A new positive cloud feedback?

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(Based on joint work with Louise Nuijens and Malte Rieck)

Prehistory

- “[W]ater vapor, confessedly the greatest thermal absorbent in the atmosphere, is dependent on temperature for its amount, and if another agent, as CO_2, not so dependent, raises the temperature of the surface, it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth more vapor ...“ [1]

- “Fig. 1 shows the distribution of relative humidity .. for summer and winter … the zonal mean distributions of relative humidity of the two seasons closely resemble one another whereas those of absolute humidity do not. These data suggest that, given sufficient time, the atmosphere tends to restore a certain climatological distribution of relative humidity … Therefore, the equilibrium temperature of the atmosphere with a fixed relative humidity depends more upon the solar constant or upon absorbers such as CO_2 and O_3 than does that with a fixed absolute humidity.” [2]

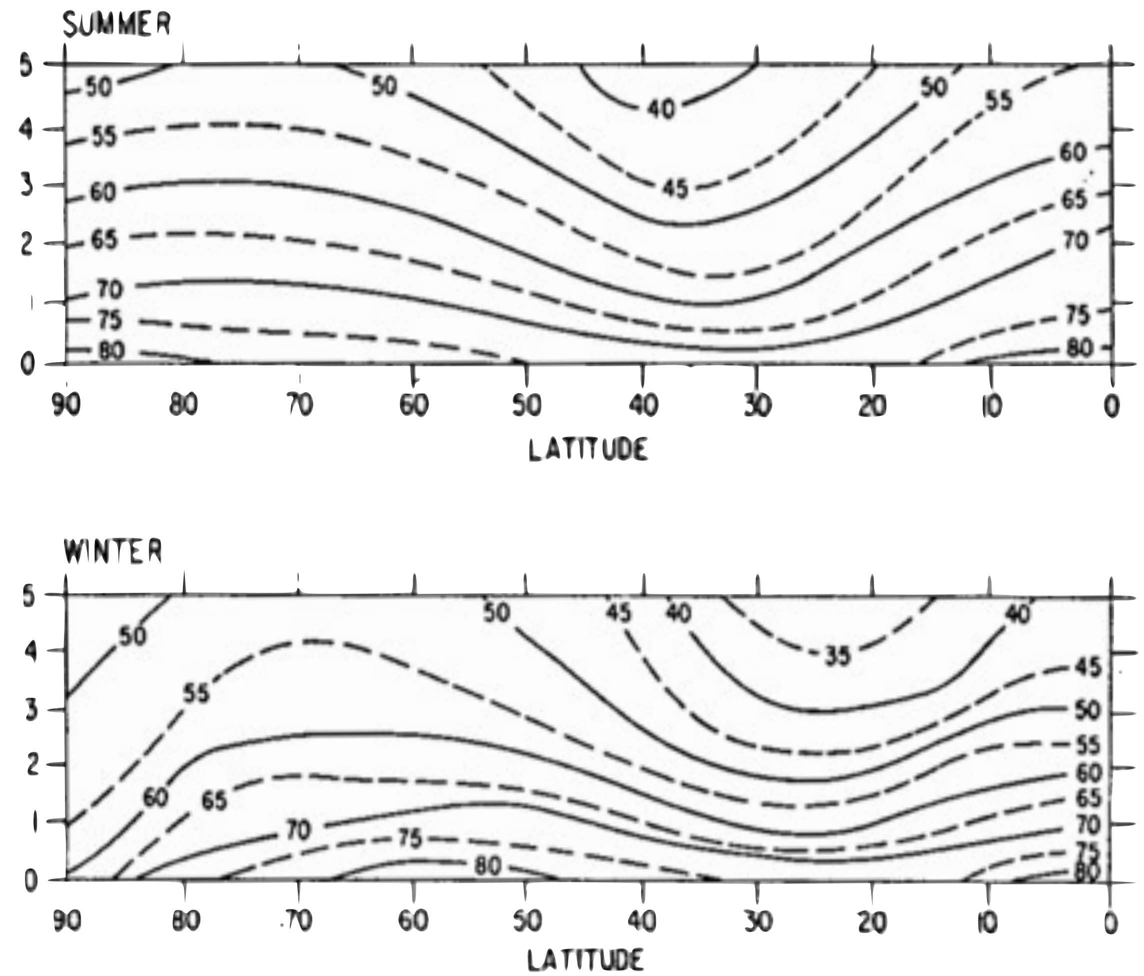


Fig 1. Latitude-height distribution of relative humidity for both summer and winter (Telegadas and London, 1954).

