Upper Tropospheric Water Vapor Simulated in CMIP5 Models: From Present-day Variations to Long-term Change Under Global Warming

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Motivation

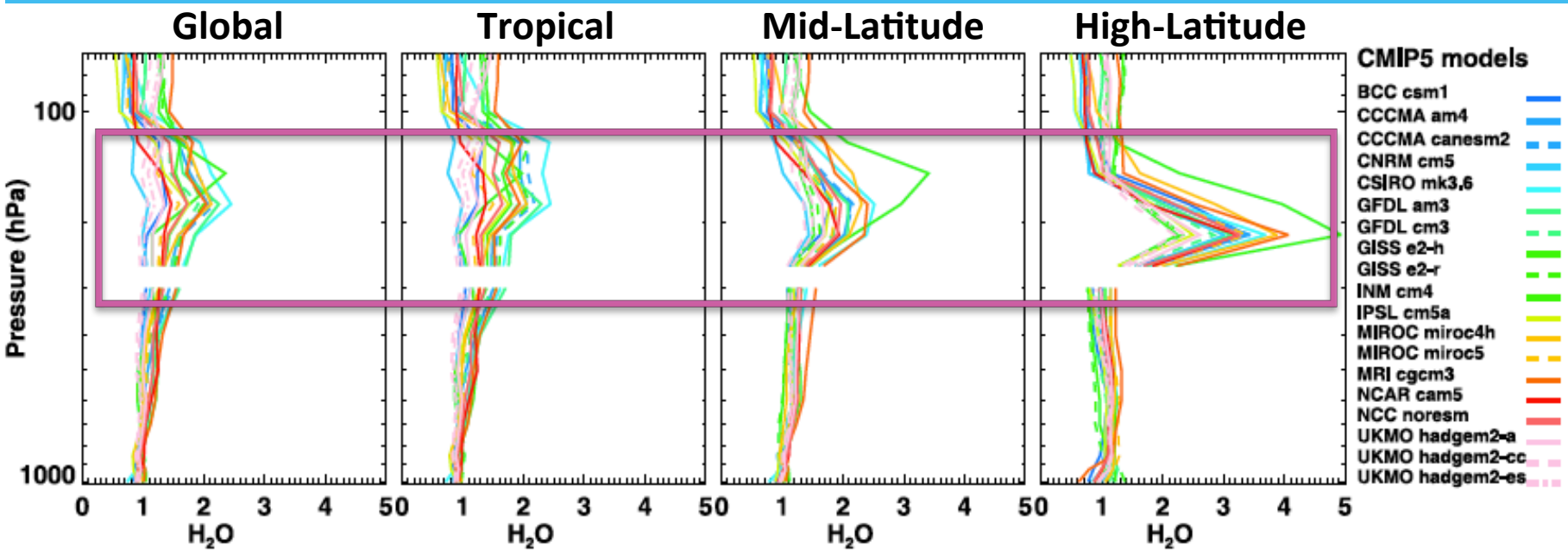


Figure 7. Ratio of multiyear CMIP5 modeled H_2O to A-Train observed values as a function of height.

Jiang et al. (2012)

- The water vapor feedback is particularly sensitive to UTWV (Soden et al. 2008).
- UTWV is one of the most **poorly** simulated quantities in climate models (Jiang et al., 2012)
- The model spreads and their differences from the observations are larger in the UT than in the LT/MT.

Part I. How do RH and temperature contribute to the water vapor errors in climatological mean?

$$\boxed{q = RH \cdot q*(T)}$$

To test relative importance of thermodynamic and dynamic components of UTWV errors, we decompose UTWV errors as:

$$\Delta(*) = (*)_m - (*)_o$$

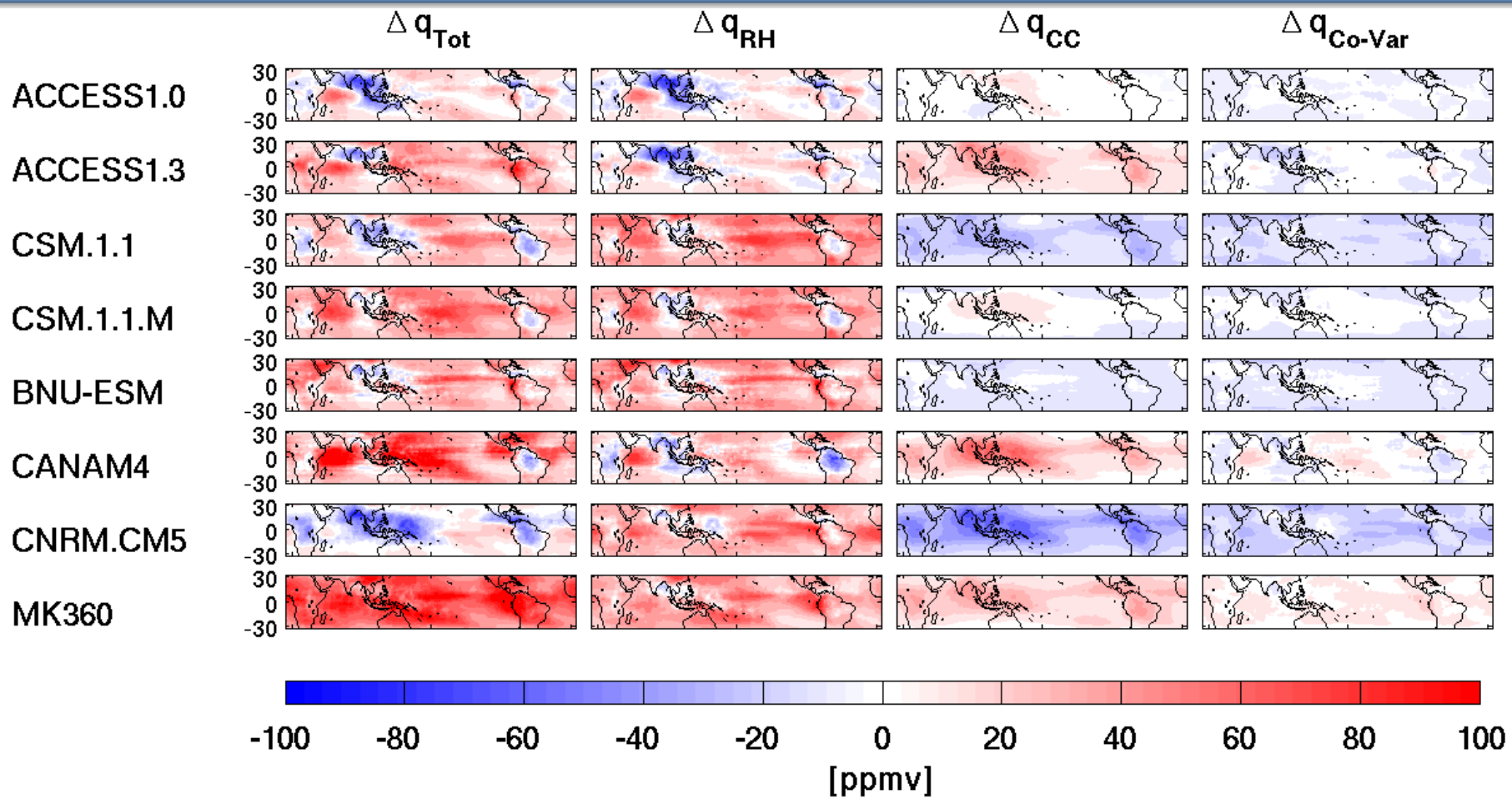
$$\Delta q_{Tot} = \underbrace{\Delta RH \cdot q*(T)_o}_{\Delta q_{RH}} + \underbrace{RH_o \cdot \Delta q*(T)}_{\Delta q_{CC}} + \underbrace{\Delta RH \cdot \Delta q*(T)}_{\Delta q_{Co-Var}}$$

