# The Hydrological Cycle Response to Rapid vs. Slow Global Warming

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*Simulations implemented by Feng He and Jiaxu Zhang*

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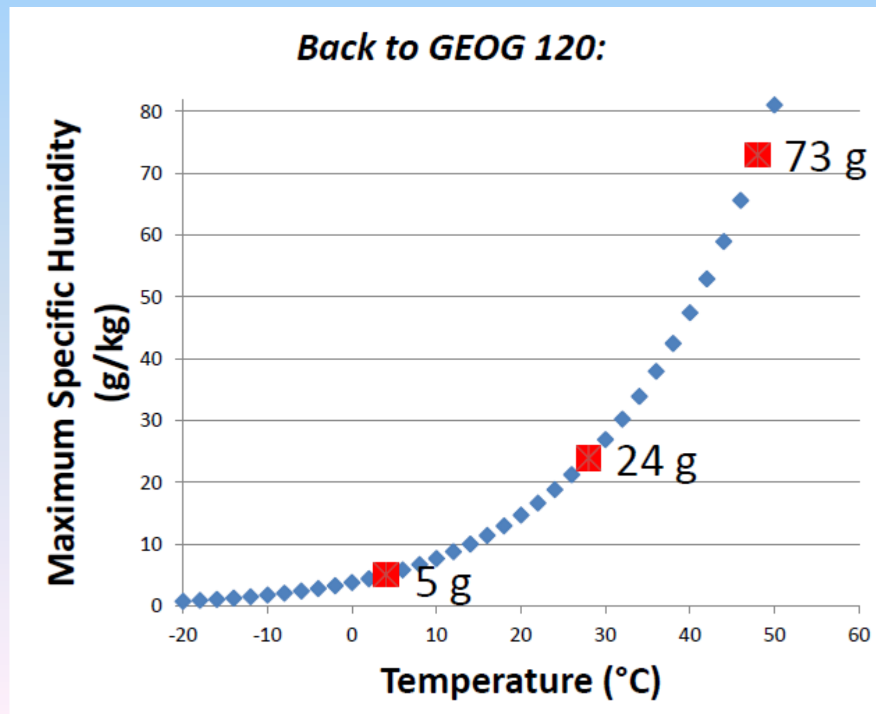
# Why do we study changing:

- Precipitation
- Water vapor???

*Photograph by Wyman Meinzer*

*AP photo appearing in The Atlantic*



*Held & Soden, 2006:*

# *Robust Responses of the Hydrological Cycle to Global warming*

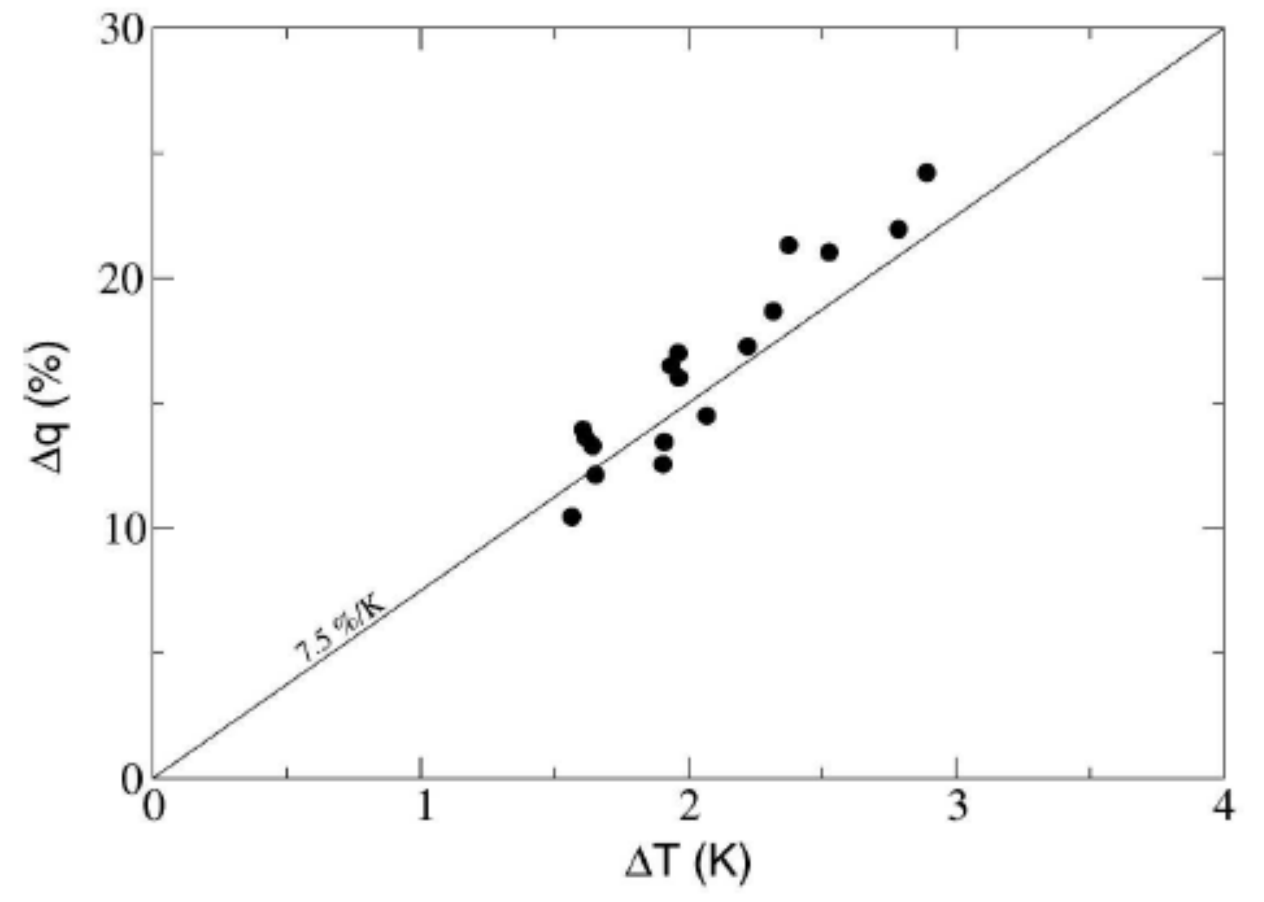



*Figure 2: Does the water vapor summed over the whole atmospheric column follow Clausius-Clapeyron for surface temperature?*

$$\frac{d \ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T)$$

*The Question:*

- *What would we see if we tried to produce the same graph using model data from a transient simulation of the past 22,000 years?*

## *The Model Run*

- CCSM3 at NCAR in Boulder, CO
- Transient simulation
  - Atmosphere, ocean, ice, and land components
  - Grid points separated by 3.75 degrees latitude & longitude for atmosphere & land, variable for ocean/ice, 26 vertical levels in atmosphere, 25 depth levels in ocean.
  - Feng He ran the simulation, which took 1 ½ years.
  - To reproduce the melting of the ice sheet, he experimented with different geographical flow patterns and amounts to best match the proxy data.

