Understanding the Hydrologic Cycle Response to Climate Change
1. Water Vapor

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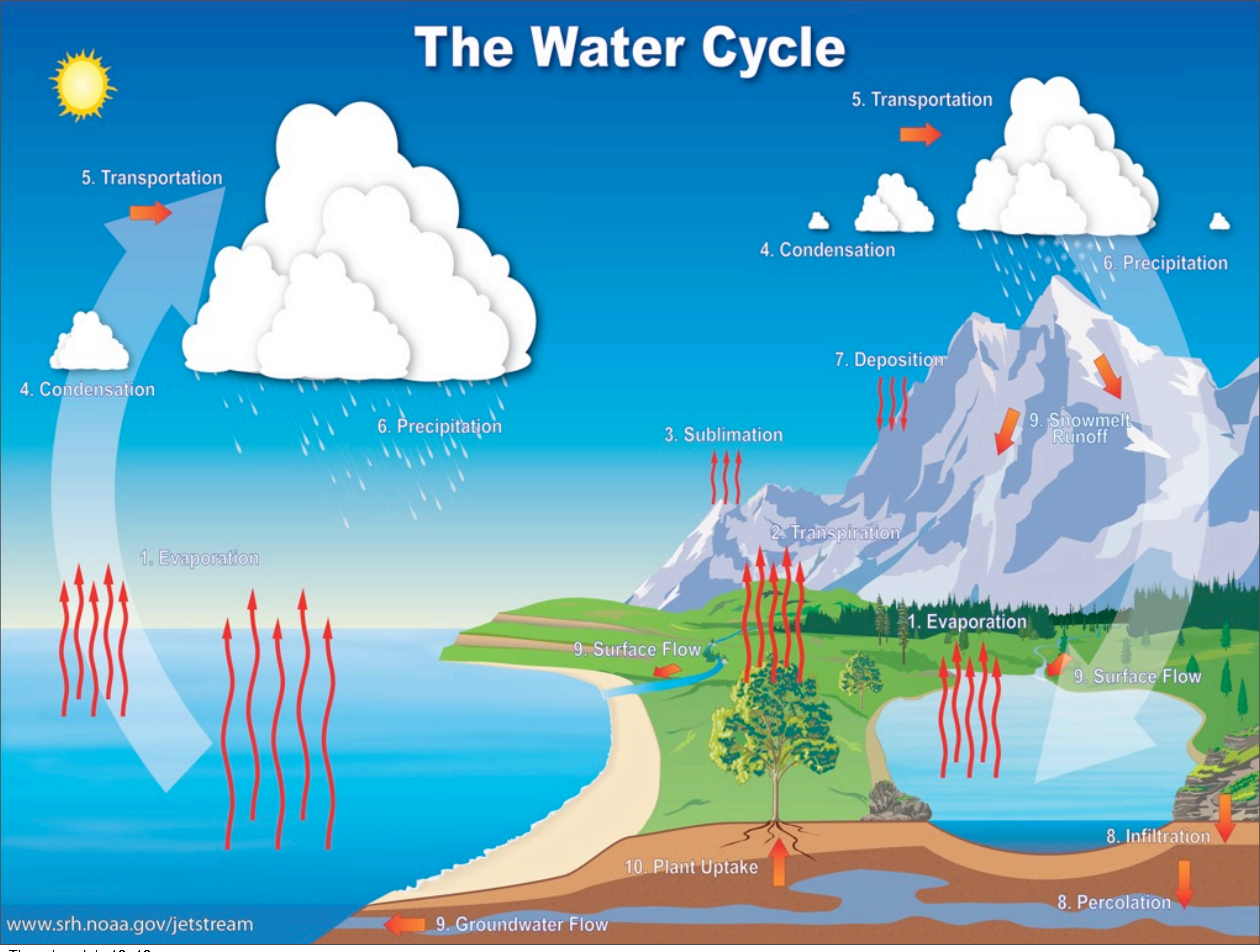
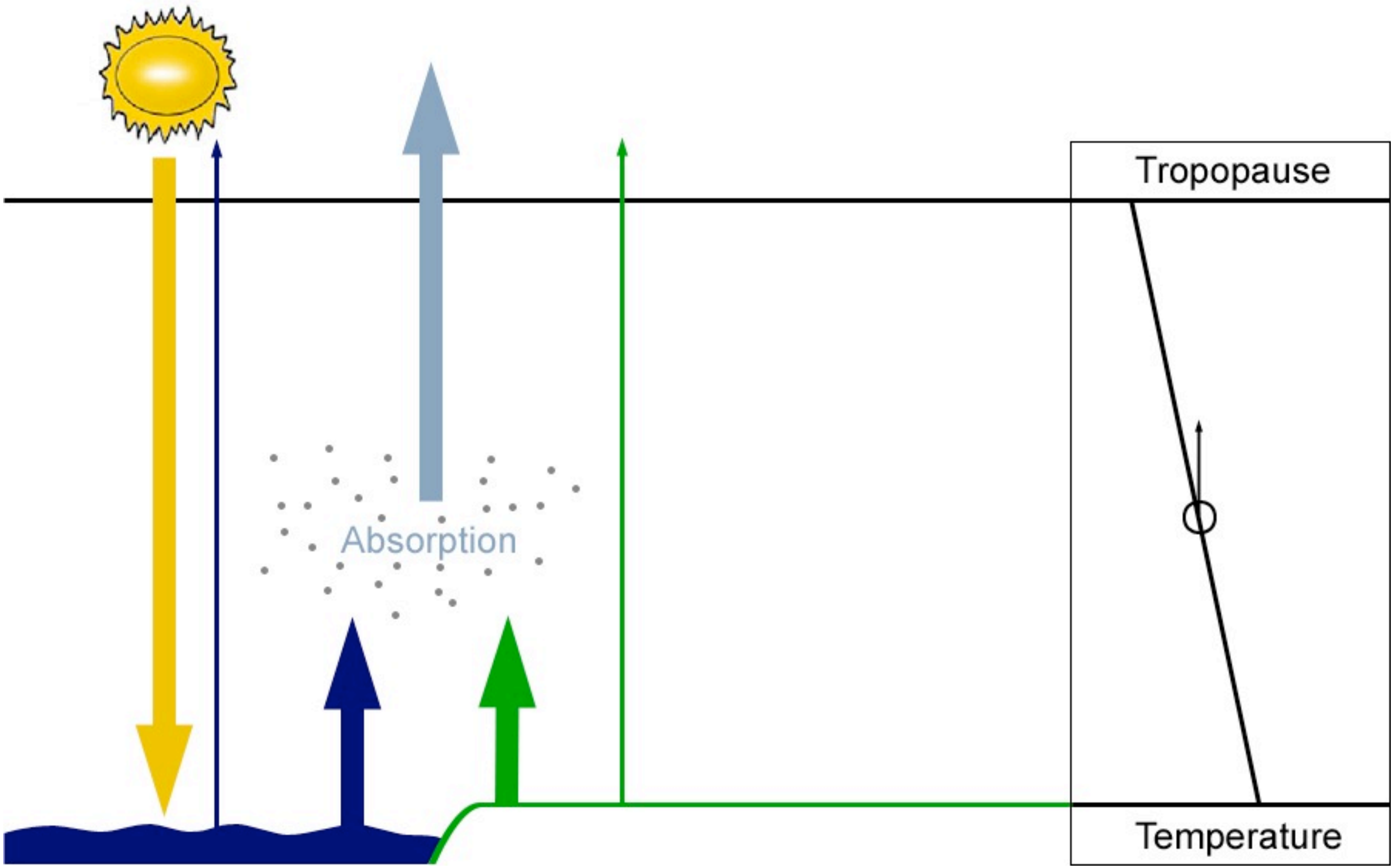
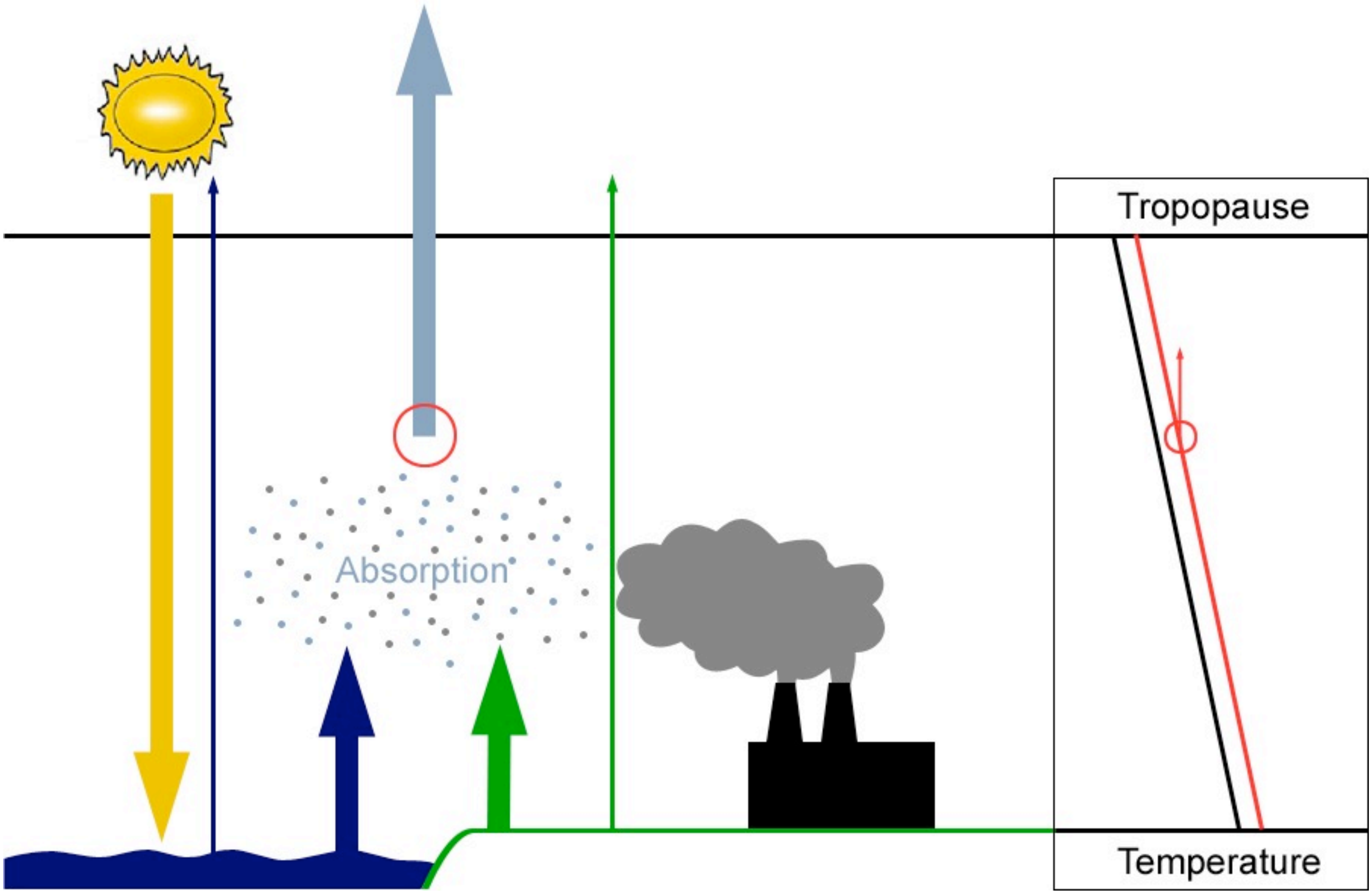