$$\Delta q_{Tot} = \Delta q_{RH} + \Delta q_{CC} + \Delta q_{Co-Var}$$

- Error due to RH is called Δq_{RH}, which is highly correlated with the circulation errors (spatial correlation ~0.5)
  ➔ dynamic component (large-scale circulation + sub-grid clouds)

- Error due to $q^*(T)$ is called Δq_{CC} because it is due to temperature error (Clausius-Clapeyron relationship)
  ➔ thermodynamic component

Part 1. Errors in Climatological Mean: UTWV Error Decomposition



- Models generally have wet biases in the UT, except CNRM.CM5.
- Over the continental regions, models tend to have dry biases.

Takahashi et al. (2015)

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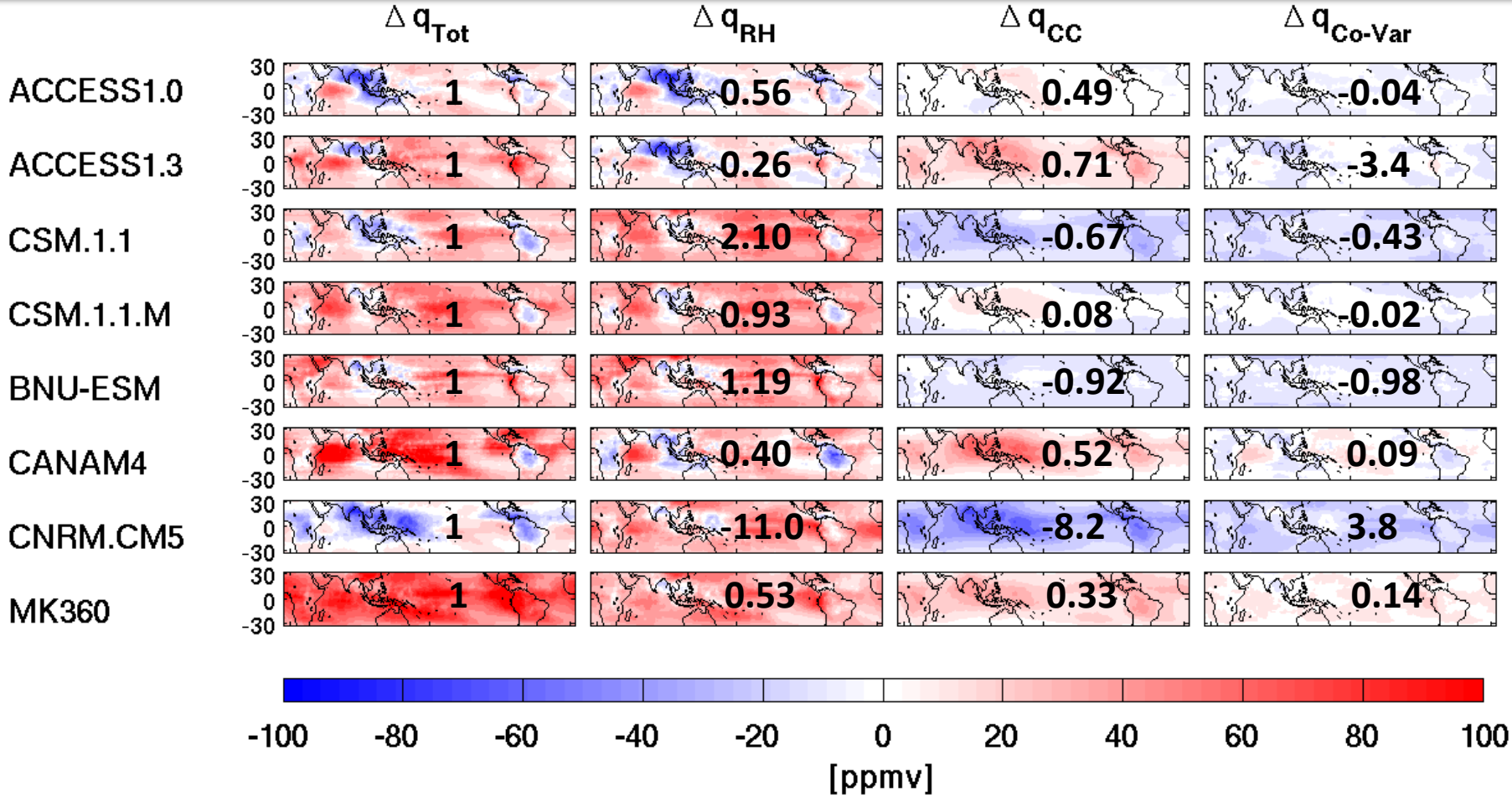