The idea that relative humidity should remain constant has long been a staple of the climate change diet

[1]Fleming JR. 1998. *Historical Perspectives on Climate Change*. New York: Oxford Univ. Press 194 pp.; [2]Manabe and Wetherald 1967 *J. Atmos. Sci.* **24**

History

- Cloud feedbacks took a long time to emerge as a possibility in the literature – the first real mention of such a possibility was by G. Plass (1956) who postulated that increased radiative cooling from cloud-top in a CO_2 depleted atmosphere would destabilize convective clouds and enhance precipitation.

- Moeller (1963) was the first to recognize the potency of potential cloud feedbacks. He estimated that: "The effect of an increase in CO_2 from 300 to 330 ppm can be compensated for completely by a change in the water vapor content of 3 per cent or by a change in the cloudiness of 1 per cent of its value without the occurrence of temperature changes at all." He further noted however that "No meteorologist or climatologist would dare to determine the mean cloudiness or the mean water vapor content of the atmosphere with such an accuracy"

- Schneider (1972) explored more systematically, and developed the modern framework for, the effects of cloud feedbacks on climate. His motivation was in part stimulated by Twomey's argument that increases in planetary pollution that accompany CO_2 increases (namely sulfate aerosol) would act to cool the climate system as a whole. Note that Schneider's early work on cloud feedbacks was very much related to the possibility that the Earth might be approaching a new ice age.

Fundamentally what was missing was an argument as to why cloudiness should depend on temperature.

Plass, G. N. (1956), *Tellus*, **8** Möller, F. (1963), *J. Geophys. Res.*, **68**
Schneider, S. H. (1972), *J. Atmos. Sci.*, **29**

The Modern

- "Case **A** assumes that the amount, height and thickness of all clouds remains constant, but their water path *L* rises in proportion to the increase in saturated vapour pressure at the surface corresponding to an increase in surface temperature (see column 5). … [It] is purely a guess based on the qualitative argument that a wetter atmosphere may lead to wetter clouds even if the dynamics of the system ensures that the amount of cloud remains roughly constant"[1]
- "On this aspect of the problem there is little controversy: Water vapor in the boundary layer will increase as climate warms to prevent the near-surface relative humidity from decreasing appreciably."[2] Which all things being equal should compound the cloud optical depth feedback introduced by Paltridge.
- Other physically based hypotheses unrelated to the water vapor feedback have also been advanced:
    - Retreat of storm tracks to regions of lower average insolation
    - Fixed Anvil Temperature Hypothesis
    - CO_2 indirect effect on stratocumulus cloud (analogous to Plass, 1956)