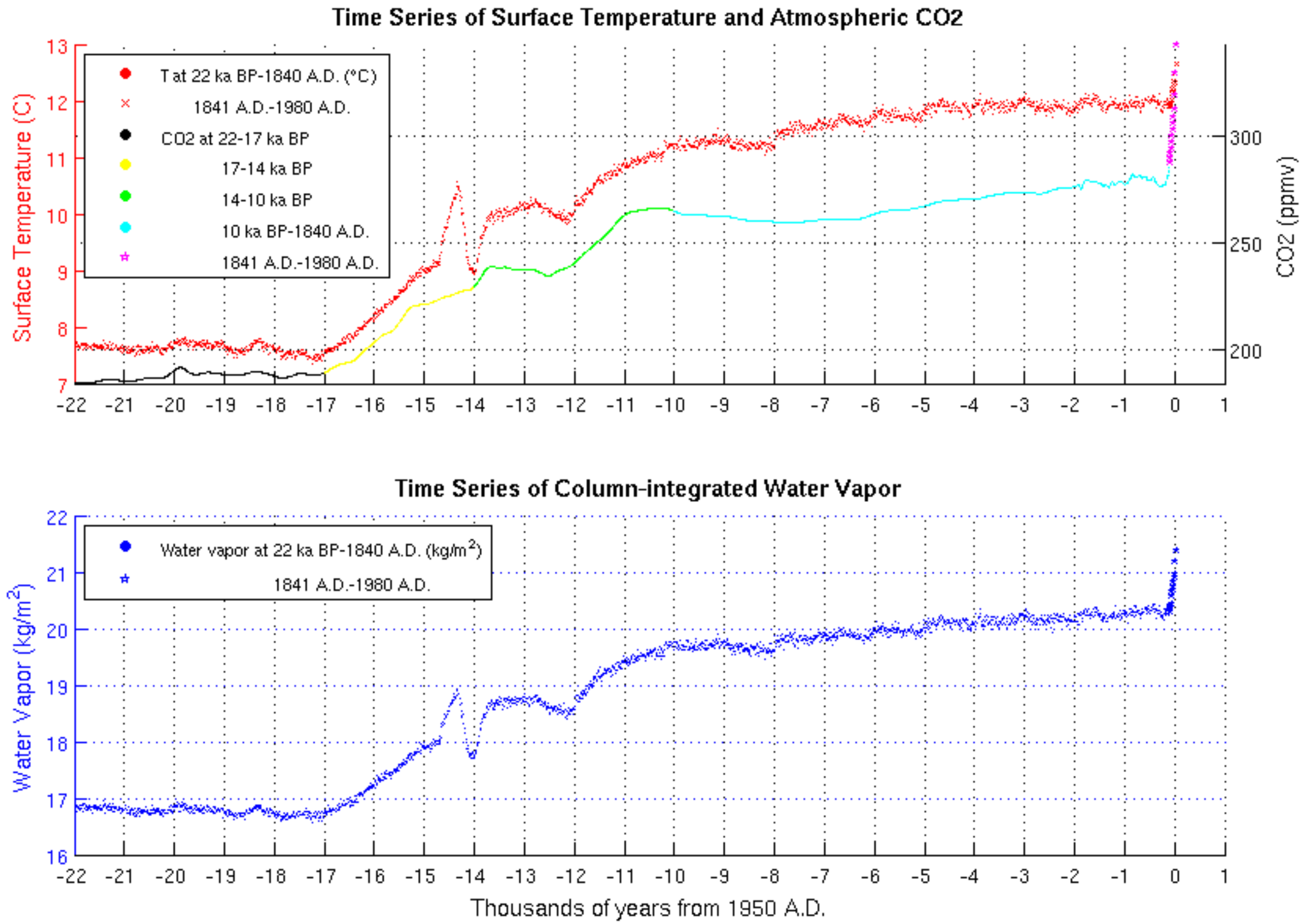



*Figure 3: Time series for the long model run.*

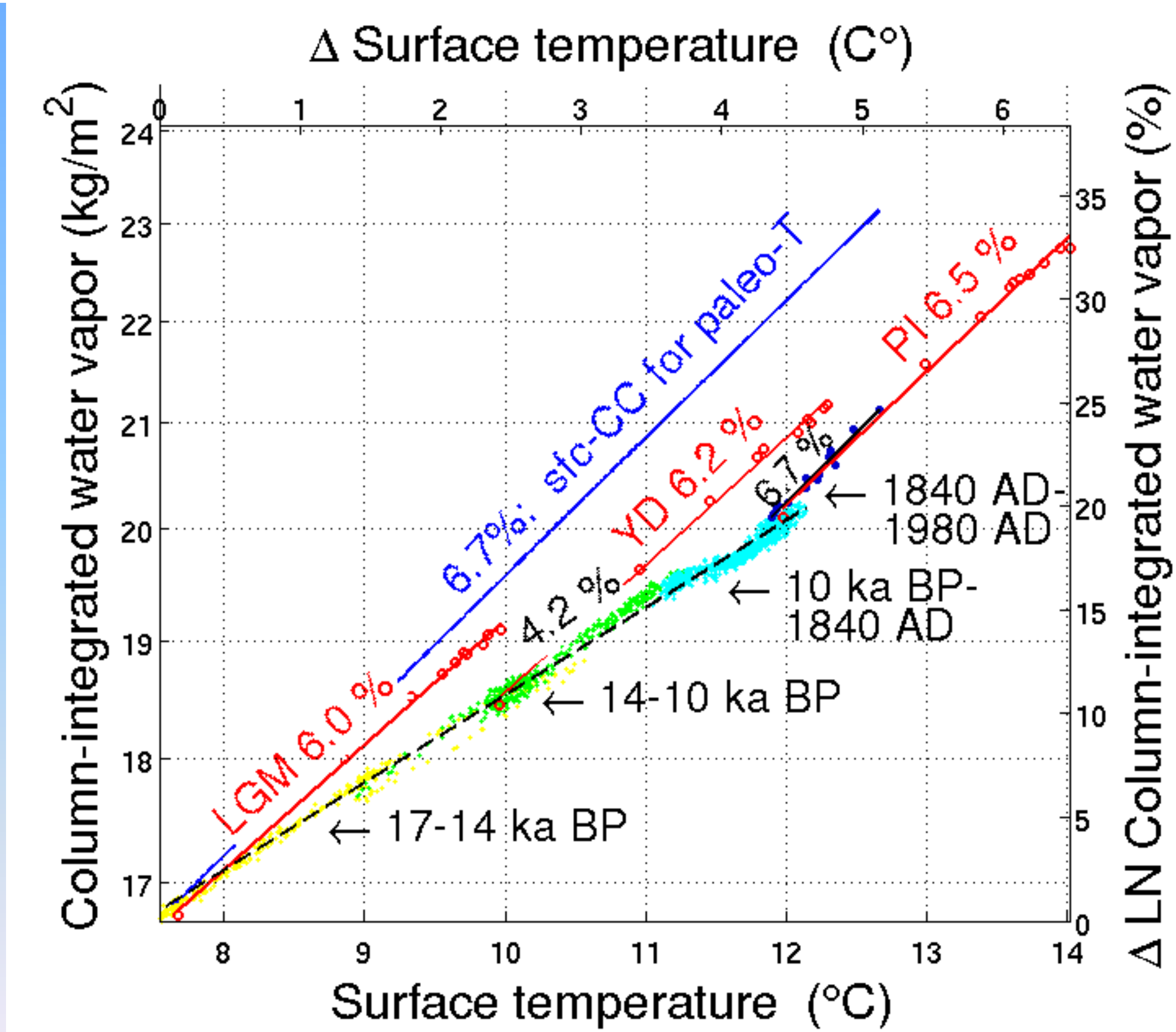



*Figure 4: Globally-averaged column-integrated water vapor vs. globally-averaged surface temperature.*

***Physical reasoning in Held & Soden, 2006:***

- *Assumptions:*

  *1. Relative humidity is ~ constant.*

  *2. Most humidity is in lower troposphere.*

- *Their Conclusion:*

  *Column-integrated water vapor will increase following the Clausius-Clapeyron relationship computed at* ***surface*** *temperature.*

***Our hypotheses*** *to explain lower rates of water vapor change with temperature in the colder past :*

1. ***Relative humidity is not constant*** *over climate-change time scales.*
2. ***Tropical upper troposphere warms more than surface.***
3. ***Tropics are the main influence on global rate of change.***