- Models generally have wet biases in the UT, except CNRM.CM5.
- Over the continental regions, models tend to have dry biases.
- 18 models show that the amplitudes of Δq_{RH} account for the largest proportion of Δq_{Tot}

Takahashi et al. (2015)

Part 2. UTWV Changes under Global Warming

Takahashi et al. (2015) found that:

- The large upper tropospheric water vapor (UTWV) errors in CMIP5 are driven by the errors in simulating RH rather than simulating temperature.

1. How do RH and temperature changes contribute to the water vapor change under global warming?

2. Can we infer the rate of long-term water vapor change from present-day interannual variations?

Part 2. (1) Water Vapor Changes under Global Warming

14 coupled atmospheric-ocean models from the CMIP5 archive

- The present-day climate: the 1980–2004 averages from the historical runs
- The future climate: the 2074-2098 averages from representative concentration pathway (RCP) 4.5 runs

The fractional water vapor changes: the differences between the future and present-day water vapor, where the notation *f* and *p* refers to the future climate and present-day climate, respectively.

$$\frac{\Delta q}{q_p} = \frac{q_f - q_p}{q_p}$$

Part 2. (1) Water Vapor Changes under Global Warming

Methodology:

First, to quantify the relative contributions of RH and temperature changes to the fractional water vapor changes, we decompose fractional water vapor changes into three terms :

$$q = q_{sat} \cdot RH$$

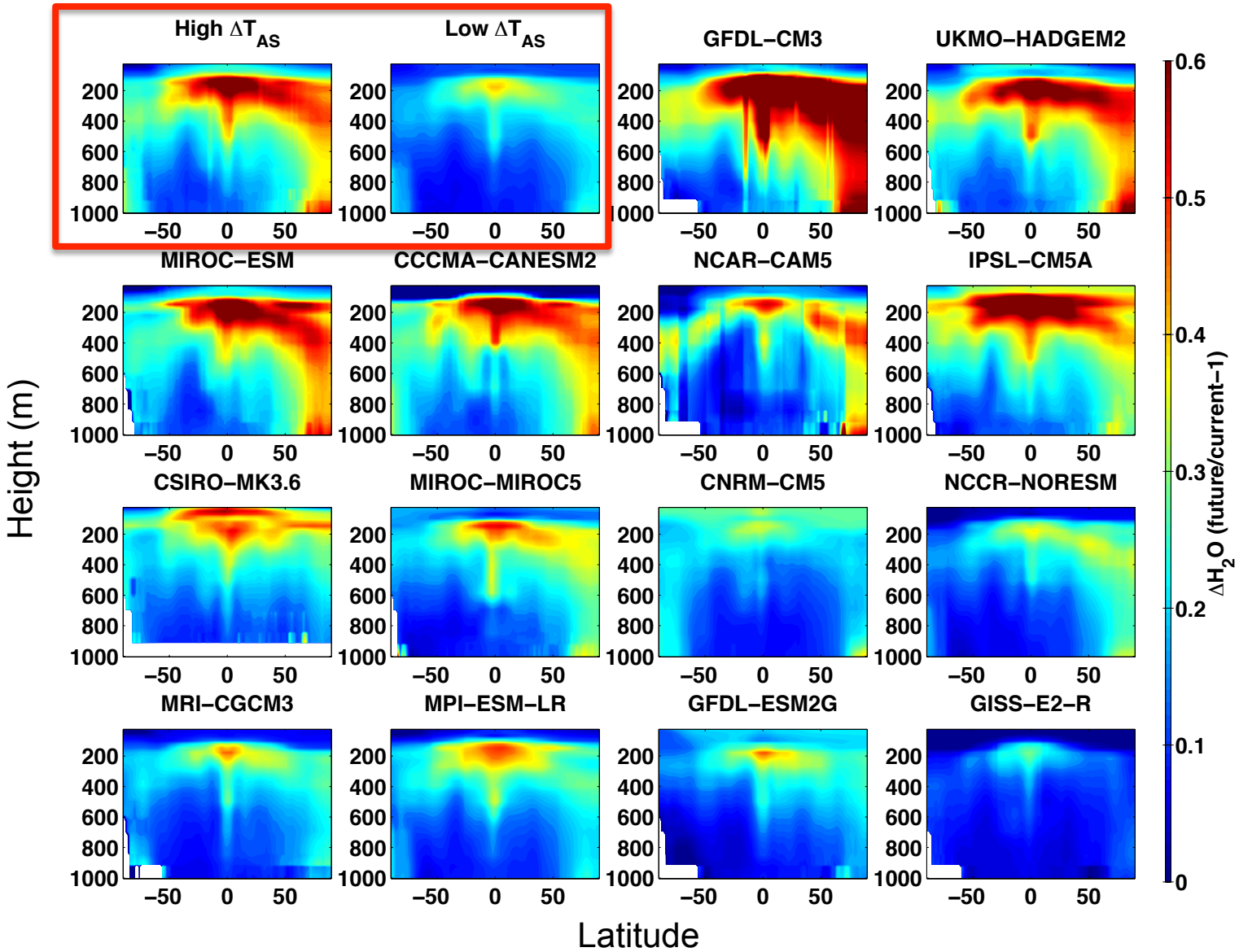
$$\boxed{\frac{1}{\Delta \overline{\overline{T_{AS}}}} \cdot \frac{\Delta q}{q_p}} = \frac{1}{\Delta \overline{\overline{T_{AS}}}} \cdot \left\{ \frac{(q_{sat})_p}{q_p} \cdot \Delta RH + \frac{RH_p}{q_p} \cdot \Delta q_{sat} + \frac{\Delta RH \cdot \Delta q_{sat}}{q_p} \right\}$$