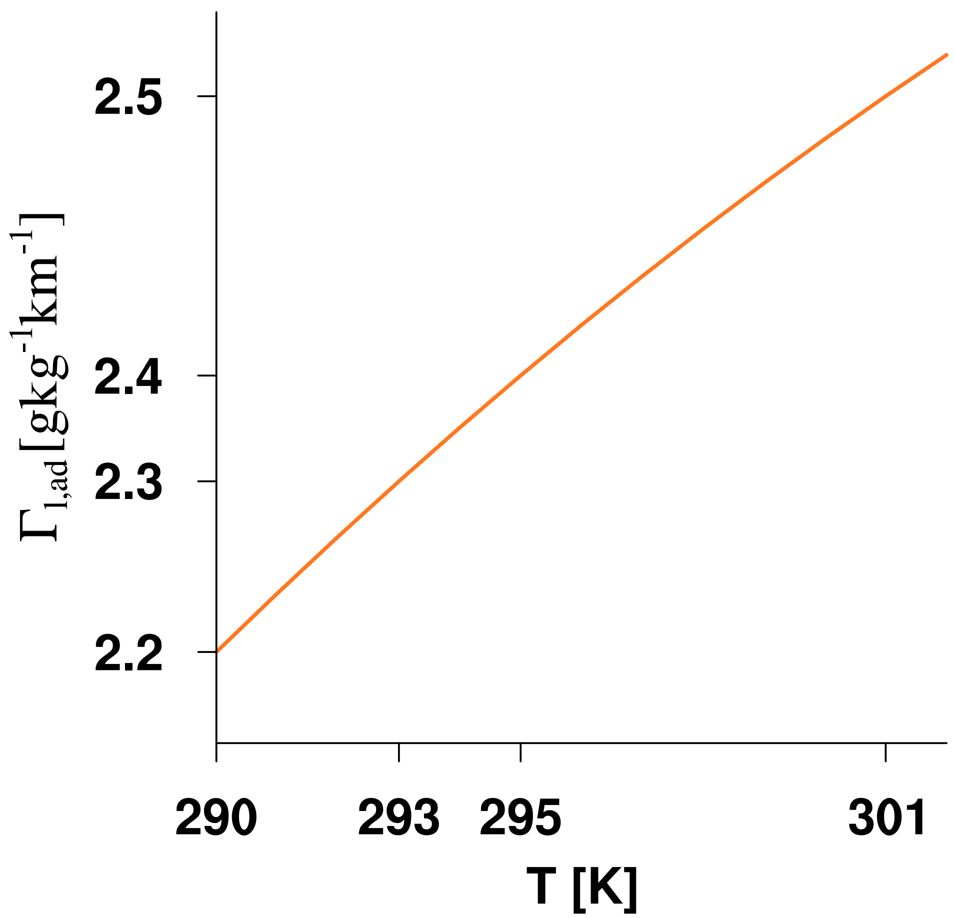
Beginning in the 1980s physical arguments as to why cloudiness should depend on the working temperature of the atmosphere began to emerge.

[1] Paltridge, G.W. (1980) *Q.J.R. Meteorol. Soc.*, **106**
[2] Held, I. M., and B. J. Soden (2000), *Annu. Rev. Energy. Environ.*, **25**

Two Issues

- The cloud optical depth feedback, or liquid water lapse rate feedback: The liquid water lapse rate of clouds may change, a variant of the temperature lapse-rate feedback.

$$\Gamma_l = q_s \frac{p}{p_d} \left[\left(\frac{L_v}{R_v T^2} \right) \Gamma_T - \frac{g}{(R_d(1-q_t) + R_v q_v) T} \right]$$