4. ***Rapid $CO_2$-induced warming affects global water vapor differently*** *than slow warming.*

***Testing Hypothesis #1 on Relative Humidity:***

- *$H_0$: Relative humidity is fairly constant over time between the LGM and the present.*

- *$H_A$: Relative humidity changes substantially between the LGM and the present.*

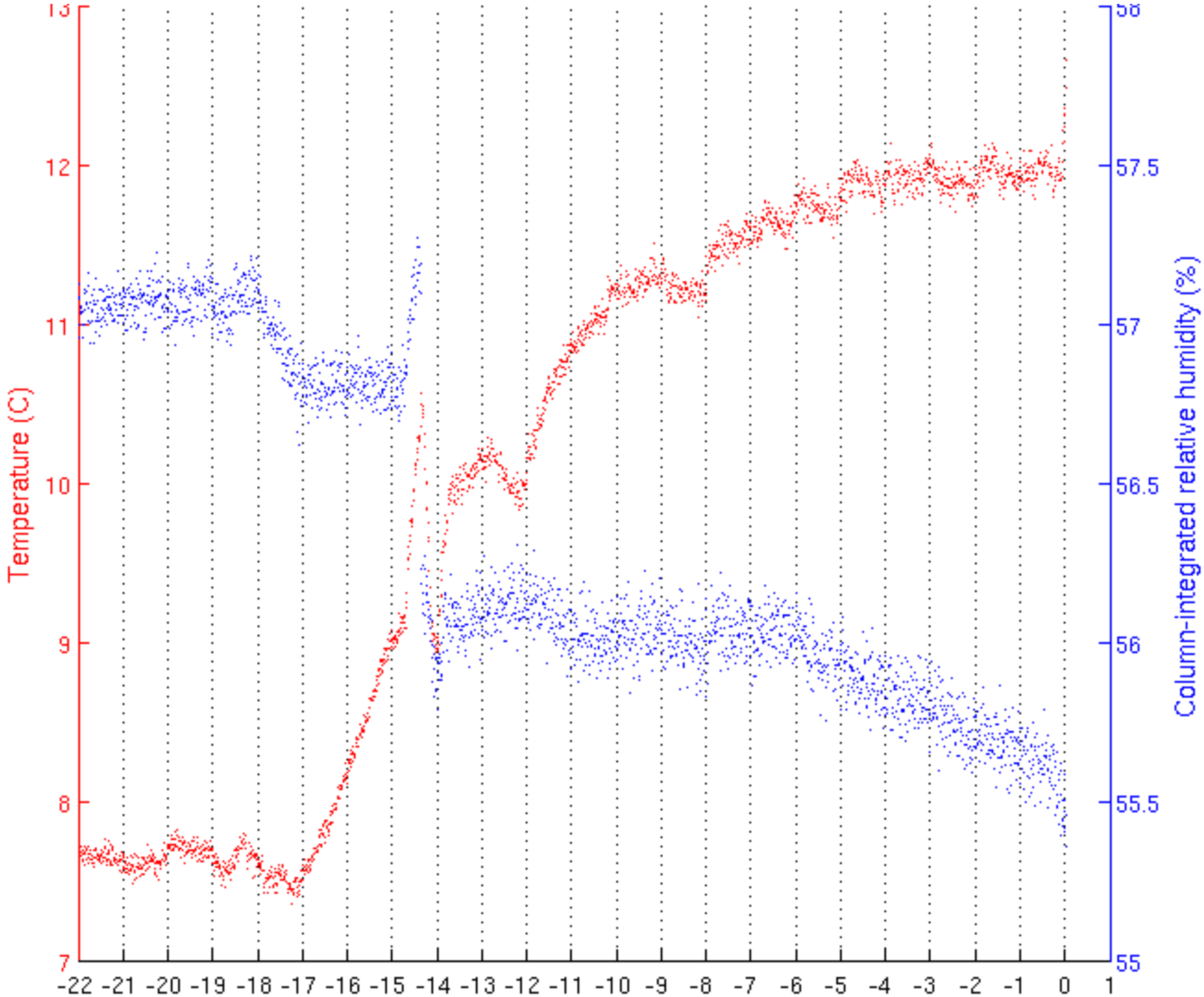



*Figure 5: Time series of surface temperature and column-integrated relative humidity*

*Conclusions about #1:*

- *Globally-averaged relative humidity is fairly* ***constant*** *over climate-change time scales.*

- *The small amount of change over the last 22,000 years is in the* ***wrong direction*** *to explain our results.*

***Testing Hypothesis #2 on Vertical Spatial Distribution of Atmospheric Water Vapor:***

- *$H_0$: Most of the water vapor is near the surface.*

- *$H_A$: A substantial amount of the water vapor is in the*
  *upper atmosphere.*