$$= \frac{1}{\Delta \overline{\overline{T_{AS}}}} \cdot \left\{ \boxed{\frac{1}{RH_p} \cdot \Delta RH} + \boxed{\frac{1}{(q_{sat})_p} \cdot \Delta q_{sat}} + \boxed{\frac{\Delta RH \cdot \Delta q_{sat}}{q_p}} \right\}$$

$$\underline{\Delta q_{Tot}} = \underline{\Delta q_{RH}} + \underline{\Delta q_{CC}} + \underline{\Delta q_{Co-Var}}$$

Part 2. (1) Water Vapor Changes under Global Warming

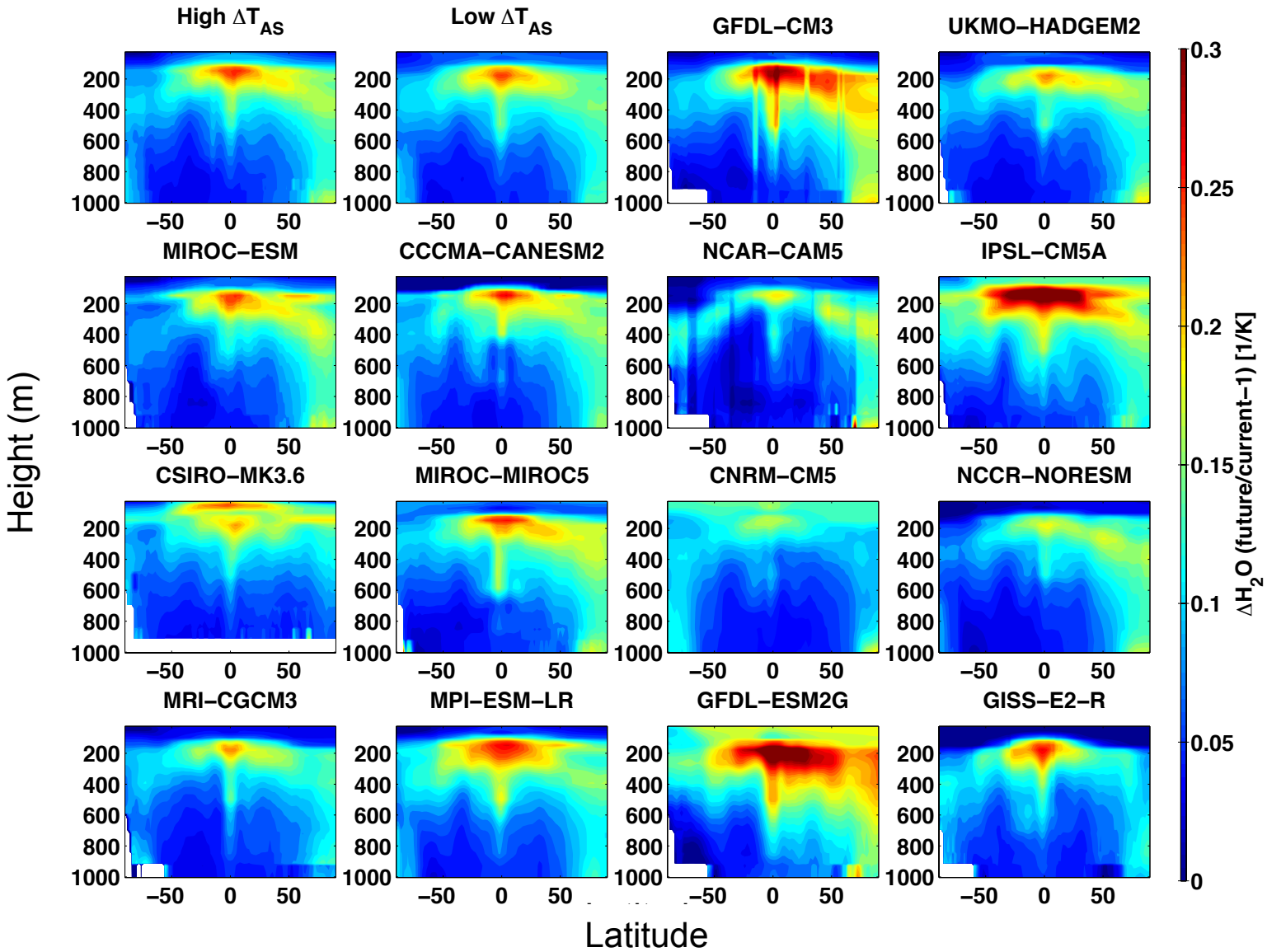
Zonal-mean fractional WV differences between the last 25 years of the 21st century (2074-2098; RCP4.5 runs) and the present-day (1980-2004; historical runs)