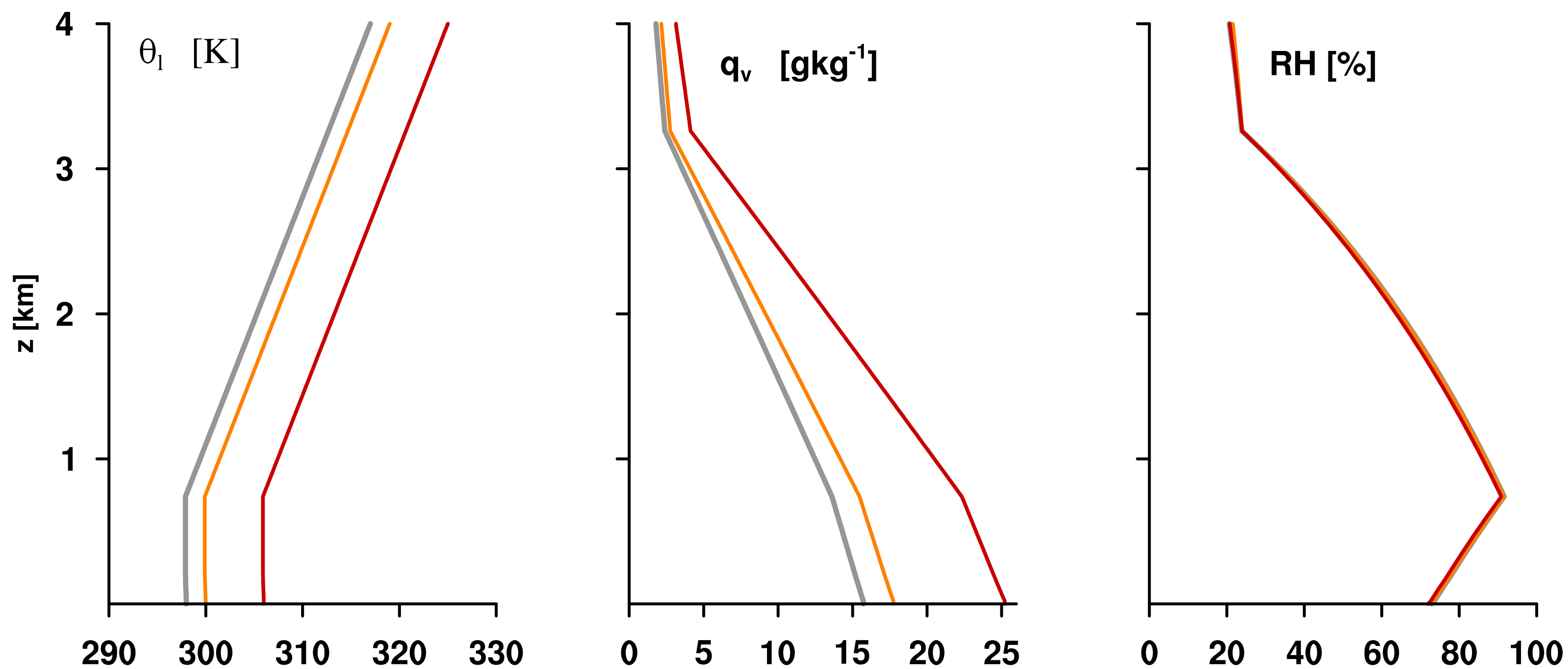


- The idea of constant relative humidity does not apply to the boundary layer; i.e., boundary layer humidities can be expected to change.