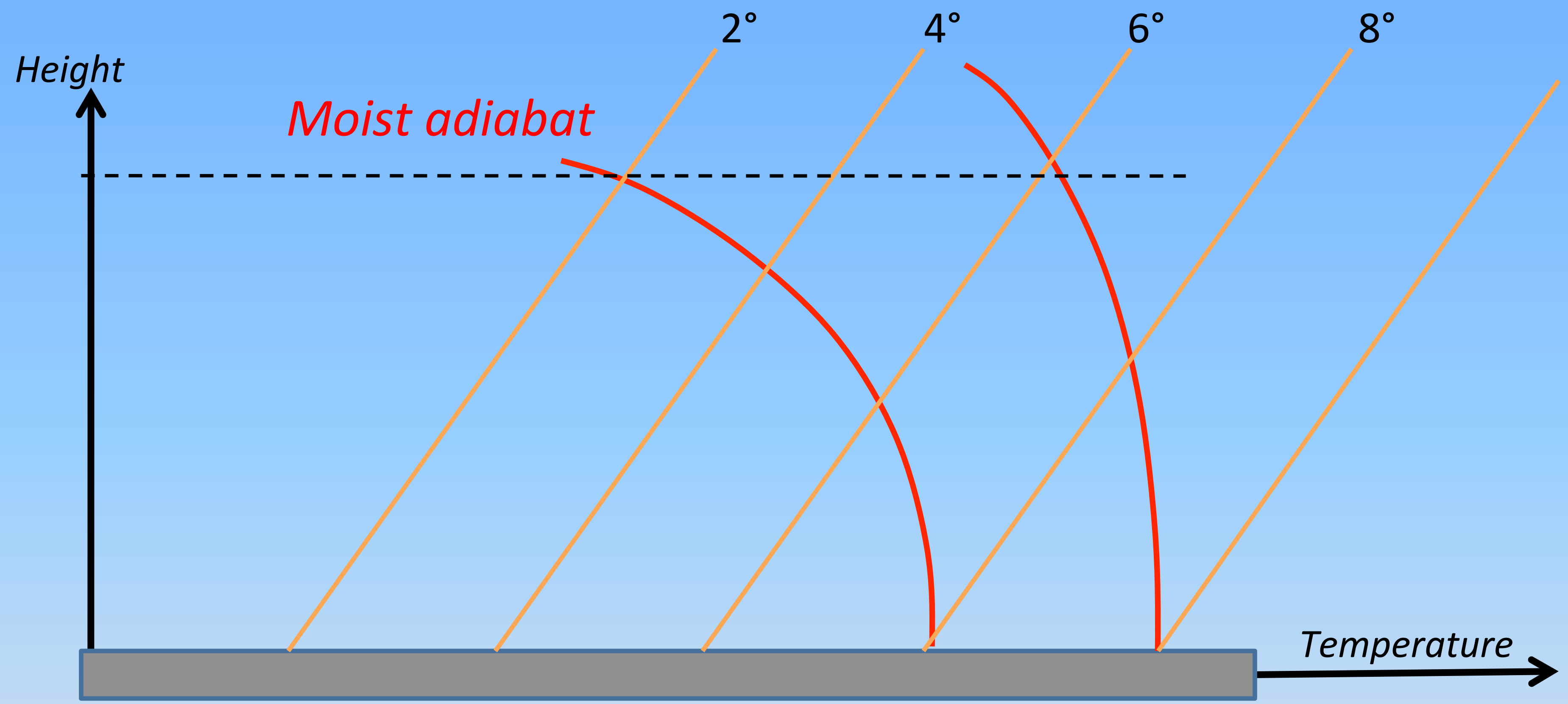



*Figure 6: Saturated atmospheres follow a moist adiabatic profile… and*
***the entire tropics follow a moist adiabatic profile…***

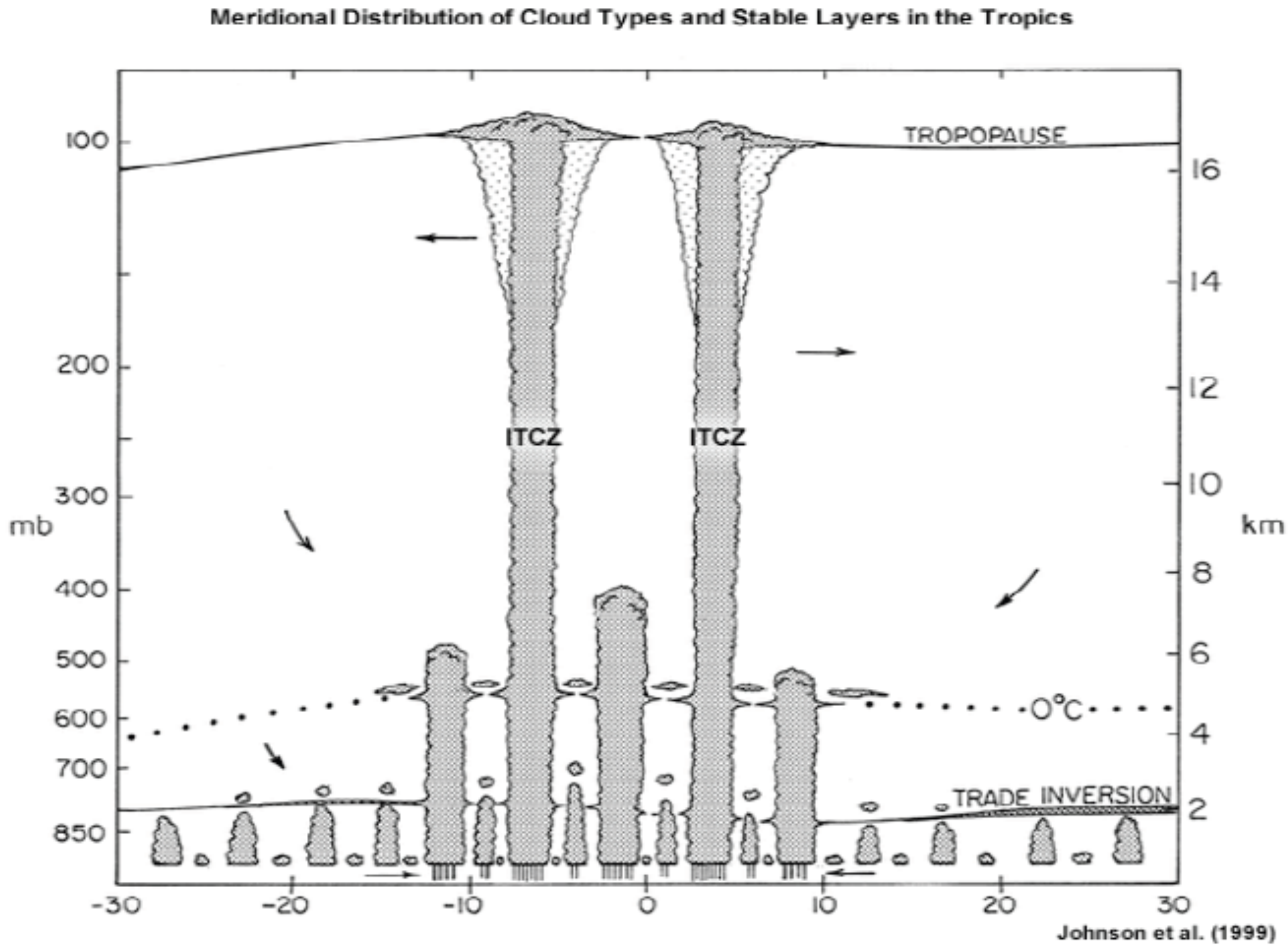



*Figure 7: From Johnson et al. (1999): Hot tower clouds extend up to the tropopause.*