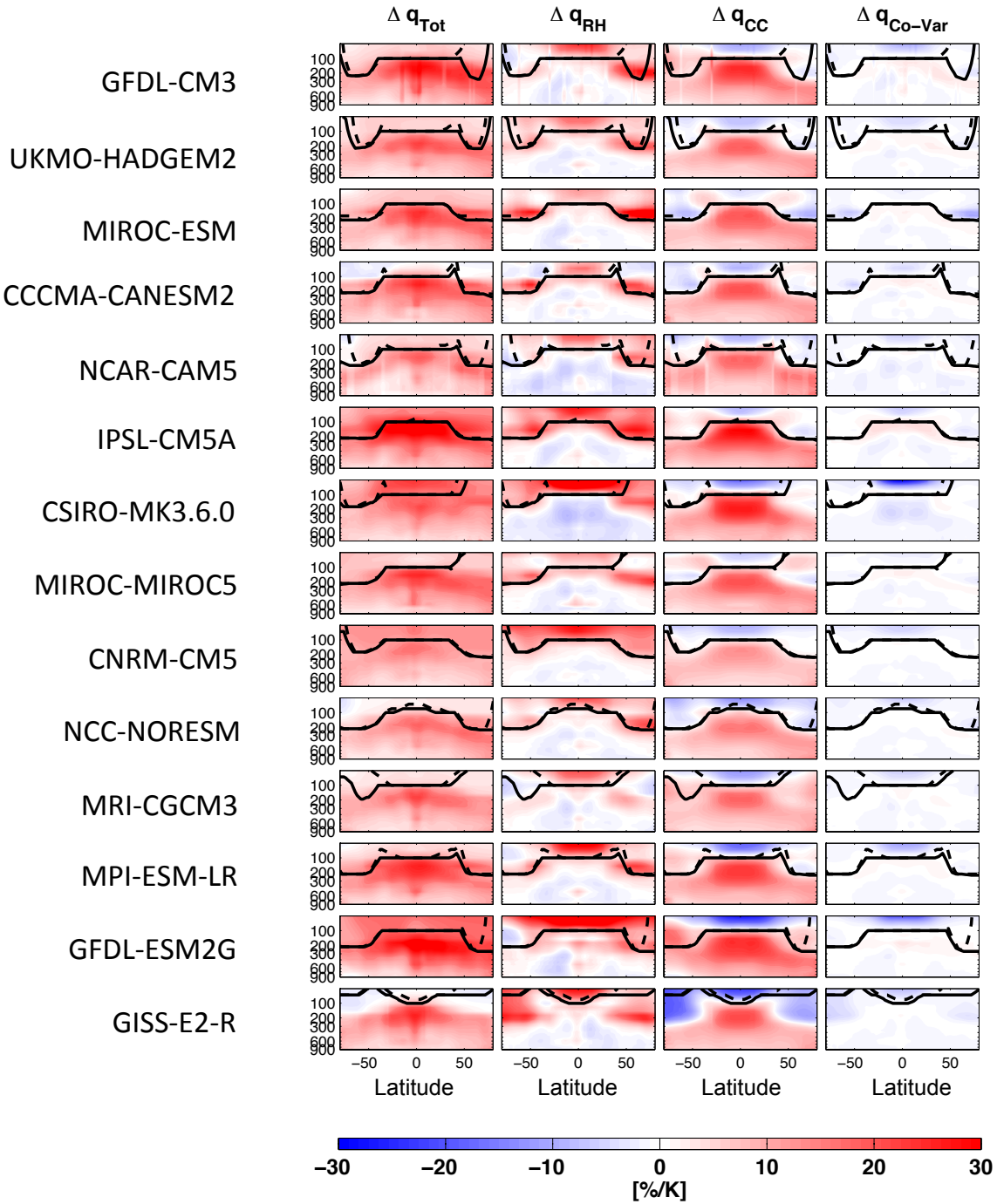
$\overline{\Delta T_{AS}}$=2.3K

Part 2. (1) Water Vapor Changes under Global Warming

Normalize the fractional water vapor changes by the change of global-mean air temperature at 2-meter height (T_{AS}).