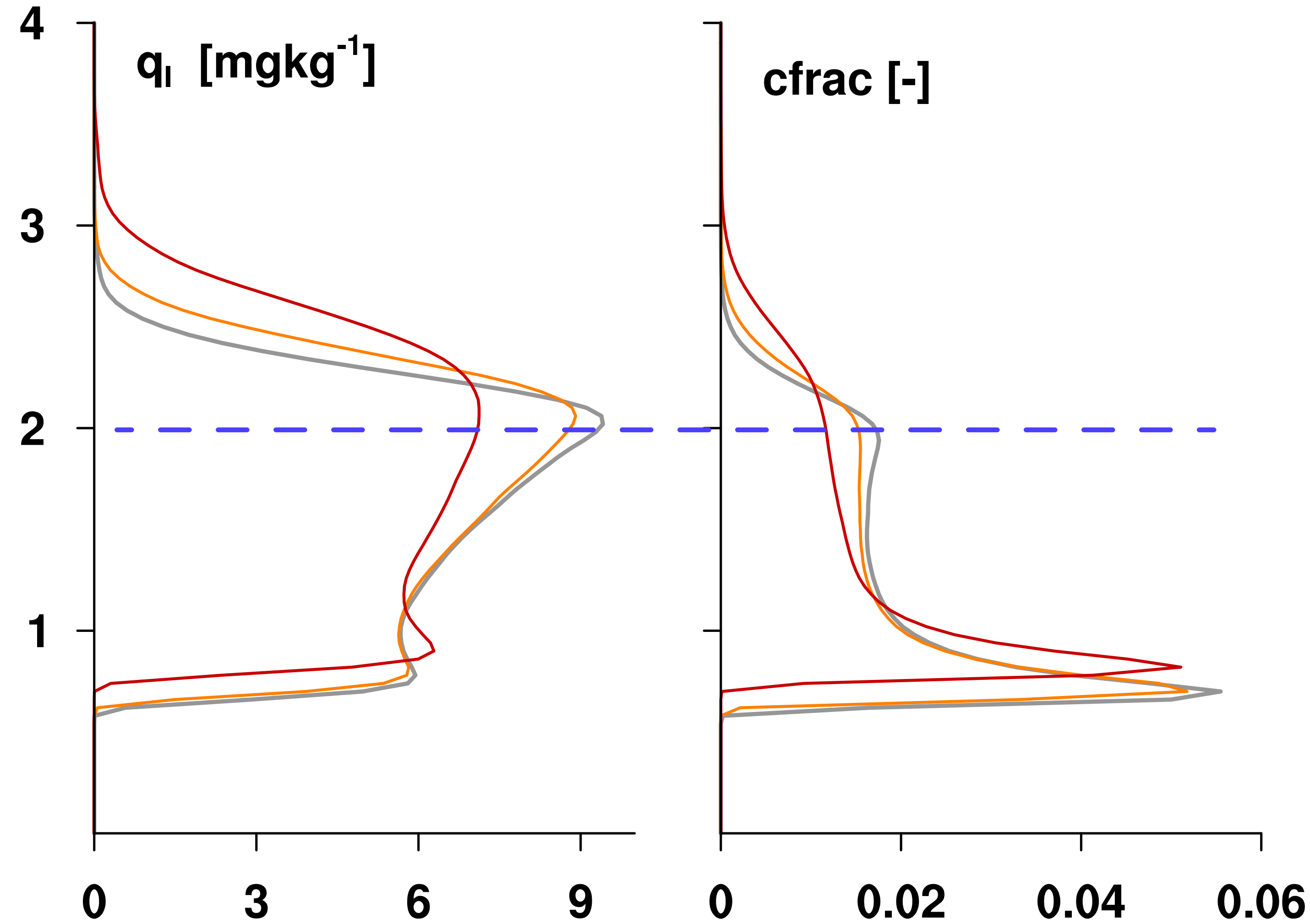
$$\overline{w'q'} = \|U\| C_h q_s \left(1 - \frac{q}{q_s} \right) \approx \|U\| C_h q_s \, (1 - \mathrm{RH})$$