The Water Cycle
5. Transportation
4. Condensation
6. Precipitation
1. Evaporation
5. Transportation
4. Condensation
6. Precipitation
7. Deposition
3. Sublimation
9. Snowmelt Runoff
2. Transpiration
1. Evaporation
9. Surface Flow
9. Surface Flow
8. Infiltration
10. Plant Uptake
8. Percolation
9. Groundwater Flow
www.srh.noaa.gov/jetstream

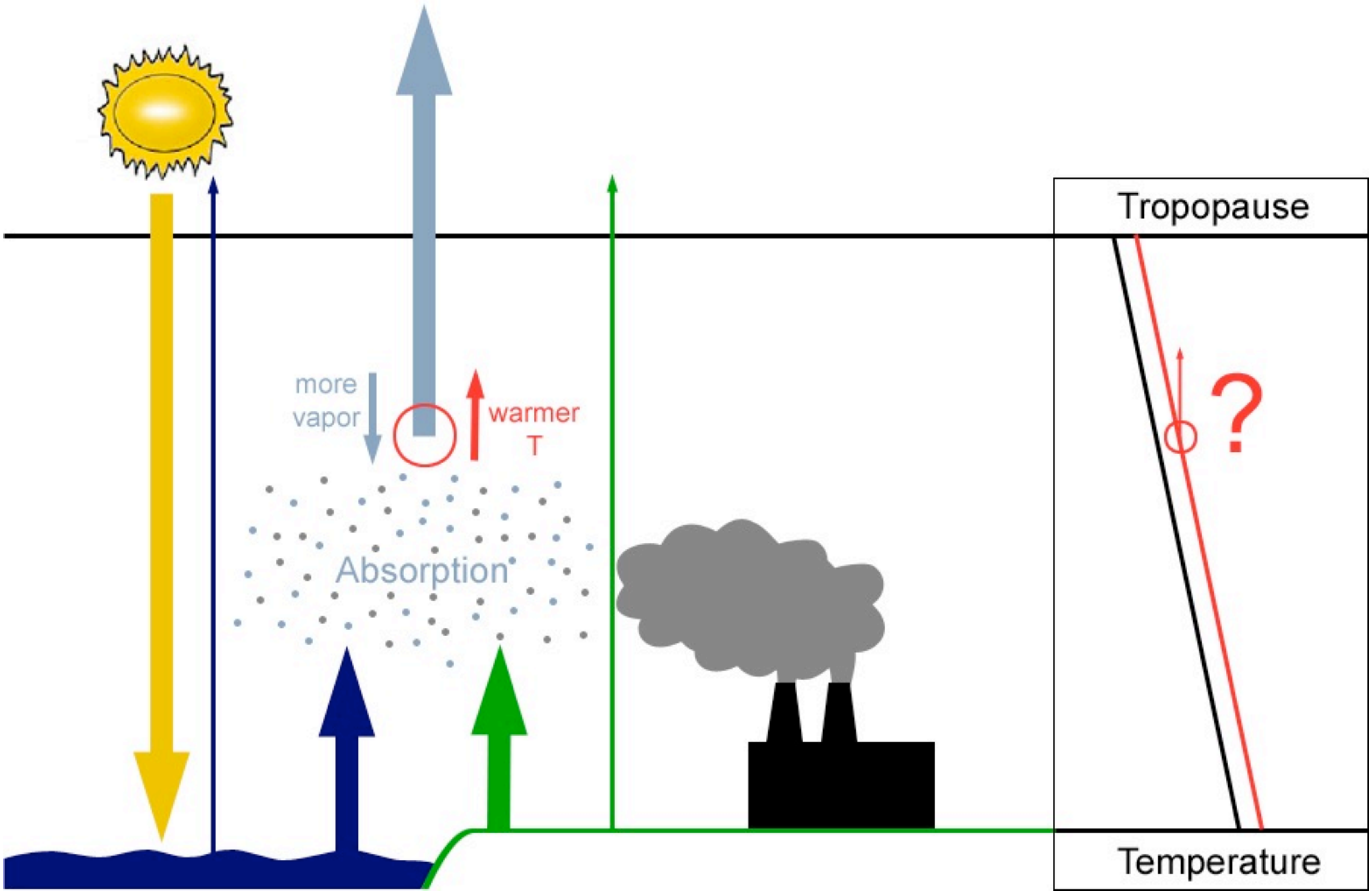
Water vapor is the most influential greenhouse gas due to its abundance and radiative properties



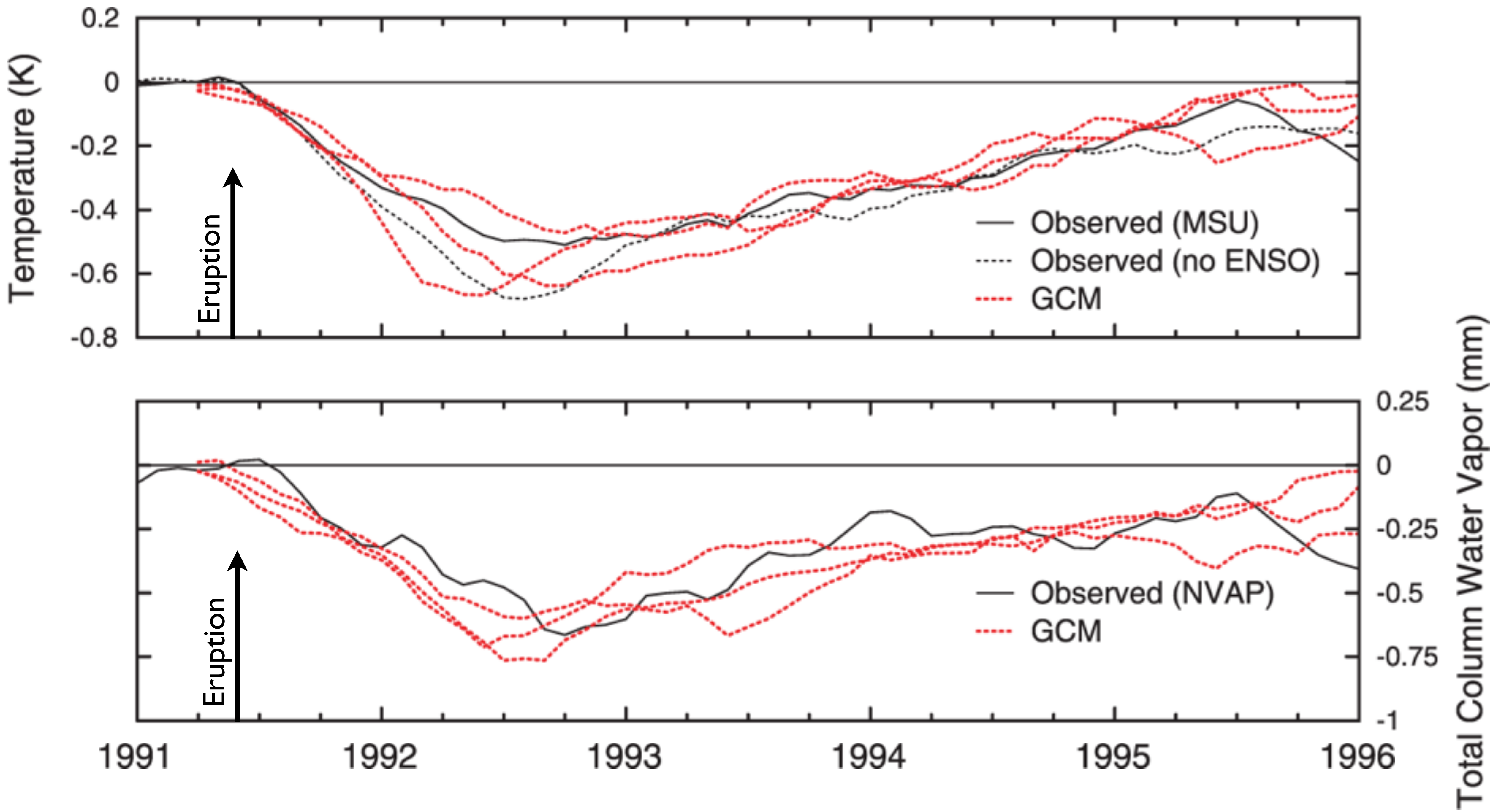
Greenhouse gas emissions increase absorption of long-wave radiation and warm the atmosphere



Water vapor is temperature dependent and may feed back positively to warming — but how much?



