure 1 shows the SST dependence of the three terms in the

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water vapor balance of this model, which satisfy the equation for the moist convective BL equilibrium

$$LH = L\,(\omega_T / g)\,\Delta q \qquad (1)$$

Where LH is the surface latent heat flux (solid curve), ω_T (dotted) is the subsidence at convective BL top, Δq (dashed) is the difference in mixing ratio between a mean for the moist BL and the dry air sinking in at the BL-top, L is the latent heat of vaporization, and g is the gravitational acceleration. Within the BL we have assumed constant divergence for simplicity, and we have computed mean BL mixing ratio from the parameterized thermodynamic structure in the model. The surface LH flux does go up with rising SST at 5 to 6 $Wm^{-2}\,K^{-1}$ (roughly the slope of the Planck function at these warm temperatures). The primary energy balance in this model is between surface evaporation (and a small surface sensible heat flux), net condensation heating in precipitating clouds in the ascending branch of the tropical circulation, and the net radiative cooling of the tropical atmosphere. However the term Δq, which is loosely tied to temperature through the Clausius-Clapyron equation (Δq is about 40% of the saturation mixing ratio at the sea surface temperature), goes up more steeply than the surface evaporation. Consequently the subsidence term, which is a measure of the convective mass circulation in the tropics, actually *decreases* with increasing SST. Even this simple model, which just satisfies tropospheric energy, water and mass balance, shows how complex are the feedbacks between the convective transports and the radiative terms.

Another issue is that, although the net mass circulation in the tropics is related to the net precipitation heating and the net radiative cooling, within convective systems there are considerably larger updraft and downdraft circulations that are related to the convective-scale dynamics, microphysics and precipitation efficiency (Betts, 1997). Although simple estimates of updraft and downdraft mass flux ratios have a long history (eg. Gray, 1973; Betts, 1973; Nitta, 1977), tracer studies (eg. Chatfield et al., 1998) would be very helpful in quantifying the magnitude of the vertical exchanges, and the total mass flow out of the BL in different convective regimes.

In more general terms, we have great difficulty in our climate models reproducing the tight coupling of the convection, cloud and radiation fields found in nature. The cirrus cloud-climate feedback loop suggested by Ramanathan and Collins (1991) is one example of a difficult process to model. What controls BL cloud fraction is also an unsolved problem; but an important one, since a 1% change of BL cloud fraction in a warmer climate has a significant impact on climate. The idealized Betts and Ridgway (1989) model discussed above simply assumed a shallow BL cloud fraction of 25%, while Shaw et al. (1997) assume a fixed value of 30%. These values are assumed because we have no adequate model for BL cloud fraction.

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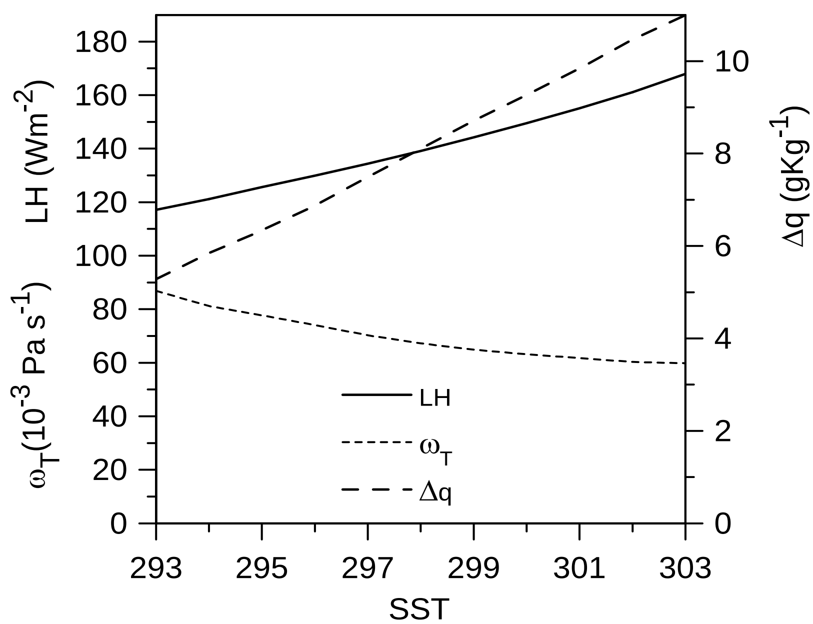

Figure 1. Variation with SST of surface latent heat flux (evaporation), vertical mass circulation and mixing ratio deficit of air sinking into the BL in the Betts-Ridgway (1989) tropical equilibrium model.

The modeling difficulty appears to be in the tight coupling of the convective and radiative transports. Betts and Ridgway (1988) showed using a diagnostic model, that in BL's over the central Pacific, the vertical enthalpy transport by the BL cloud field (associated largely with the condensation, upward advection and evaporation of liquid water in the cloud field) is comparable to the energy transport by the perturbation radiation field. Both are playing a key role in maintaining the cloud field we observe. This equilibrium state of the moist oceanic BL involves a subtle balance of the radiative cooling and heating, the surface fluxes and the internal kinetic energy generation and transports by the cloud field, which we do not fully understand, and have not yet been able to model satisfactorily. Consequently we do not know whether shallow cloud fraction will go up or down in a warmer climate. We also do not know how changing the cloud droplet spectrum will impact the shallow BL equilibrium, or the BL cloud fraction, so a fixed cloud fraction remains a simplifying but unsatisfactory assumption.

My conclusion is that the possible role of sulfate feedback on BL cloud albedo needs to be placed in the broader context of understanding climatic controls on the vertical transports by convective clouds and on BL cloud fraction equilibrium.

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