Large Eddy Simulation

- Simulations based on the RICO (Rain in Cumulus over the Ocean) test case developed by the GCSS Boundary Layer Working Group.
- Typical trade-wind convection, arguably the planets most prevalent cloud type.
- Extensive use of this case to study physical, microphysical and numerical sensitivities.
- Experimental methodology is based on two sets of simulations, each set containing a CONTROL, a +2 K and a +8 K simulation.
- Sensitivity to numerics, sample noise, *etc*., has been explored but not decisive.

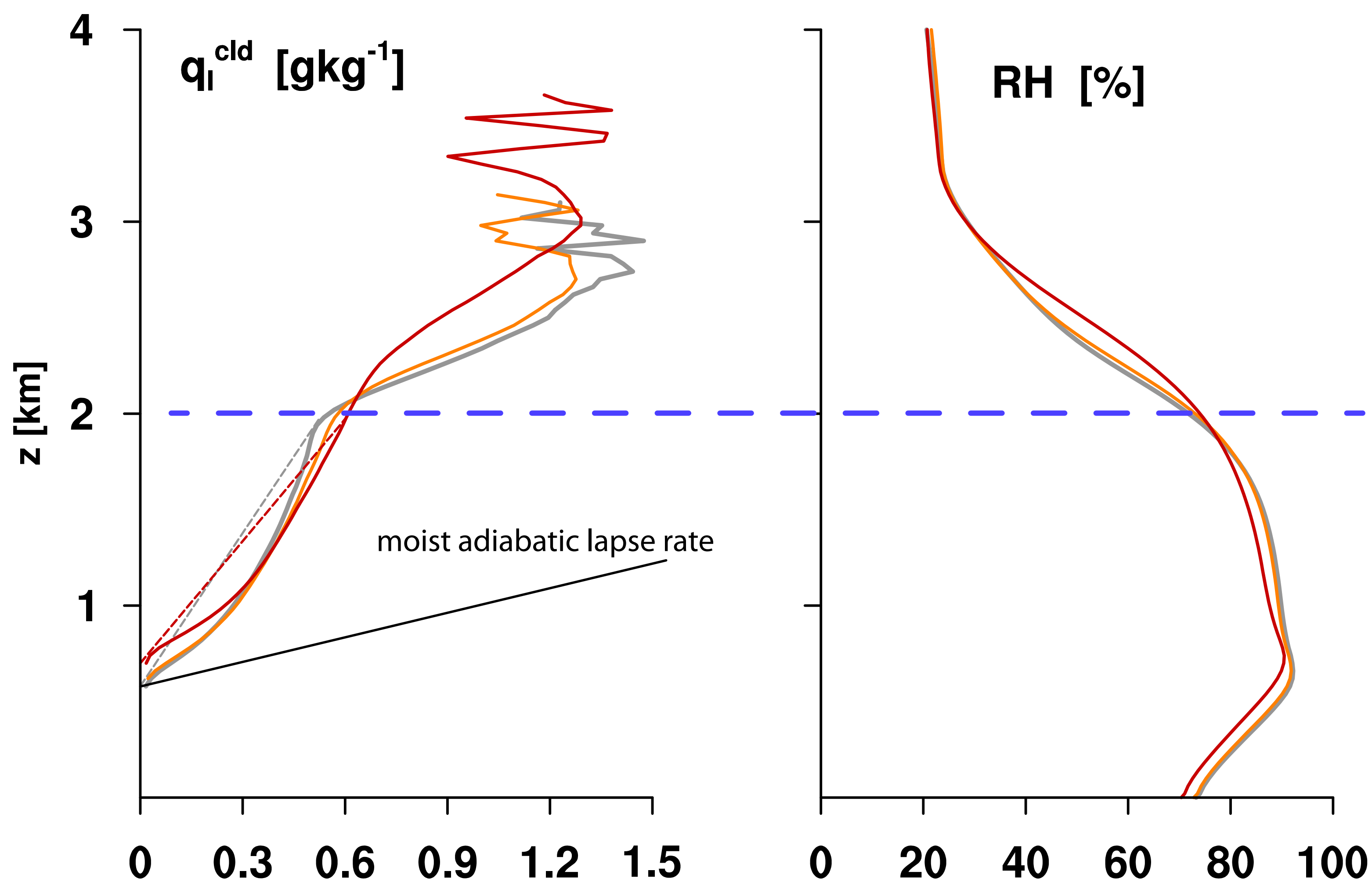


Vertical Profiles



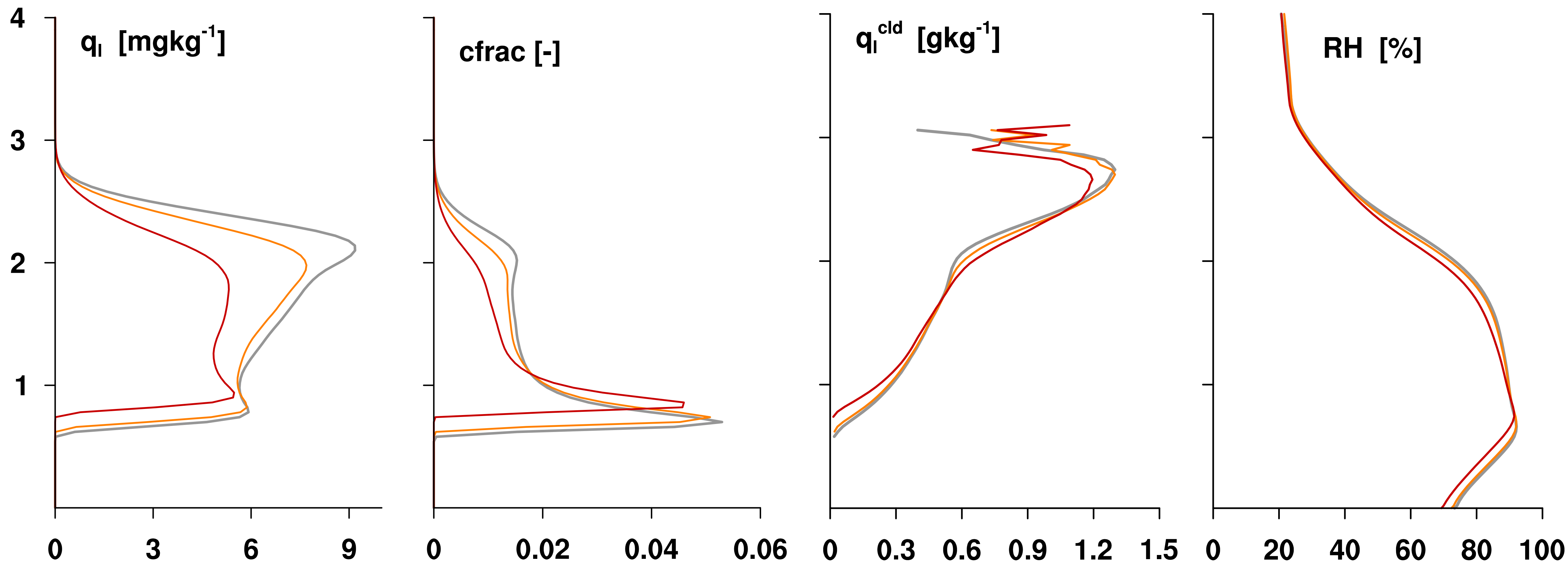
- Warmer layers have a higher cloud base, and are deeper by a similar amount, so cloud depth is not changing appreciably (as hypothesized by Paltridge)
- But cloud liquid water is reduced, as is cloud fraction at every (depth normalized) layer.
- Similar effects are seen in data (e.g., DelGenio and Wolf's recent analysis of ARM data)