Clues: the response to the eruption of Mount Pinatubo

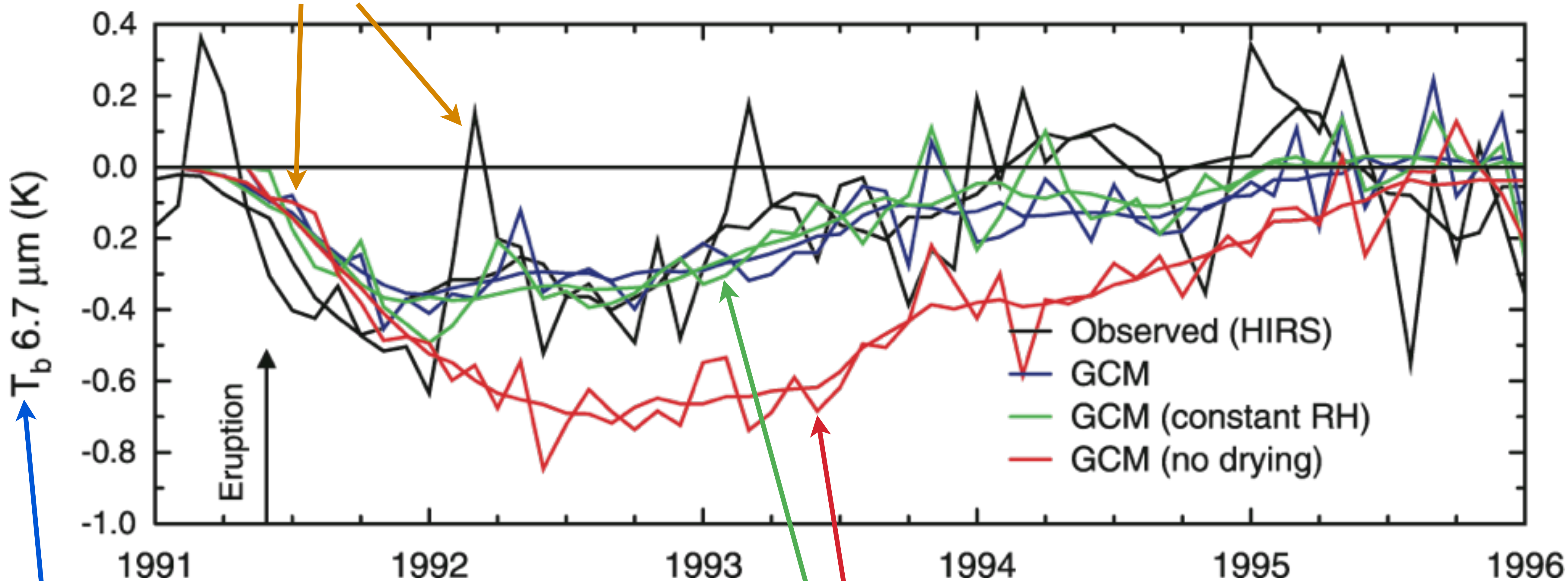


Temperature and water vapor can be observed by satellite instruments and simulated by climate models

Soden et al. 2002

Clues: the response to the eruption of Mount Pinatubo

Climate model simulations can be evaluated by estimating what a real satellite would measure if it could observe "GCM world"



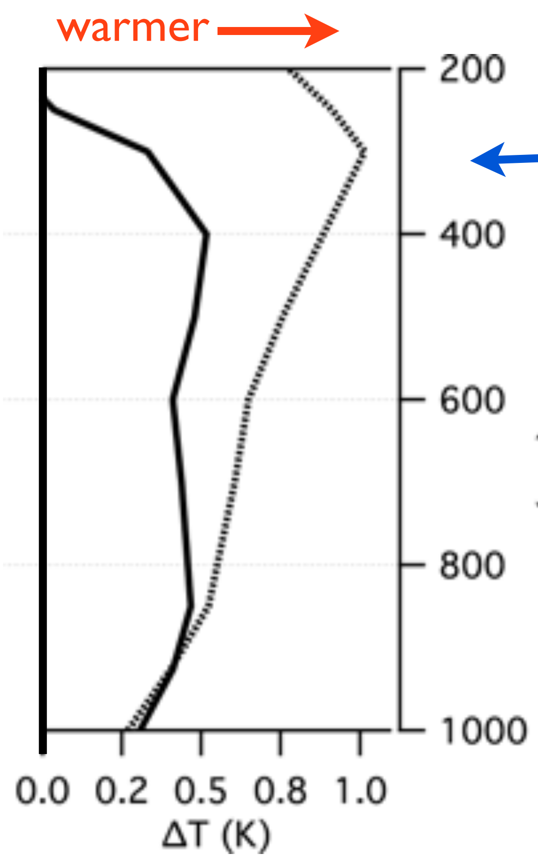
6.7 µm is a water vapor absorption band

The GCM can also be used to simulate limiting cases, such as constant relative or specific humidity

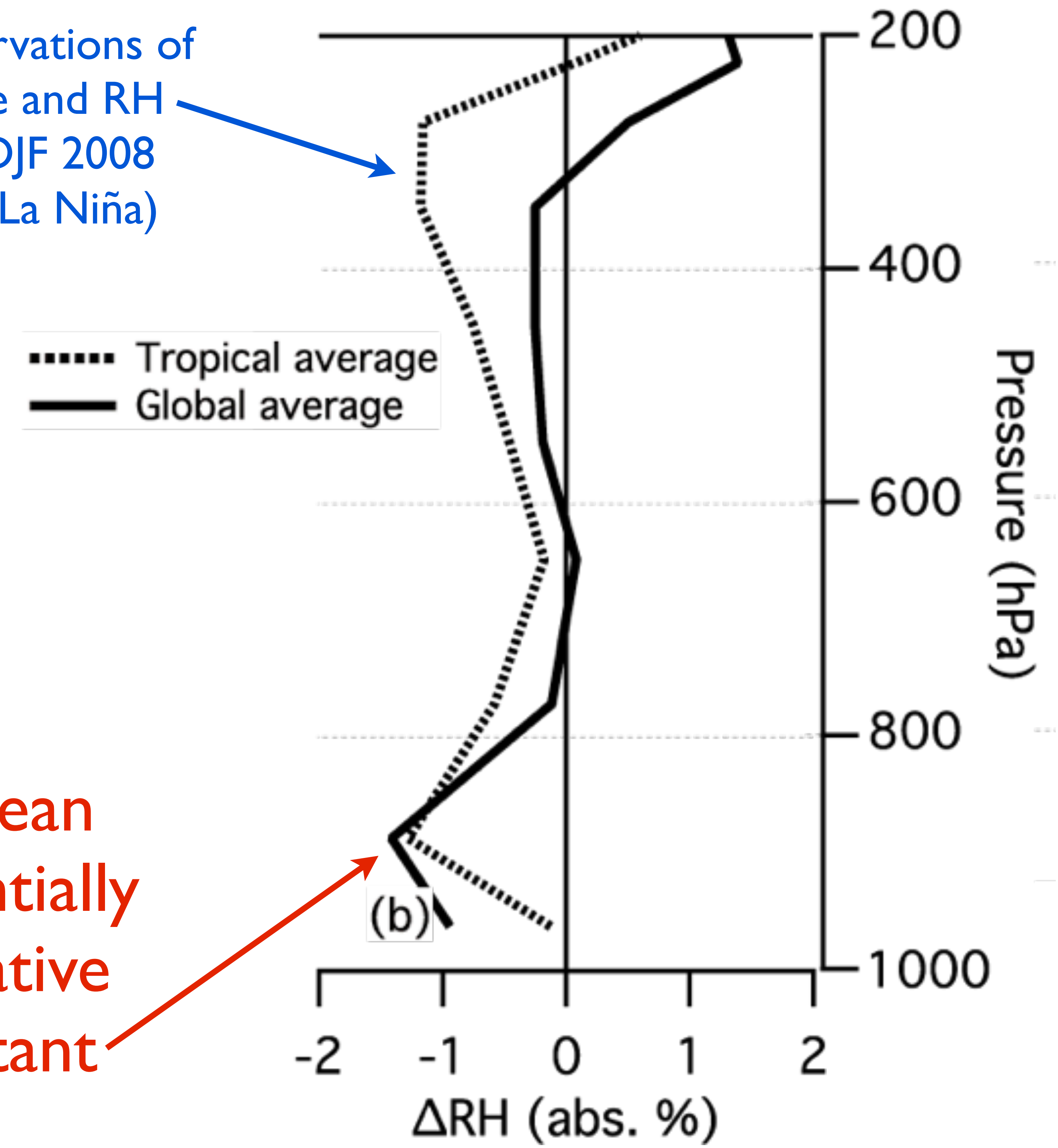
Observations and climate model simulations are very similar to a **constant relative humidity** limiting case

Soden et al. 2002

Clues: the response to El Niño–Southern Oscillation



satellite observations of temperature and RH DJF 2007–DJF 2008 (El Niño – La Niña)



The tropical and global mean temperature varied substantially with ENSO phase, but relative humidity was nearly constant

Dessler et al. 2008

The Clausius–Clapeyron Equation

- Saturation vapor pressure (e^*)
- latent heat of vaporization (L_v) ($\sim 2.5\times10^6$ J kg^{-1})