*So specific humidity is increasing aloft as surface temperature rises:*

- *T**he percentage increase** in saturation specific humidity should be **greater at height**.*
- *So we asked whether the **increasing proportion of water vapor aloft** is an important factor.*

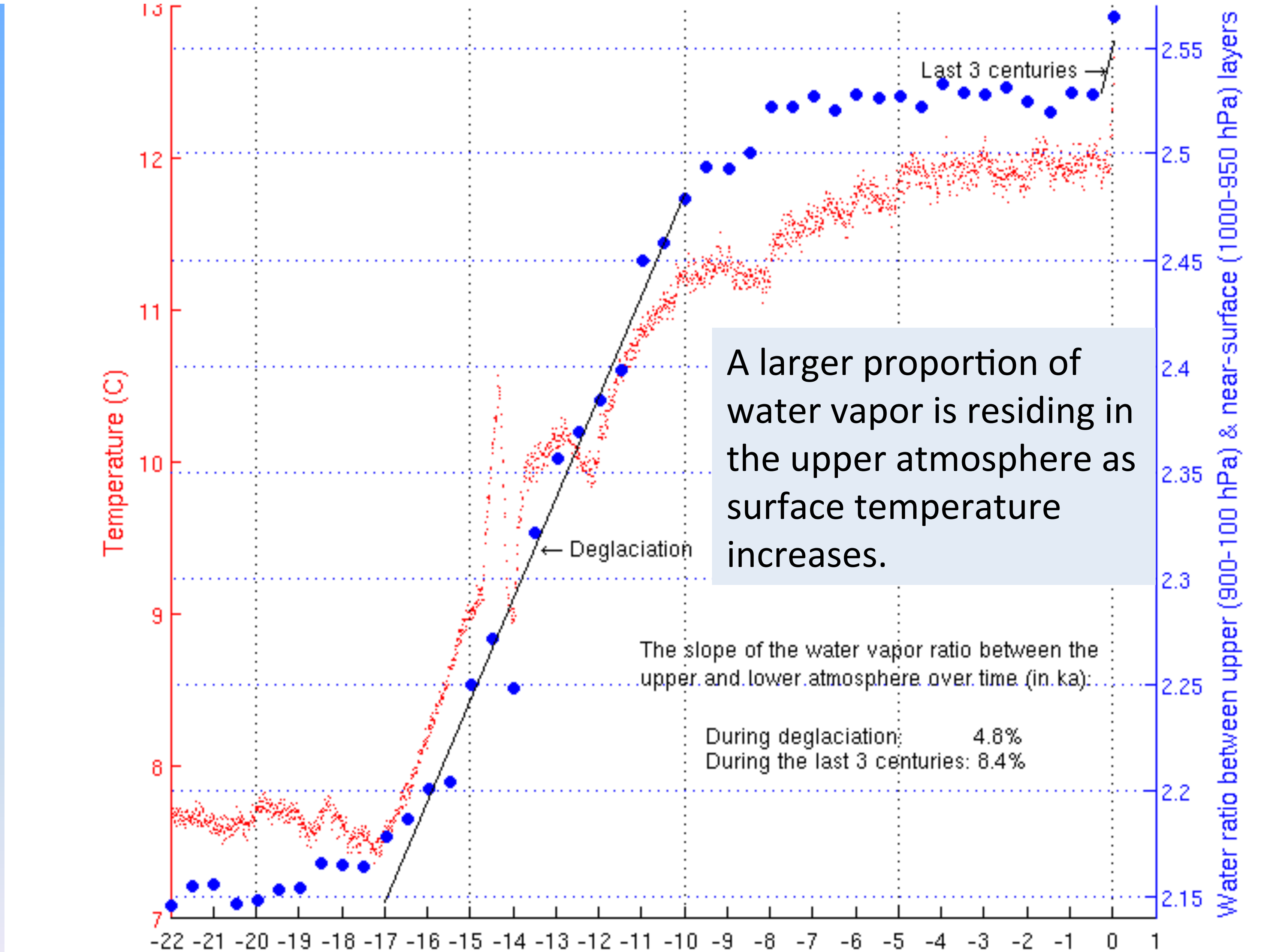



*Figure 8: Time series of water-equivalent ratio between upper & lower atmosphere, divided at 925 hPa.*

*Conclusions about #2:*

- *U**pper-atmospheric water vapor** is increasingly important with global warming.*

- *The change in column-integrated atmospheric water vapor is **NOT** well described by the **surface**-Clausius-Clapeyron relationship.*

## *Testing Hypothesis # 3 on tropical influence:*

- *$H_0$: Water vapor increases are uniform as a function of latitude.*
- *$H_A$: Water vapor increases vary as a function of latitude.*