ΔT_{AS}=2.3K

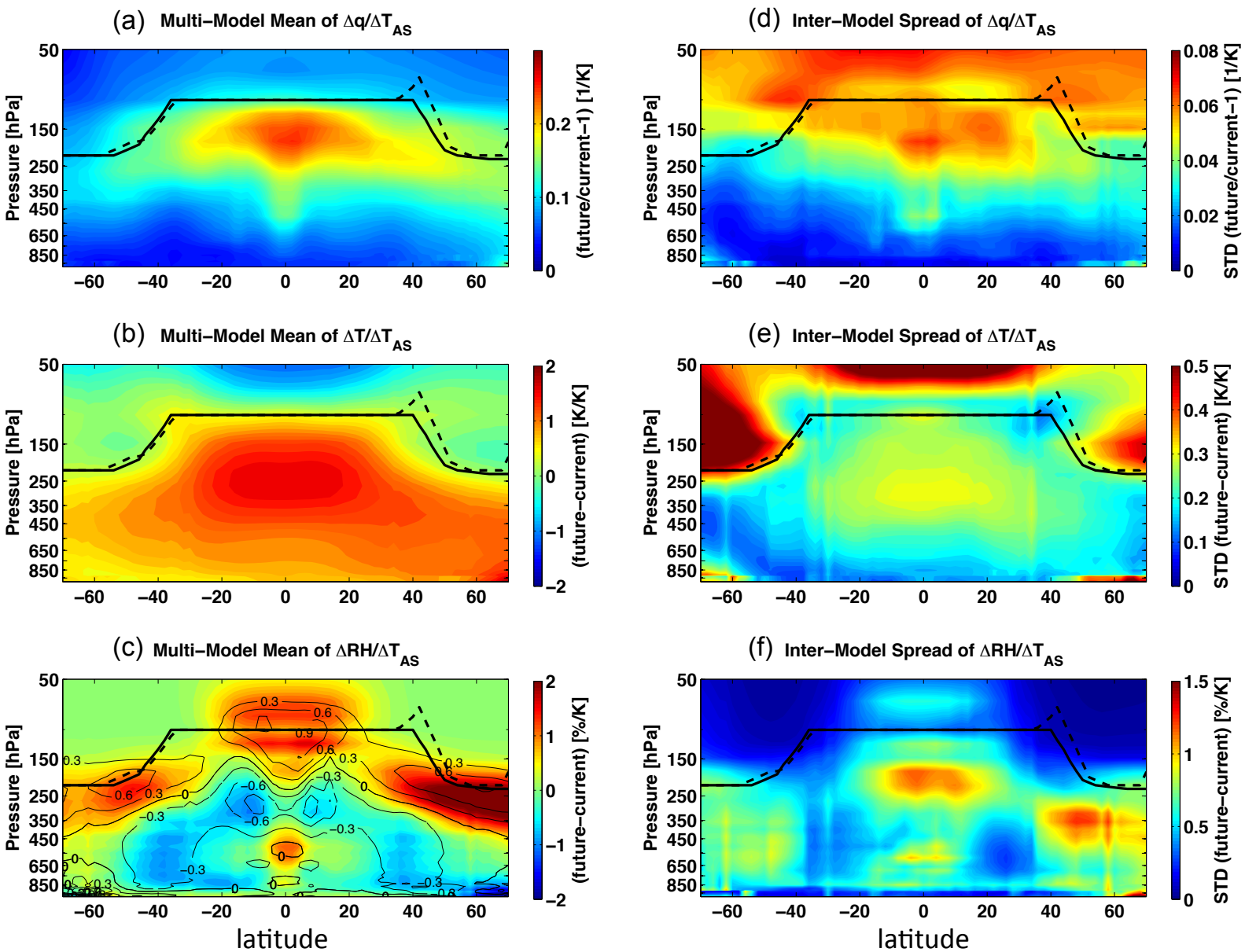


Cold point tropopause in current climate (black lines) and a warmer climate (black-dotted line)

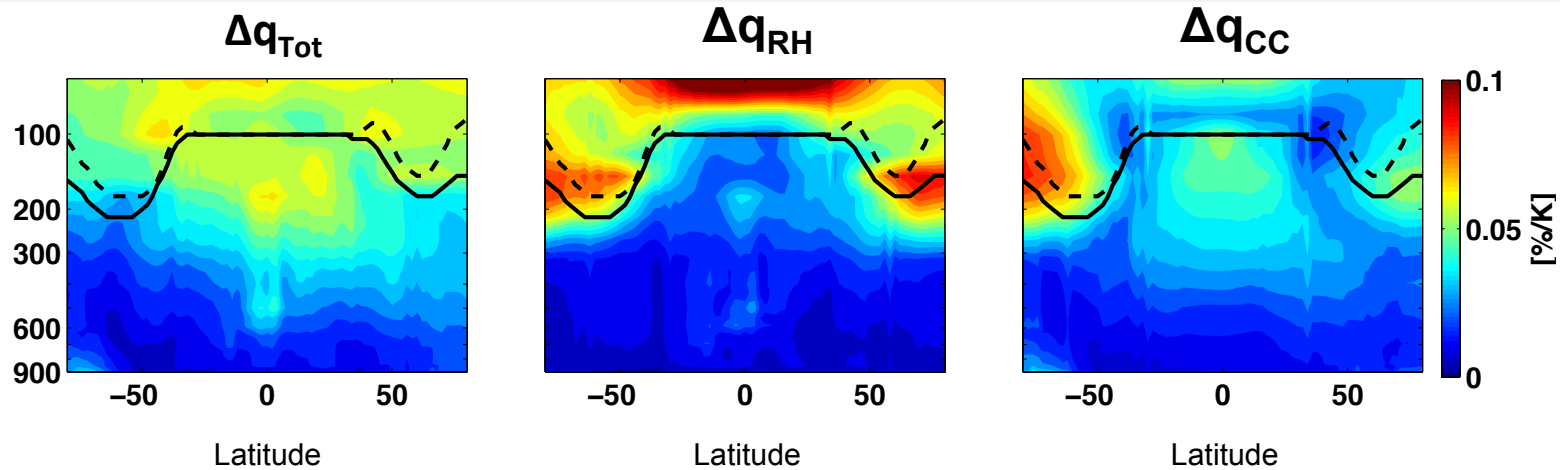
- In a warmer world, Δq_{Tot} is generally dominated by Δq_{CC} throughout the troposphere.
- The relative contribution of RH increases with height while the temperature contribution decreases with height.
- Large discrepancy exists in the simulated tropopause height, suggests a significant model deficiency in representing stratosphere-troposphere exchange.