$$\frac{\partial \ln e^*}{\partial T} = \frac{L_v}{R_v T^2}$$

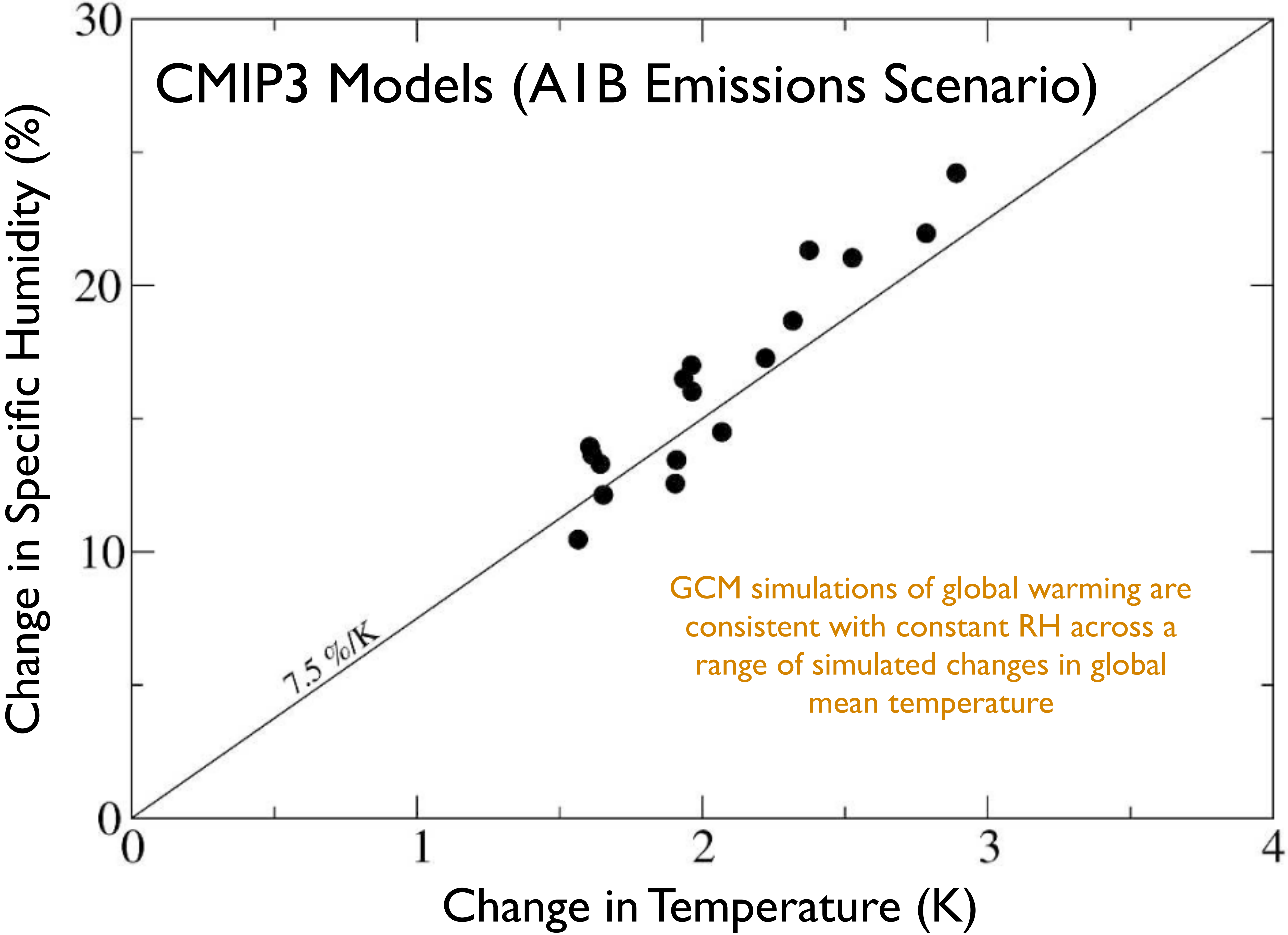
- Gas constant for water vapor (R_v) (461 J K^{-1} kg^{-1})
- Temperature (T) ($\sim$280 K)

The Clausius–Clapeyron Equation

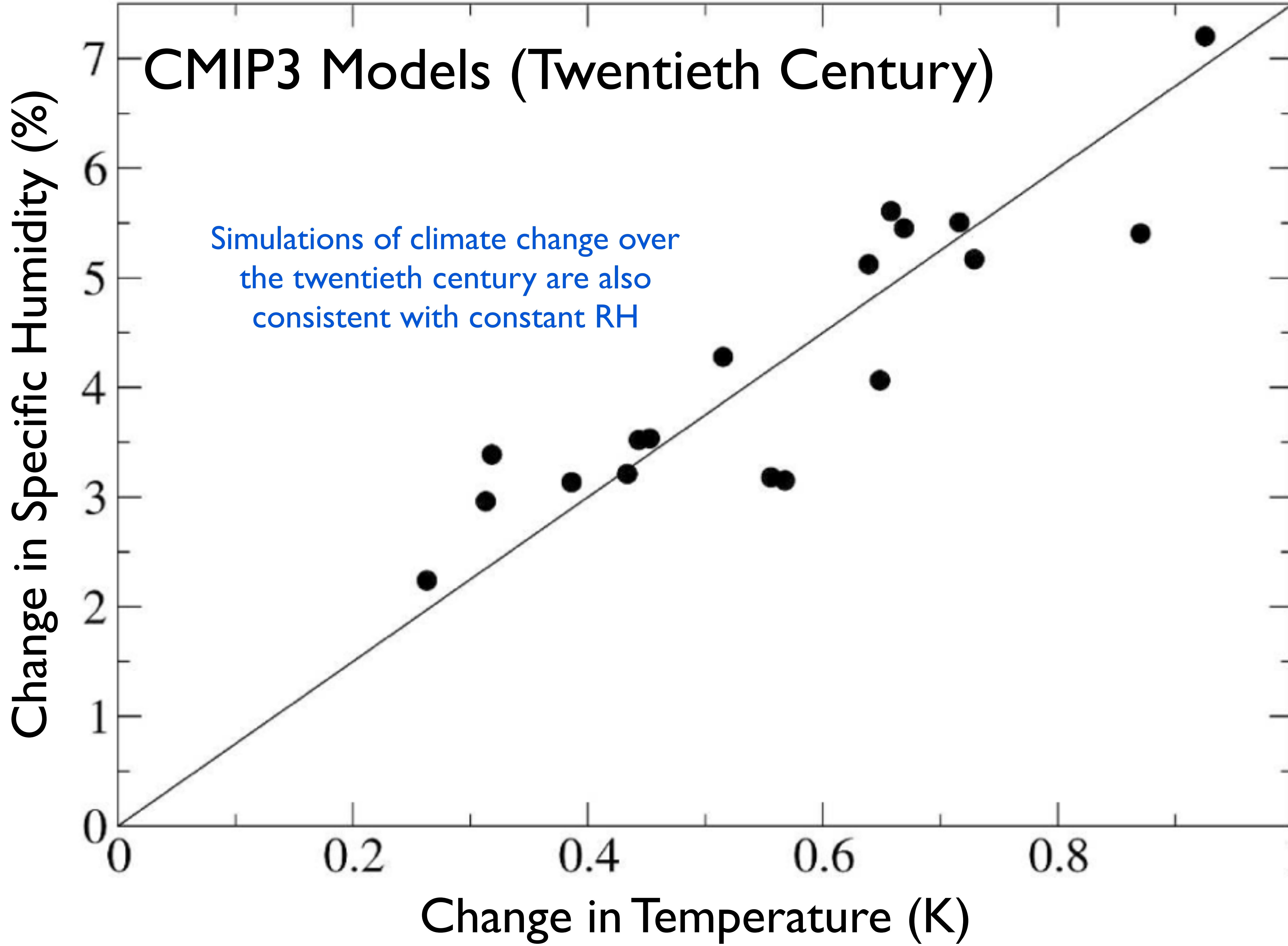
$$\frac{\partial \ln e^*}{\partial T} = \frac{L_v}{R_v T^2} \sim 7\%\ \mathrm{K}^{-1}$$

For RH to be roughly constant, e and e^* must both change at roughly $7\%\ \mathrm{K}^{-1}$

$$\frac{\partial RH}{\partial T} = \frac{\partial}{\partial T}\left(\frac{e}{e^*}\right) \approx 0$$



Held and Soden 2006

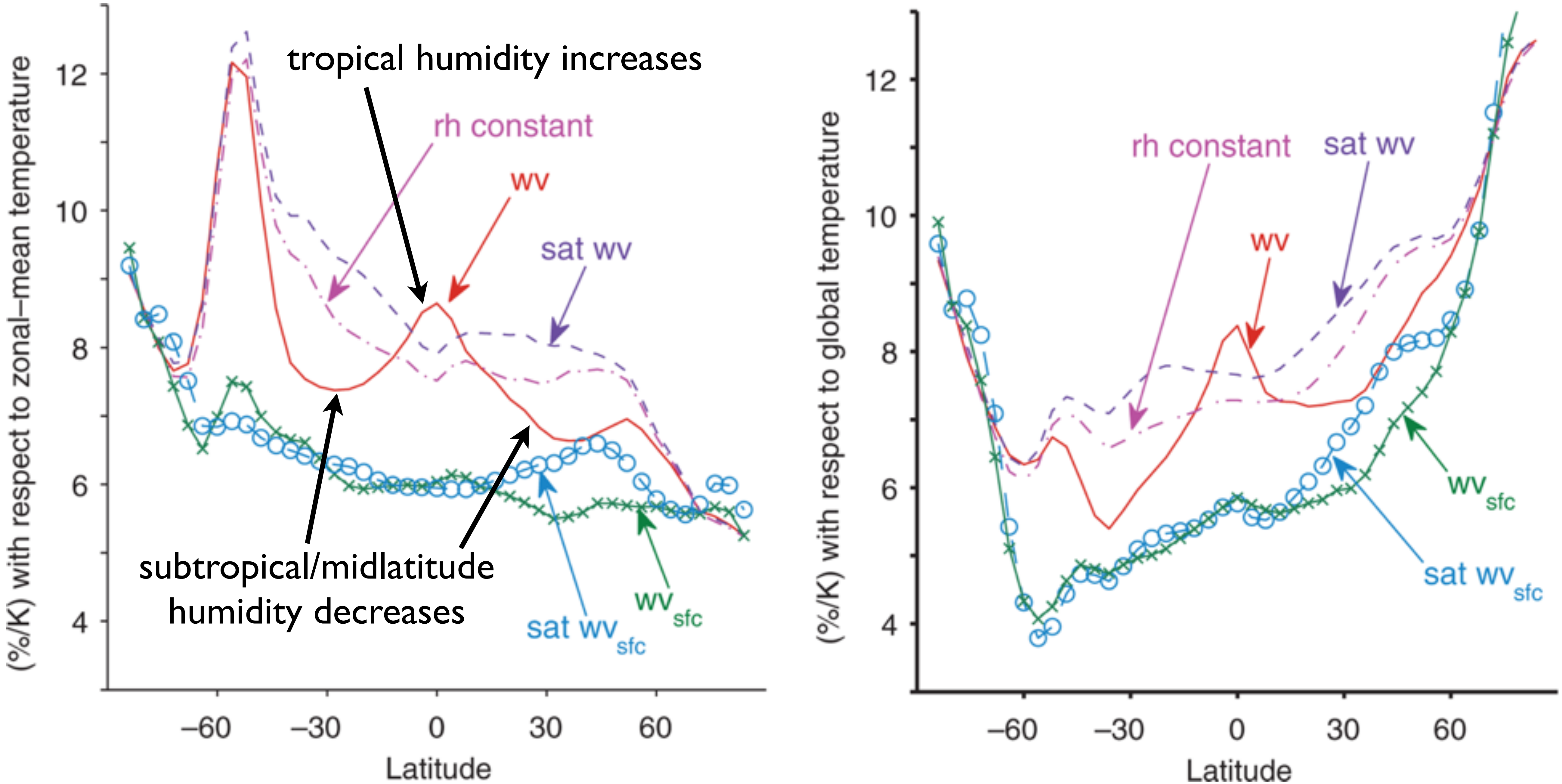


Held and Soden 2006

Simulated and observed trends in global mean total column water vapor are generally consistent with constant RH