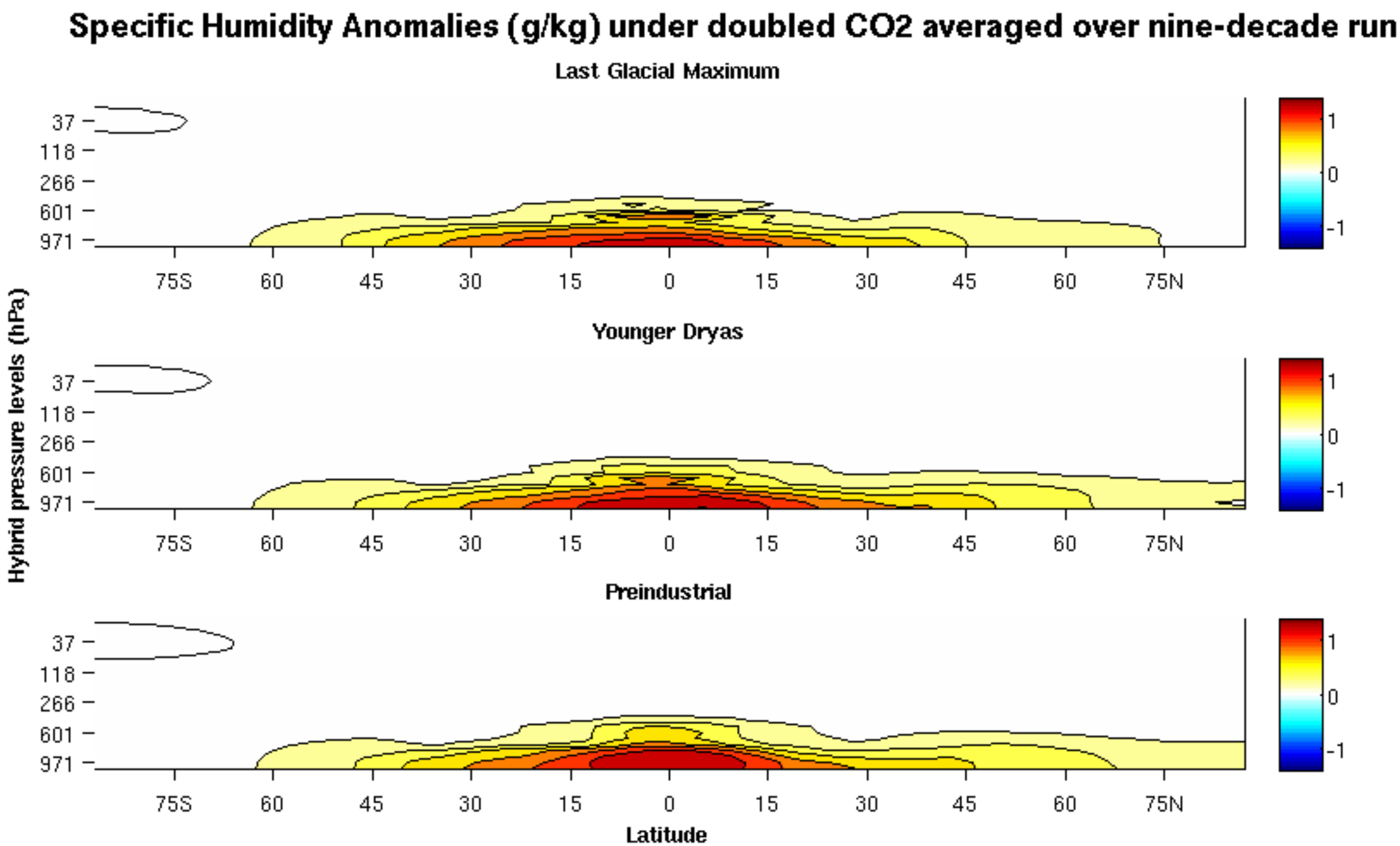



*Figure 9: Most of the water vapor increase under rapid warming is concentrated in the tropics.*

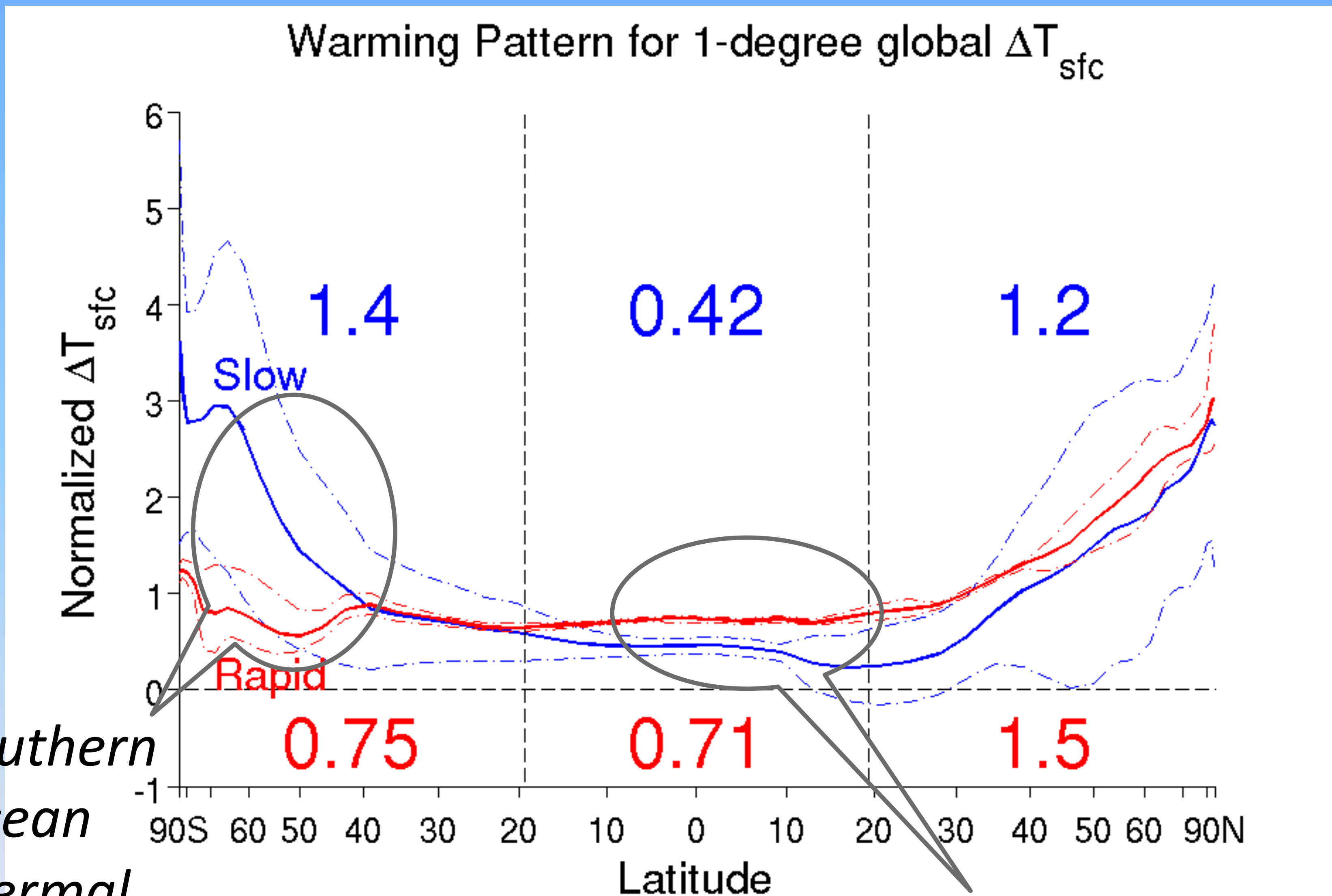
*Conclusions about #3:*

- *The **tropics dominate** the latitudinal distribution of water vapor.*
- *The change in column-integrated atmospheric water vapor is **NOT** well described by a **globally-averaged** surface-Clausius-Clapeyron relationship.*

## *Testing Hypothesis # 4 on the rate of warming:*

- *$H_0$: The rate of warming has no influence on column-integrated water vapor.*