Part 2. (1) Water Vapor Changes under Global Warming

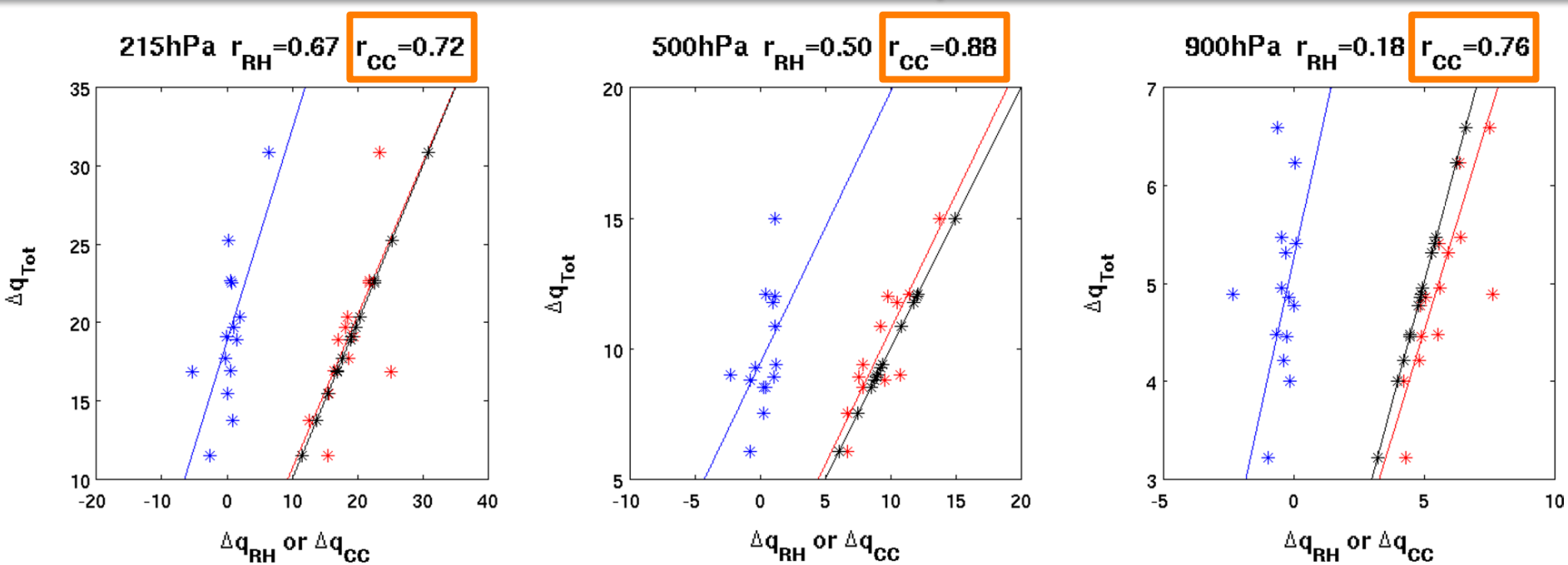
Cold point tropopause in current climate (black lines) and a warmer climate (black-dotted line)



The standard deviation of inter-model differences



The inter-model spread



Part 2. Linkage Between Interannual Variations and Long-term Climate Change

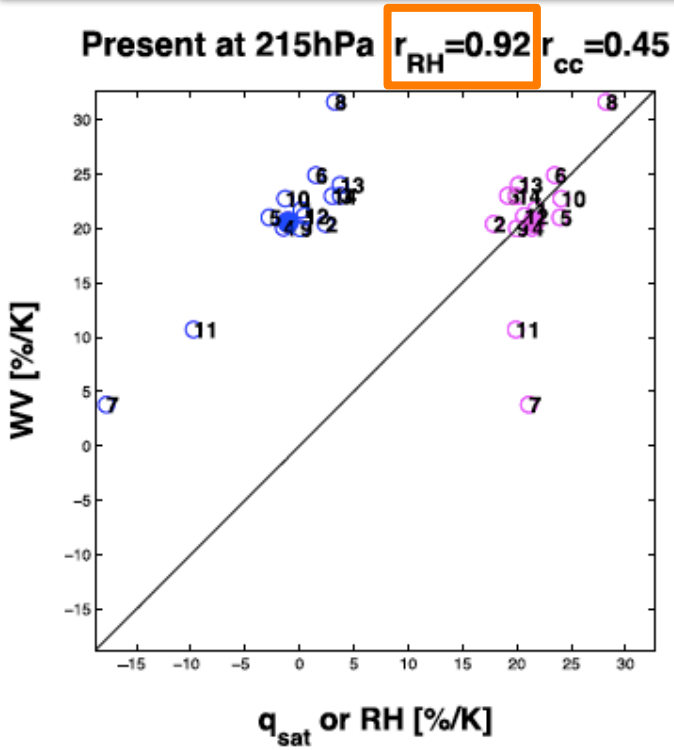
Hypothesis: The observed interannual variations of water vapor could be used as a proxy to project water vapor feedback under climate change.

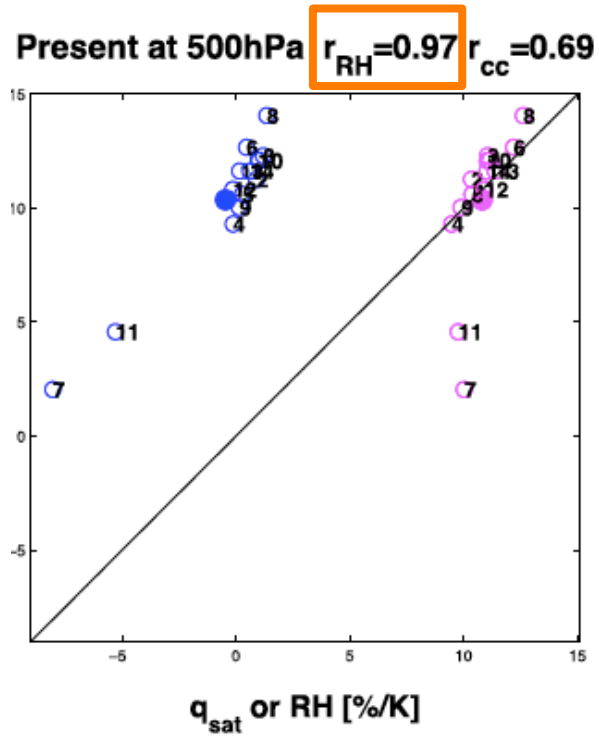
To find a linkage between the future climate and current climate, we compare:

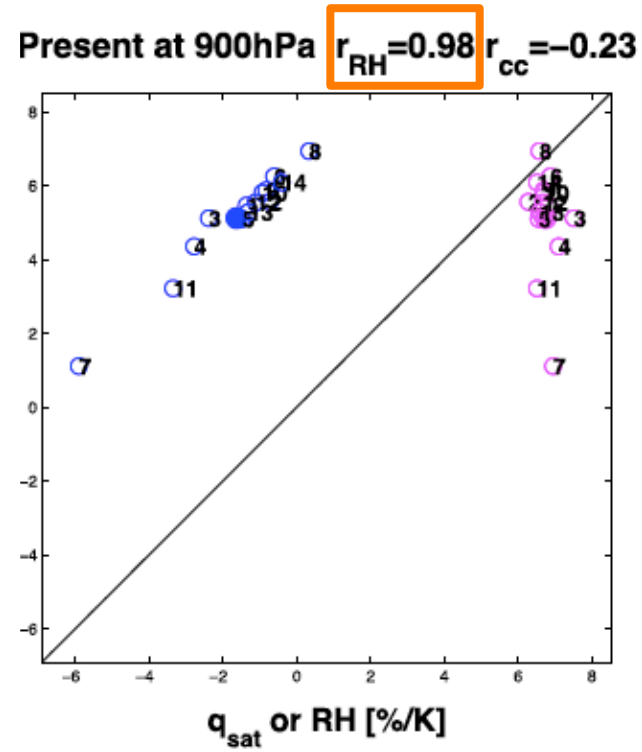
- The rates of water vapor change under global warming (***long-term rates***)
  - the centennial difference between the RCP4.5 (2074-2098) and historical runs (1980-2004)

- The rates of water vapor change derived from inter-annual variability in the current climate (***interannual rates***)
  - the de-seasonalized fractional water vapor in historical runs (1980-2004)

The Inter-model Spread for Interannual Variations



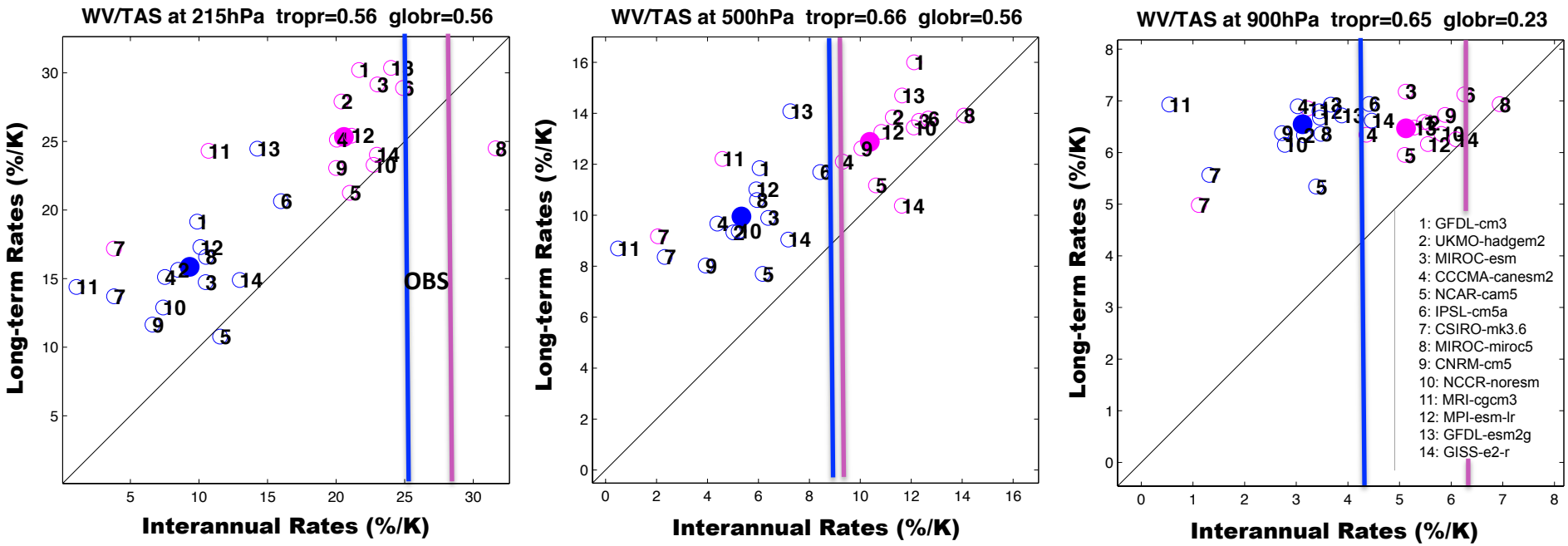




WV rates vs. *q_{sat} rates; WV rates* vs. *RH rates*

- The contribution of the inter-model differences in the RH *rates* to the water vapor *rates* are larger than that of *q_{sat} rates* to water vapor *rates*.

Linkage Between Long-term and Short-term Water Vapor Changes



Average over the tropics; Average over the globe

- The interannual and long-term rates of water vapor change per degree of surface warming are NOT equal.
- Long-term rates are generally higher than interannual rates over the tropics and over the globe for most models.
- The inter-model spreads in long-term and short-term rates are correlated.
- Simulated interannual UTWV changes per degree of surface warming are biased low compared to the MLS observations.

Summary

- **For climatological means, the model simulated RH differences contribute mostly to the simulated UTWV differences.**

- **Under global warming, the simulated temperature changes dominate the water vapor changes. The inter-model spread in UTWV changes are primarily contributed by the model spread in temperature changes, while the model disagreements in RH changes also contribute significantly.**

- **For the interannual variations, the inter-model spread in UTWV sensitivity to surface temperature is dominated by the model differences in simulating the RH variations.**

- **Long-term rates of UTWV change per degree of surface warming are generally higher than the rates on the interannual time scales => El Niño is not a surrogate of global warming.**

- **Inter-model spreads on the long-term and short-term rates of water vapor change are correlated => an emergent constraint on the long-term water vapor feedback.**

- **Takahashi, H., Hui Su, and J. H. Jiang, 2015: Error analysis of upper tropospheric water vapor in CMIP5 models using "A-Train" satellite observations and reanalysis data, *Clim Dyn.*, doi: 10.1007/s00382-015-2732-9.**
- **Takahashi, H., Hui Su, and J. H. Jiang, 2016: Water Vapor Changes Under Global Warming and the Linkage to Present-day Interannual Variabilities in CMIP5 Models, *Clim Dyn.*, doi: 10.1007/s00382-016-3035-5.**