ΔWV	Time Period	Source
7.3% K^{-1} (6.5–8.2% K^{-1})	21^{st} century	CMIP3 Models (A1B–20C3M) O'Gorman & Muller 2010
7.4% K^{-1} (6.3–8.5% K^{-1})	21^{st} century (constant RH)	CMIP3 Models (A1B–20C3M) O'Gorman & Muller 2010
6.9±3.6% K^{-1}	1988–2006	SSMI Santer et al., 2007
6.6±0.4% K^{-1}	1989–2008	SSMI/ERA-Interim O'Gorman et al. 2012

Zonal Mean Changes in Humidity



Although simulated global mean RH stays roughly constant, there are important regional deviations from this rule

O'Gorman and Muller 2010

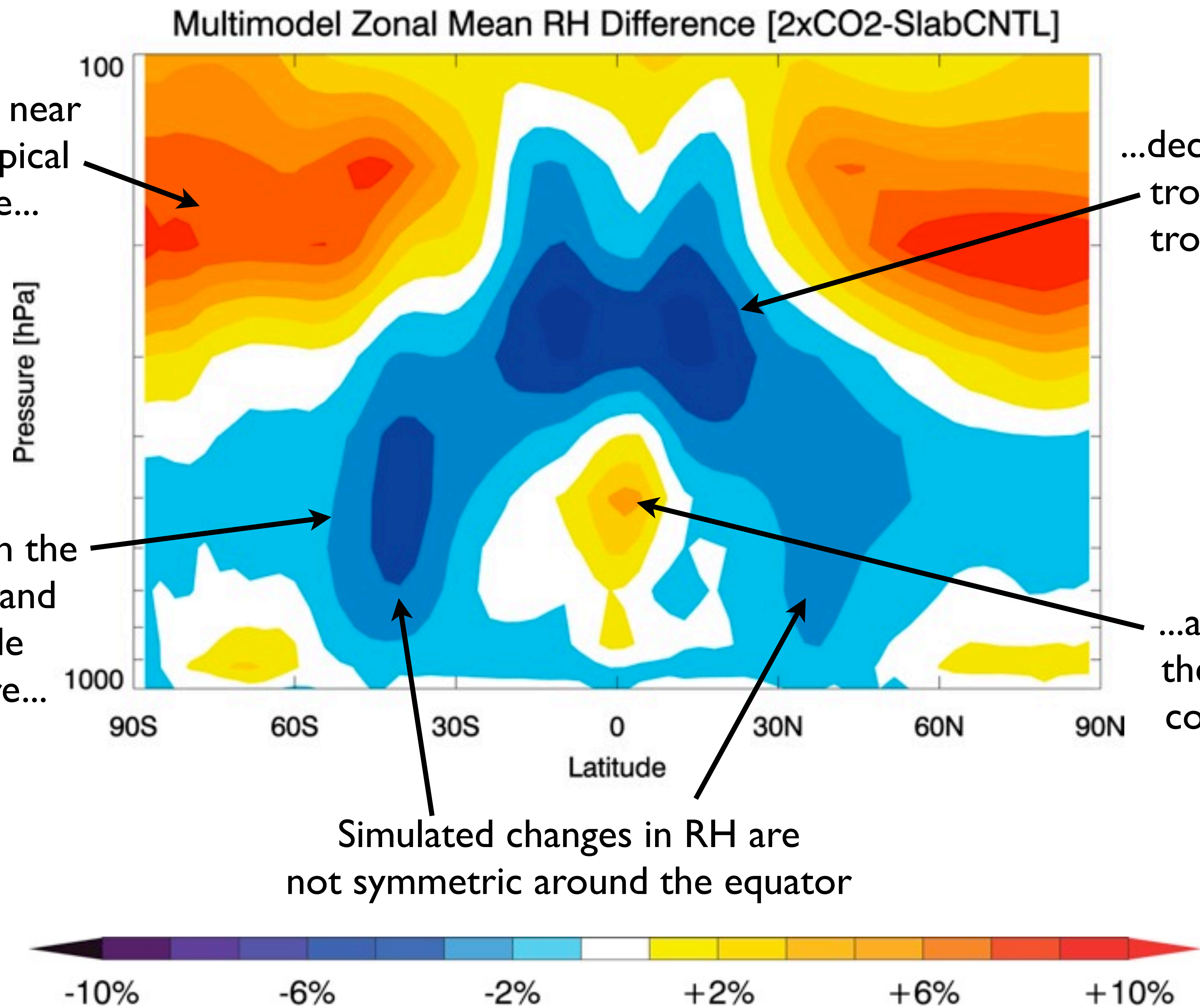
Simulated Changes in Zonal Mean Relative Humidity

RH increases near the extratropical tropopause...

...decreases in the tropical upper troposphere...

...decreases in the subtropical and midlatitude troposphere...

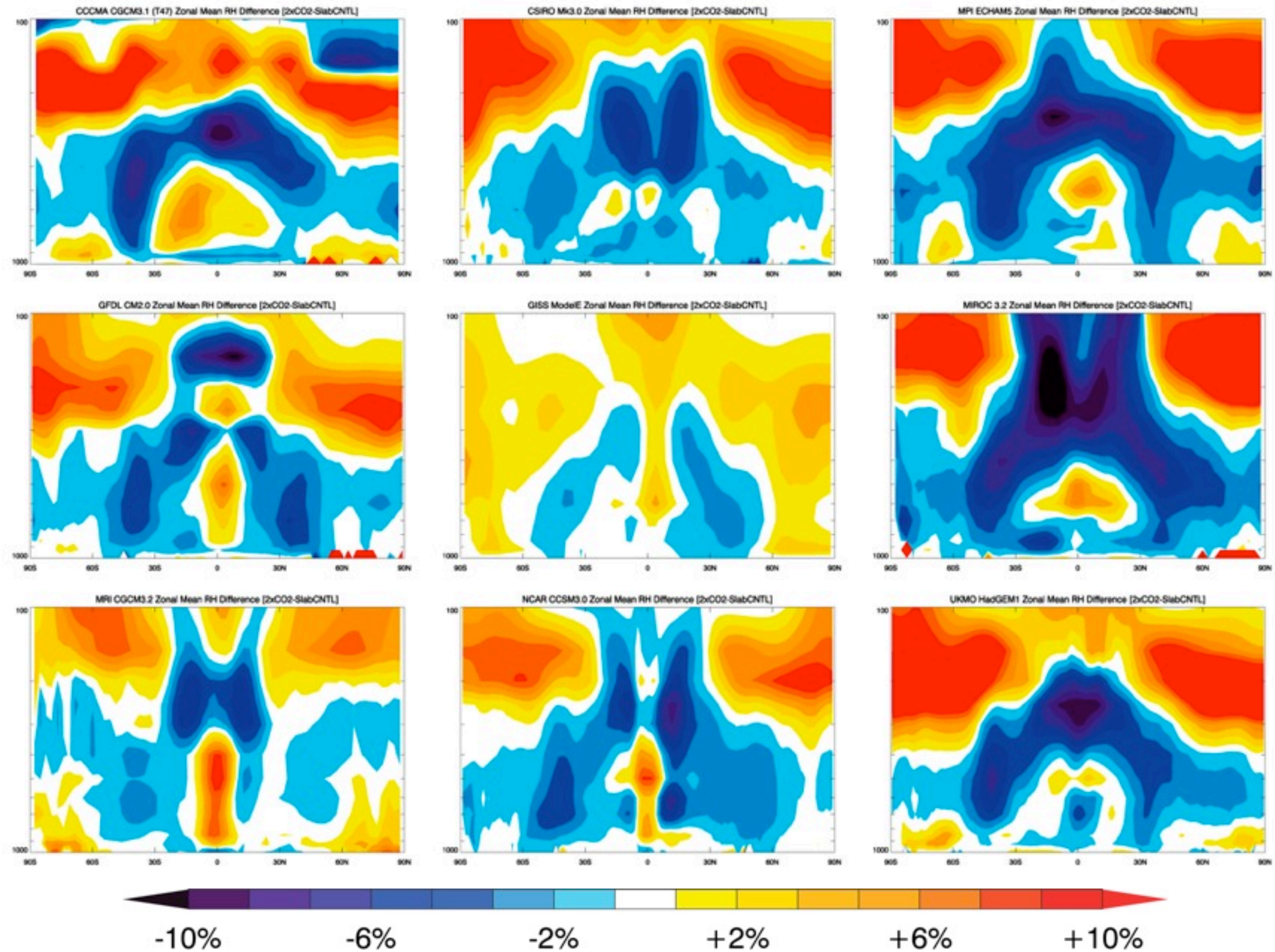
...and increases in the tropical deep convective zone.