- *$H_A$: The rate of warming does influence column-integrated water vapor.*




*Southern Ocean thermal inertia*

*More tropical warming per global T increase*

*Figure 10: The normalized surface warming pattern*

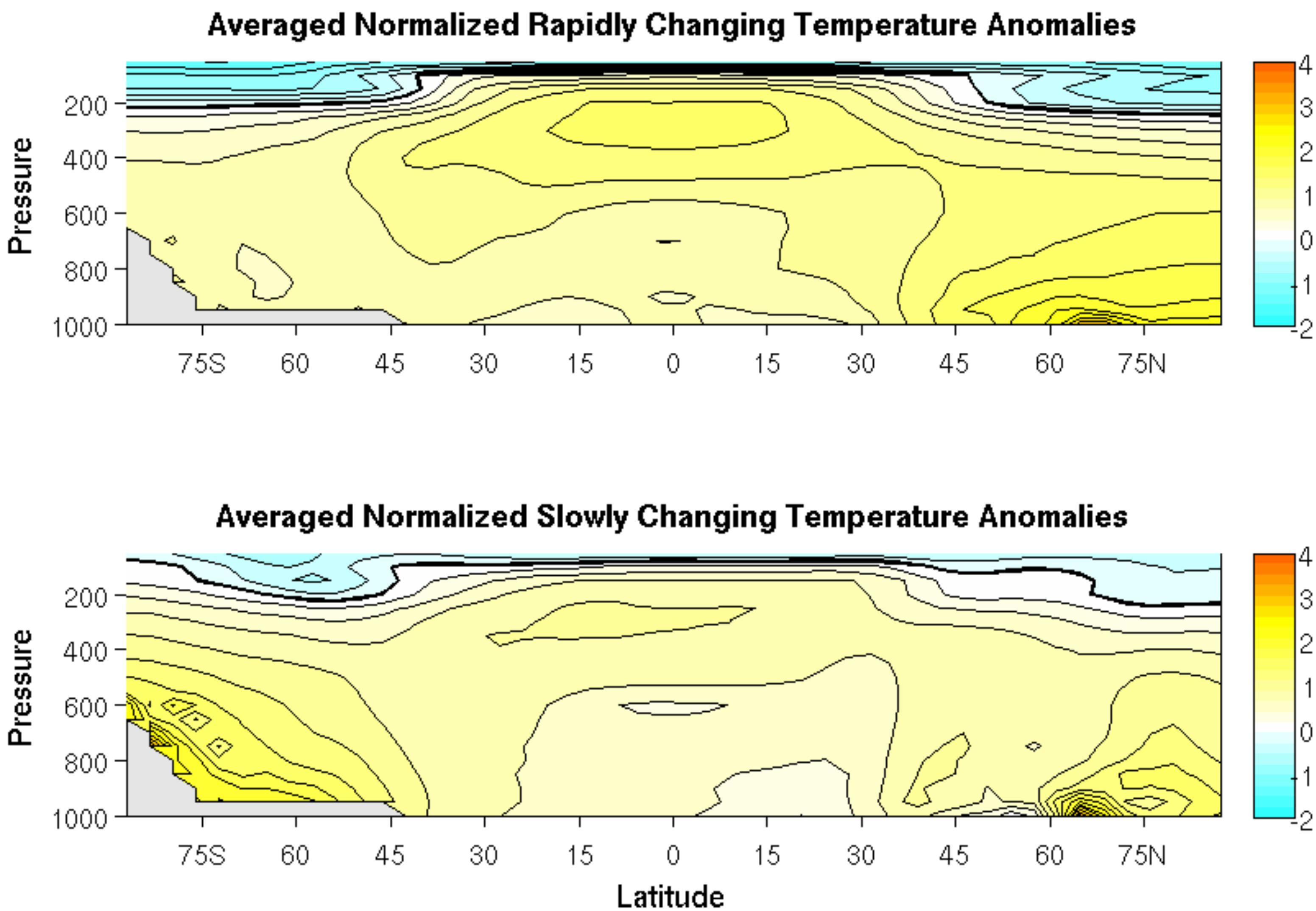



*Figure 11: "Local" normalized temperature change patterns*

## *Conclusions about #4:*

- *Rapid warming results in a higher rate of water vapor change than slow warming.*
  - *For the* ***rapid case****:*
    - *The Southern Hemisphere is not in equilibrium.*
    - *The Southern Ocean is drawing heat from the overlying atmosphere.*
    - *For a one-degree* ***global****-average temperature increase, a larger share of the heating occurs in the tropics.*
    - *Thus, more of the increased global water vapor comes from the tropics.*
    - *The wet tropics drive a higher* ***globally-averaged*** *rate of water vapor change per degree surface warming.*

## *Predicting the rate of change:*

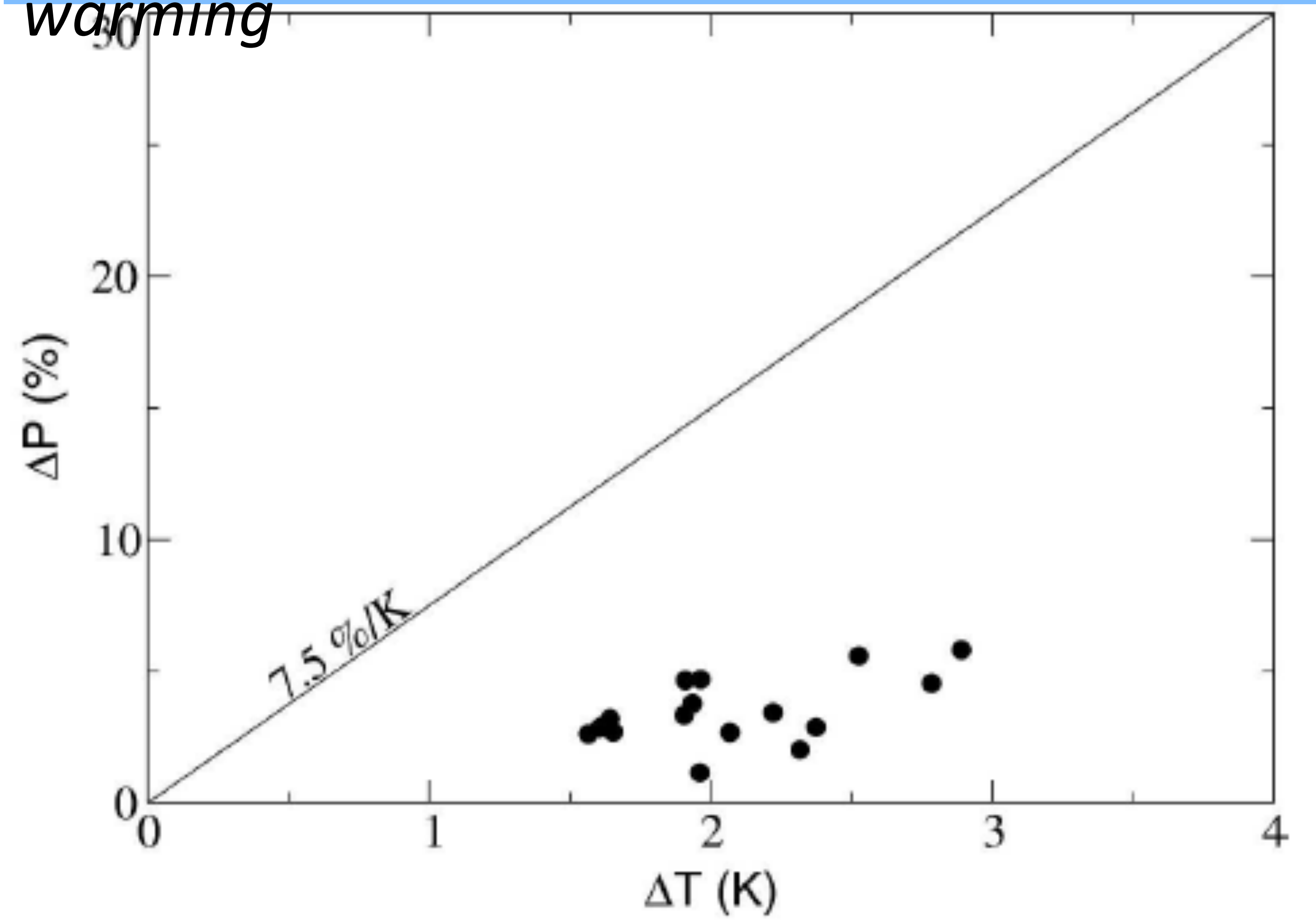
$$\frac{\delta \ln(\bar{Q})}{\delta \bar{T}_s} \approx \alpha + \frac{1}{\delta \bar{T}_s} \ln \frac{\int \int_{p_0}^{0} q_0(x,y,p) exp(\alpha \delta T') \mathrm{d}p \mathrm{d}S}{\int \int_{p_0}^{0} q_0(x,y,p) \mathrm{d}p \mathrm{d}S}$$