Conditional Sampled Water and RH



- Inside the clouds the liquid water increases more rapidly through cloud layer, as predicted by theory; but much less than adiabatically (almost by definition).
- That liquid water on average does not show this increase is indicative of reduced cloud fraction. This is consistent with a somewhat drier boundary layer, albeit somewhat deeper.
- Note that secondary turrets that penetrate above the inversion show a different behavior, but these are rare.

Repeating this exercise with fixed surface fluxes

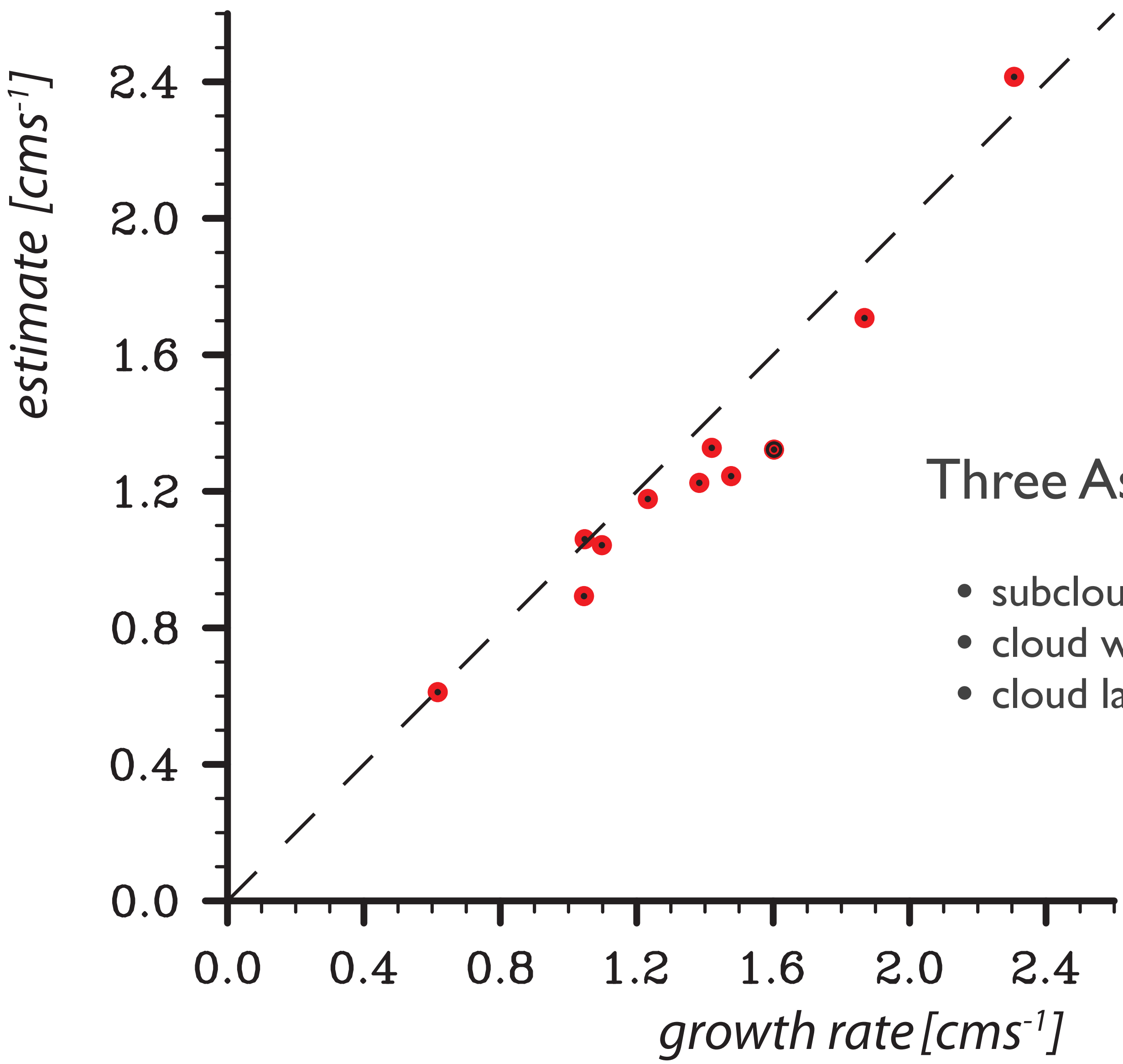


- Liquid water reduction with increasing temperature is more pronounced.
- Cloud base still increases with increasing temperature, but cloud top now does not change.
- Relative humidity is reduced everywhere.

Remarks

- For trade-wind cumulus simulations increasing temperatures for an initial sounding with a fixed relative humidity leads to:
  - larger surface fluxes (especially latent heat)
  - a deeper and drier cloud/boundary layer
  - clouds whose liquid water increases more rapidly with height
  - but overall less cloud and similar or less liquid water.
- If the surface fluxes are held constant, for instance to anticipate an energy balance control, these effects are more pronounced.

How does this work?



Three Assumptions:

- subcloud layer <=> dry cbl
- cloud water *in cloud layer* is stationary
- cloud layer density slaved to sublcoud layer

The primary driver of PBL deepening is the flux of moisture into the inversion, and this in turn scales with the surface latent heat flux. Stronger surface moisture fluxes demand a deeper boundary layer.

Stevens, B. (2007), On the Growth of Layers of Nonprecipitating Cumulus Convection, J. Atmos. Sci., 64(8), 2916–2931

How should the surface fluxes change?

- Imagine a fluid at fixed relative humidity being humidified due to a flux of moisture into the fluid. Now, consider the case at two different temperatures.
- To maintain the same rate of moistening the flux of moisture needs to increase with temperature, in essentially the same way as it does in the LES, i.e., proportional to q_s.
- This should also happen at all of the boundaries. (top; bottom; and laterally from large-scale advection). In the LES we actually underestimate the drying from large-scale advection because we keep it constant. Also if the fixed anvil temperature hypothesis is correct then we also under anticipate drying.
- In and of itself this would constitute a positive cloud feedback on climate. Also because deeper clouds and a deeper boundary layer enhance the long-wave cloud forcing.
- But this leaves the puzzle as to how to reconcile Held and Soden's argument that the boundary layer moistens because surface energy balance can not sustain such large fluxes.

Summary

- The idea of constant relative humidity is a staple of the climate science diet, but carrying the thought through to its logical conclusions leads to some puzzles. If you like one can think of this as a problem of epsilons. Constant RH is a O(1) argument, clouds are O(ε) in RH, while precipitation is O(ε^2).
- To maintain a constant relative humidity at a higher temperature implies a stronger surface flux, particularly a stronger latent heat flux.
- To a first approximation the rate of boundary layer deepening scales with the surface latent heat flux.
- Hence one expects a deeper boundary layer, but on average a drier boundary layer with less clouds in a warmer climate.
- While clouds are on average wetter, i.e., the liquid water lapse rate changes as anticipated, the signal from fewer clouds dominates and overall, in our ansatz, cloudiness decreases in a warmer climate, thus constituting a positive feedback.
- On a larger scale these signals are challenging to reconcile with the surface energy budget.
- Also many caveats because our ansatz is over-simplified. Still it helps us think through more complex (realistic?) cases.