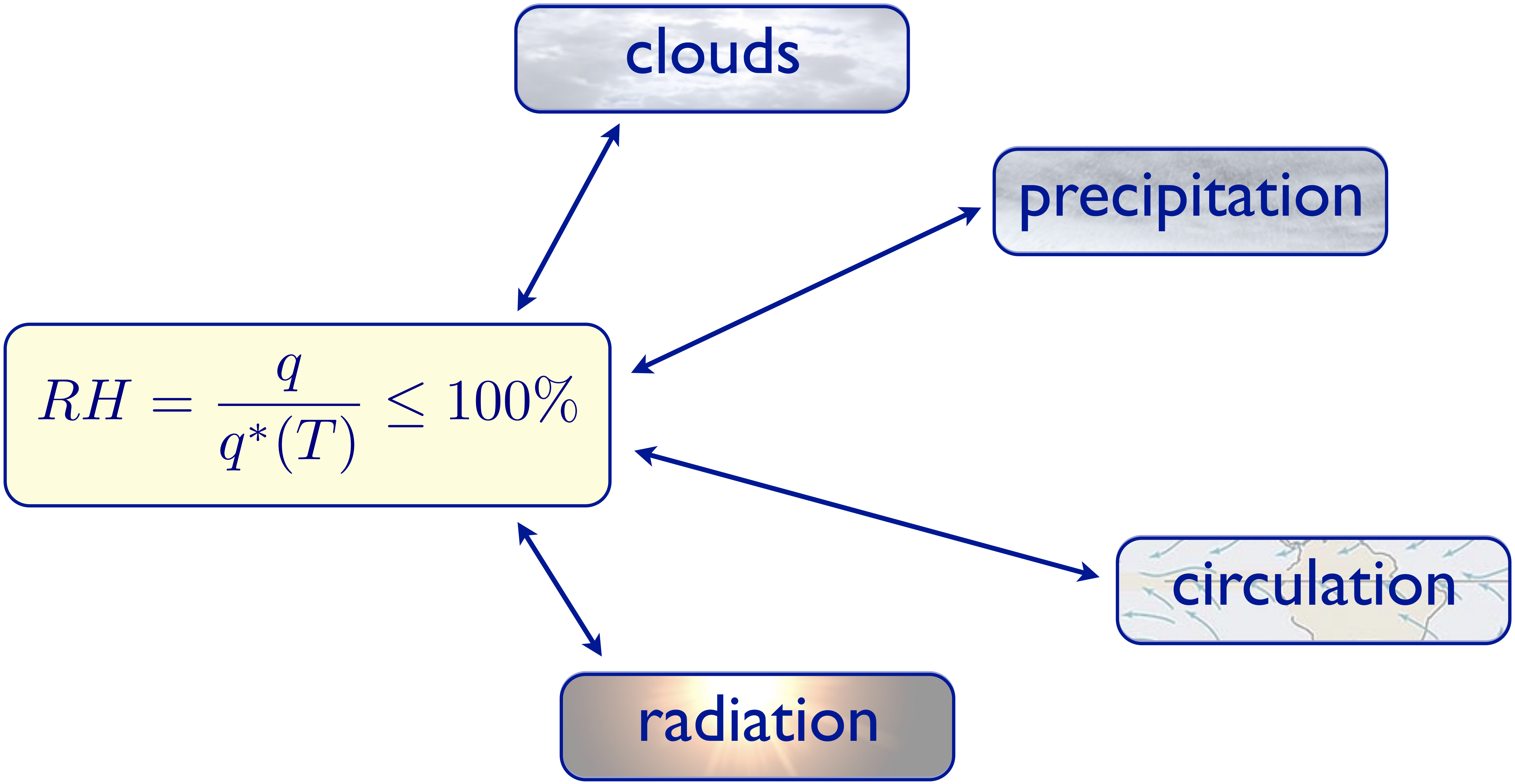
Simulated changes in RH are not symmetric around the equator

Wright et al. 2010

These changes are qualitatively consistent in CMIP3 GCMs

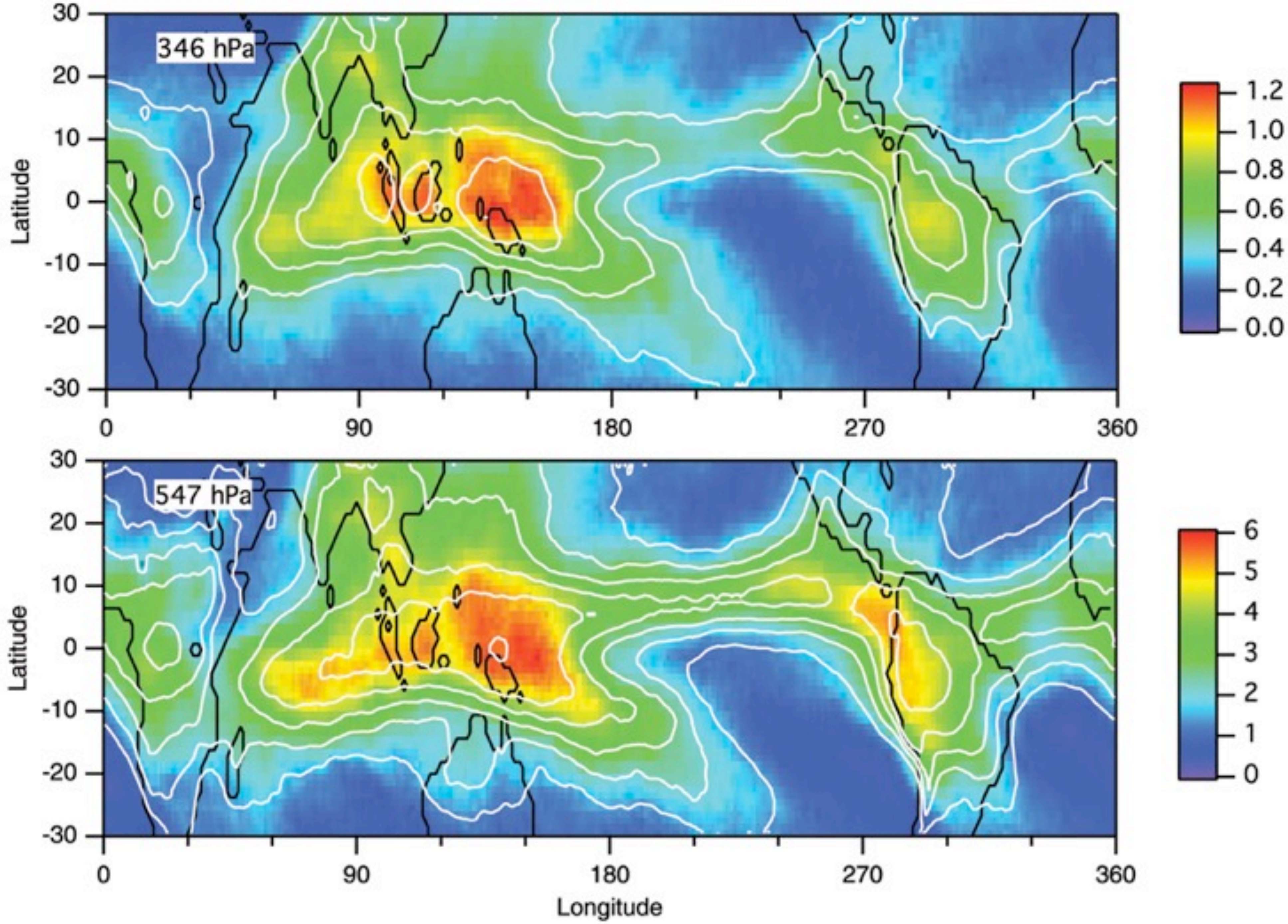


Changes in the distribution of RH have implications for global and regional climate changes...



...so what controls these changes?

Advection–Condensation Models



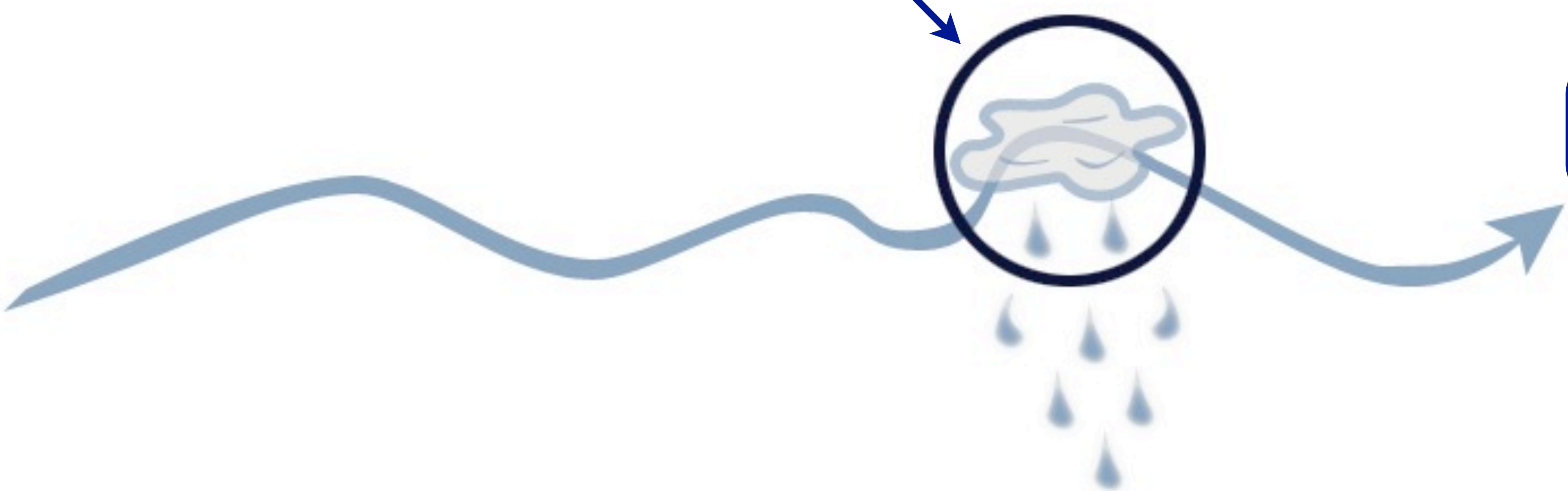
atmospheric water vapor can be simulated using only large-scale winds and temperature

Dessler & Minschwaner 2007

Advection–Condensation Models

The water vapor mixing ratio at any point is determined by the temperature at its location of last saturation...