*Clausius-Clapeyron relationship*

*Larissa's new term*

*Held & Soden, 2006:*

*Robust Responses of the Hydrological Cycle to Global warming*




$$P = Mq$$

*Figure 12: Global-mean precipitation change vs. global-mean surface temperature change*

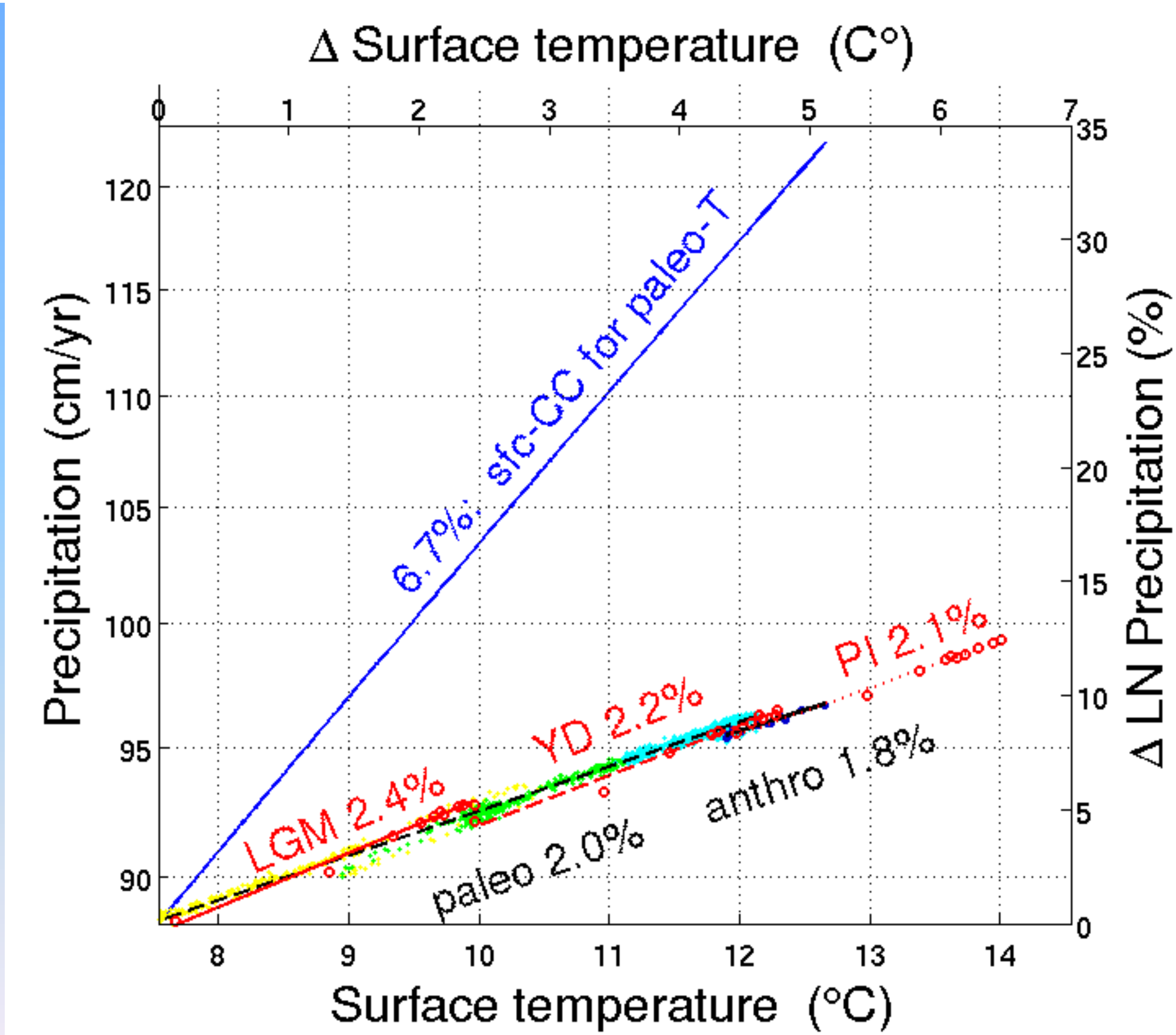



*Figure 13: Globally-averaged precipitation vs. globally-averaged surface temperature*

*Summary:*

- *Regarding the faster rate of global water vapor increase with temperature over the 21$^{st}$ century (as compared to the past 22,000 years):*
  - ➢ *Relative humidity changes are not relevant.*
  - ➢ *The increase in the proportion of water vapor in the tropical upper atmosphere is a secondary factor.*
  - ➢ *Uptake of heat by the Southern Ocean in the rapid-warming (non-equilibrium) scenario results in a greater portion of the global water vapor increase coming from the tropics.*

- *Global precipitation changes at the same rate whether warming is fast or slow.*

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