$$RH(\mathbf{x}^*) = 100\%$$
$$\Downarrow$$
$$q(\mathbf{x}^*) = q^*(T)$$



$$q(\mathbf{x}) = q(\mathbf{x}^*)$$

Advection–Condensation Models

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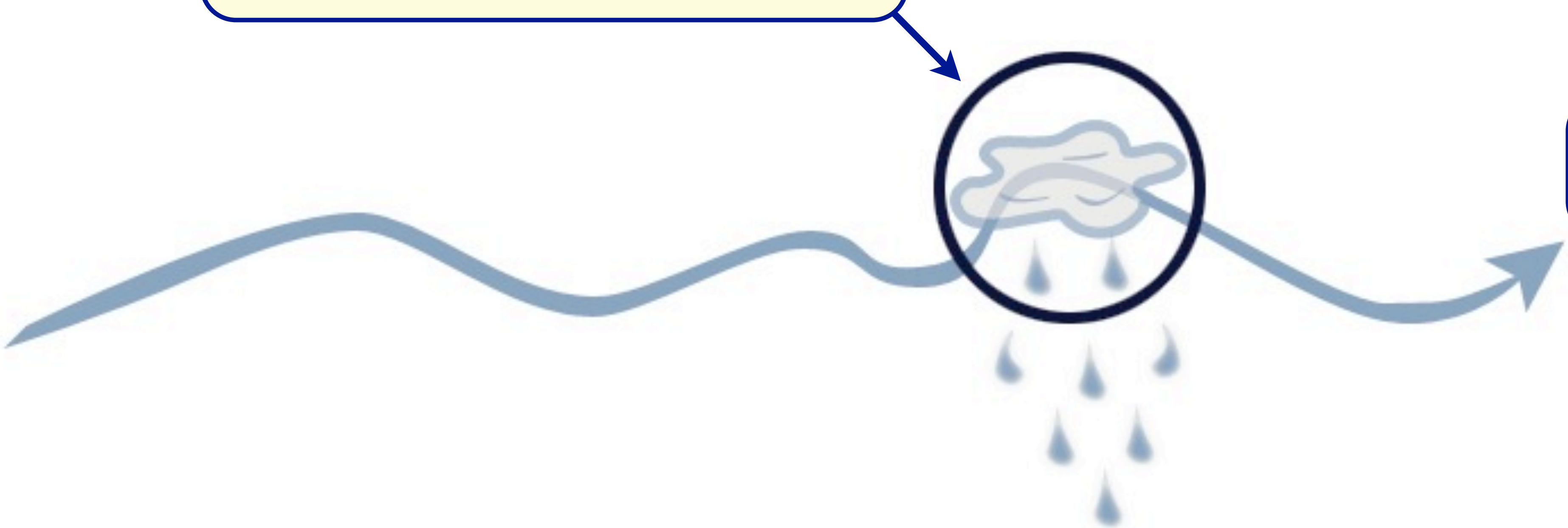
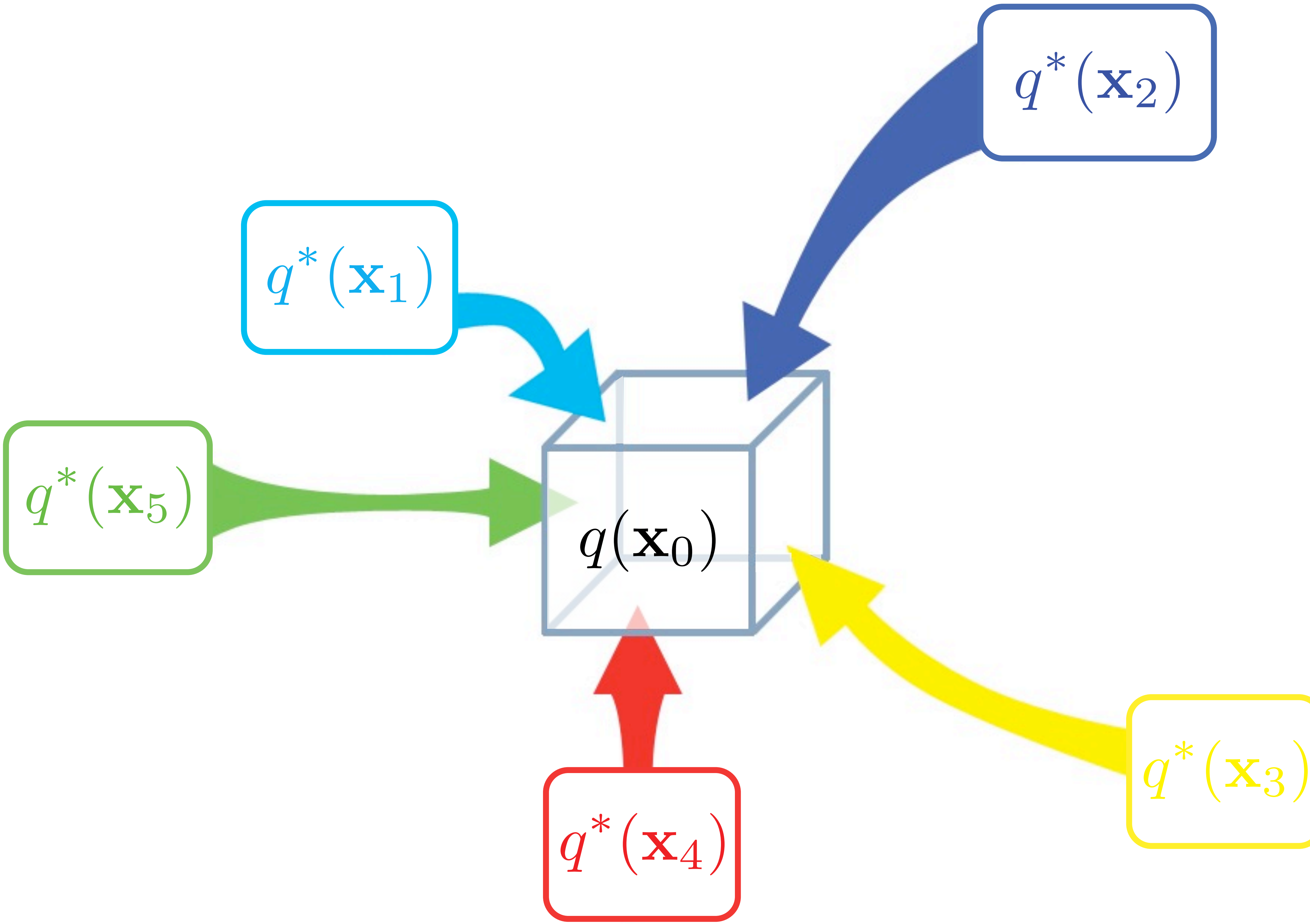


$$q(\mathbf{x}) = q(\mathbf{x}^*)$$

...but that's only for a point — we need more information to reconstruct water vapor for a volume (such as a GCM grid cell)

We can treat the specific humidity in a volume as the linear combination of q^* in all locations of last saturation

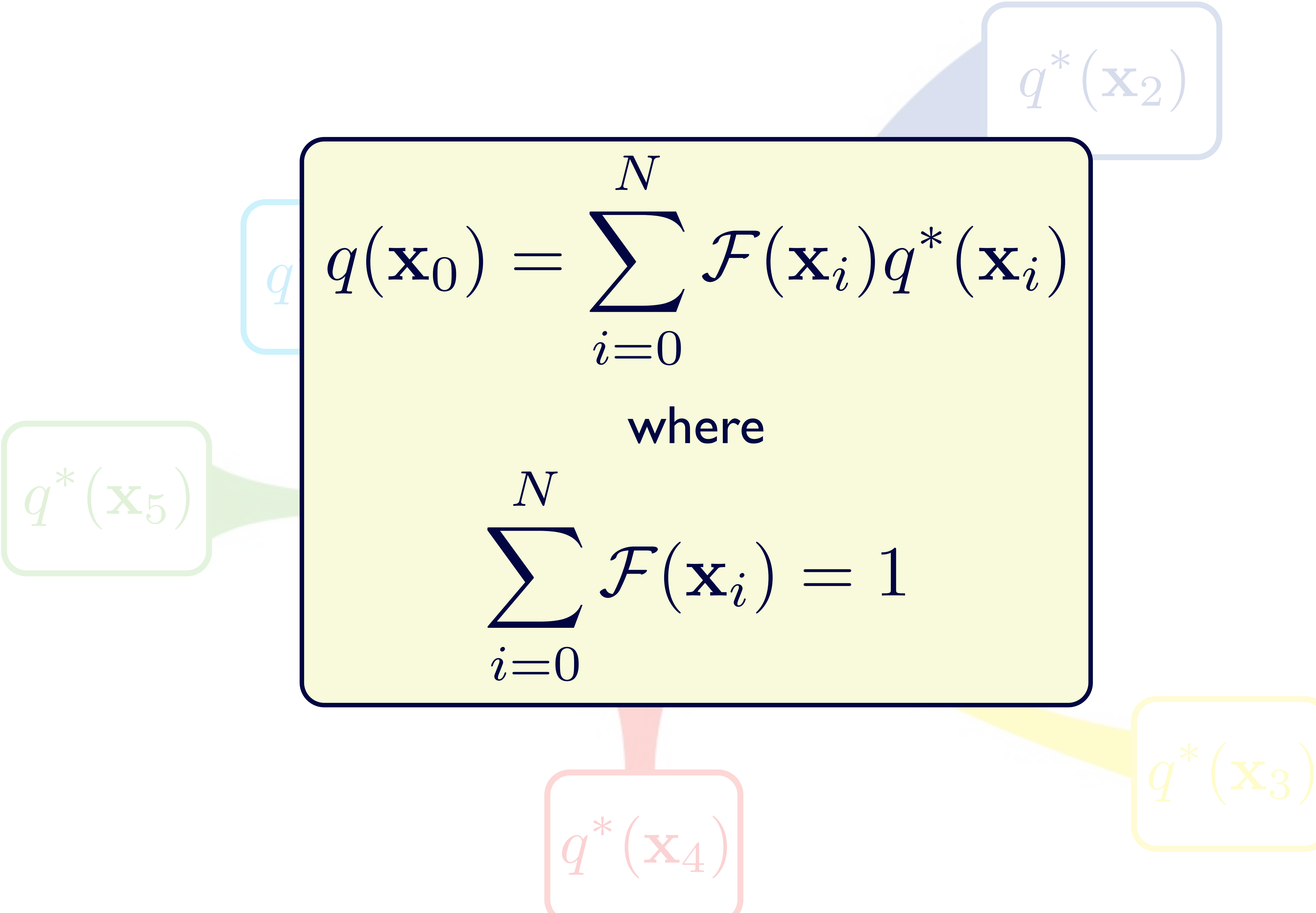


We can treat the specific humidity in a volume as the linear combination of $q*$ in all locations of last saturation

$$q(\mathbf{x}_0) = \sum_{i=0}^{N} \mathcal{F}(\mathbf{x}_i) q^*(\mathbf{x}_i)$$

where

$$\sum_{i=0}^{N} \mathcal{F}(\mathbf{x}_i) = 1$$



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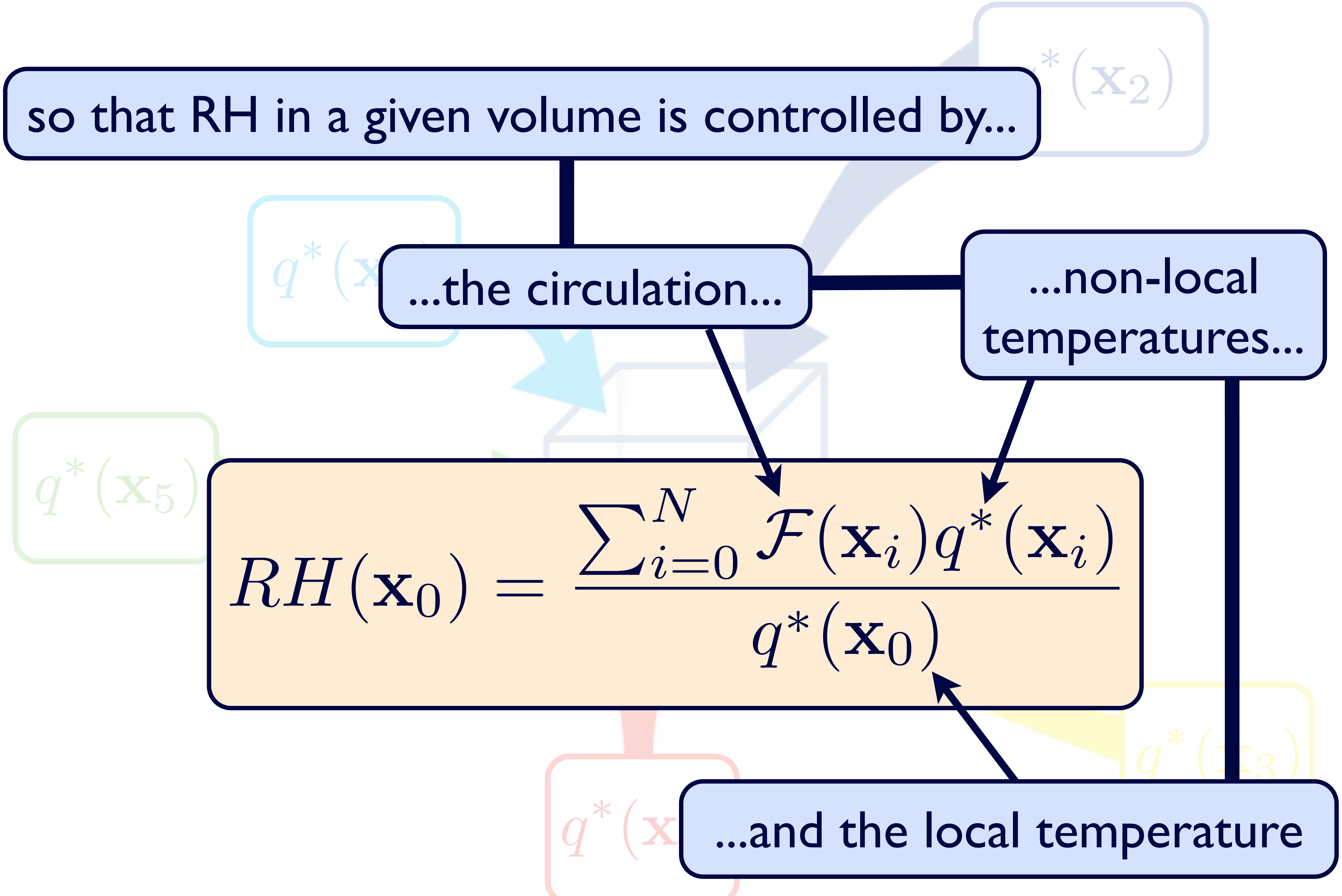


$$RH(\mathbf{x}_0) = \frac{\sum_{i=0}^{N} \mathcal{F}(\mathbf{x}_i)\, q^*(\mathbf{x}_i)}{q^*(\mathbf{x}_0)}$$

We apply a pair of global models to explore how each of these factors contributes to the RH response to warming

GISS ModelE

GCM to simulate modern and doubled CO_2 climates

temperature
and
circulation

MATCH

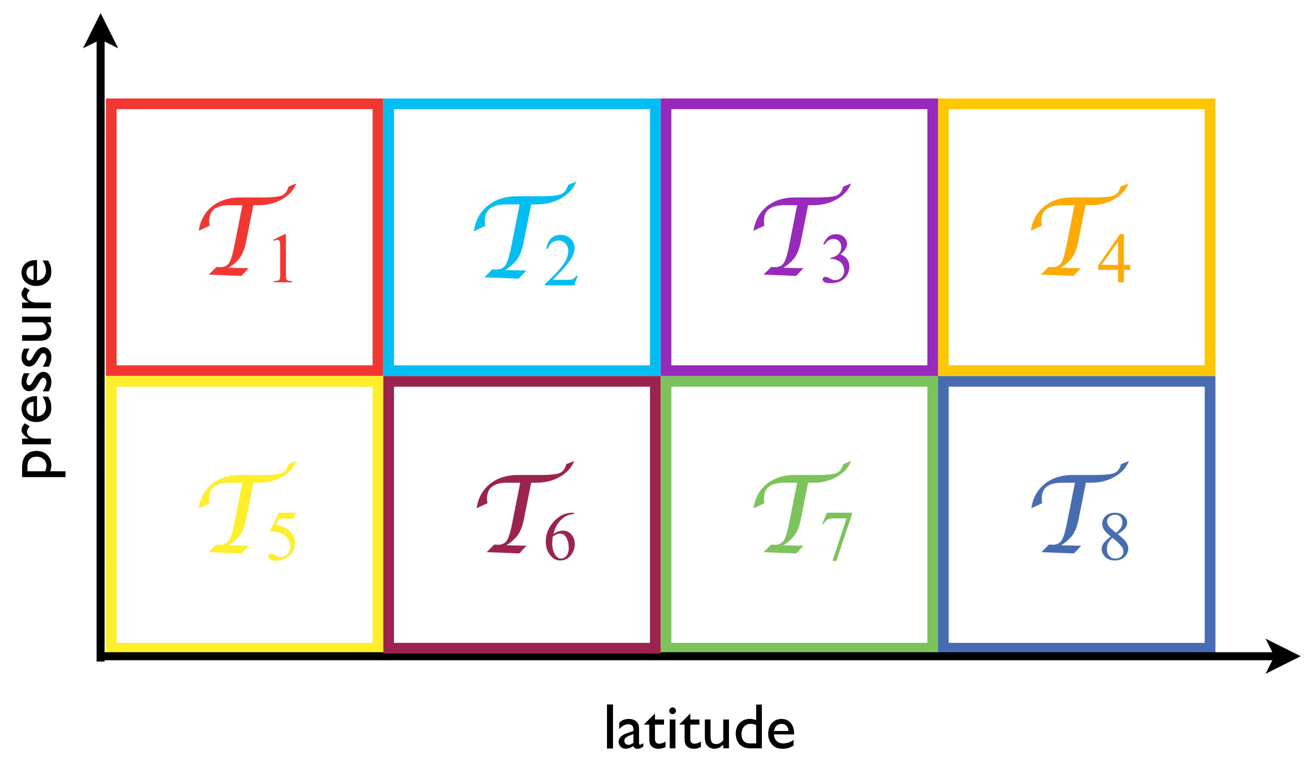
Tracer transport model driven by GCM fields for flexibility

last saturation tracers to evaluate contributions of temperature and circulation

Wright et al. 2010

Tracer Formulation

Divide the atmosphere into N zonally axisymmetric tracer domains



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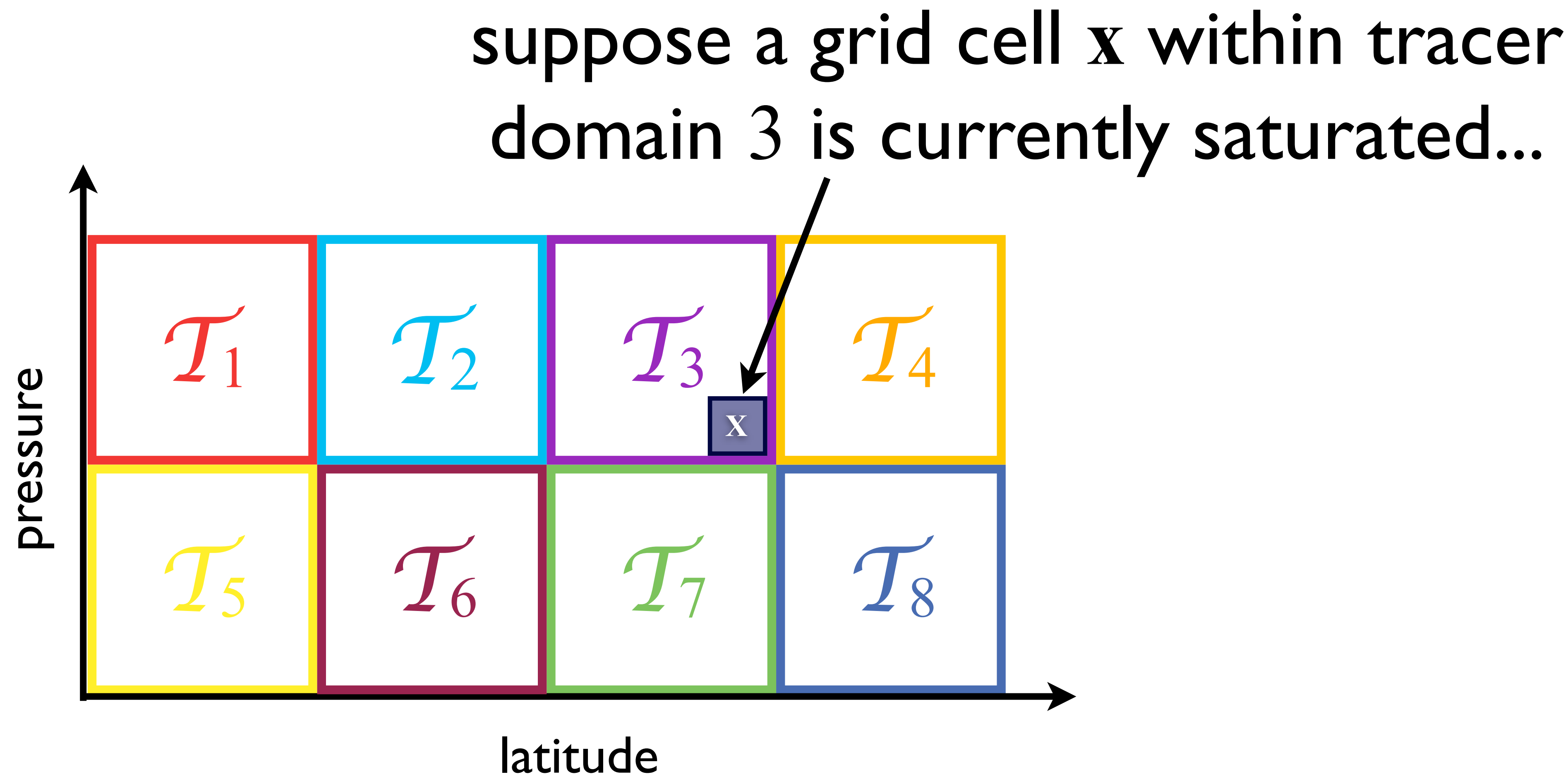
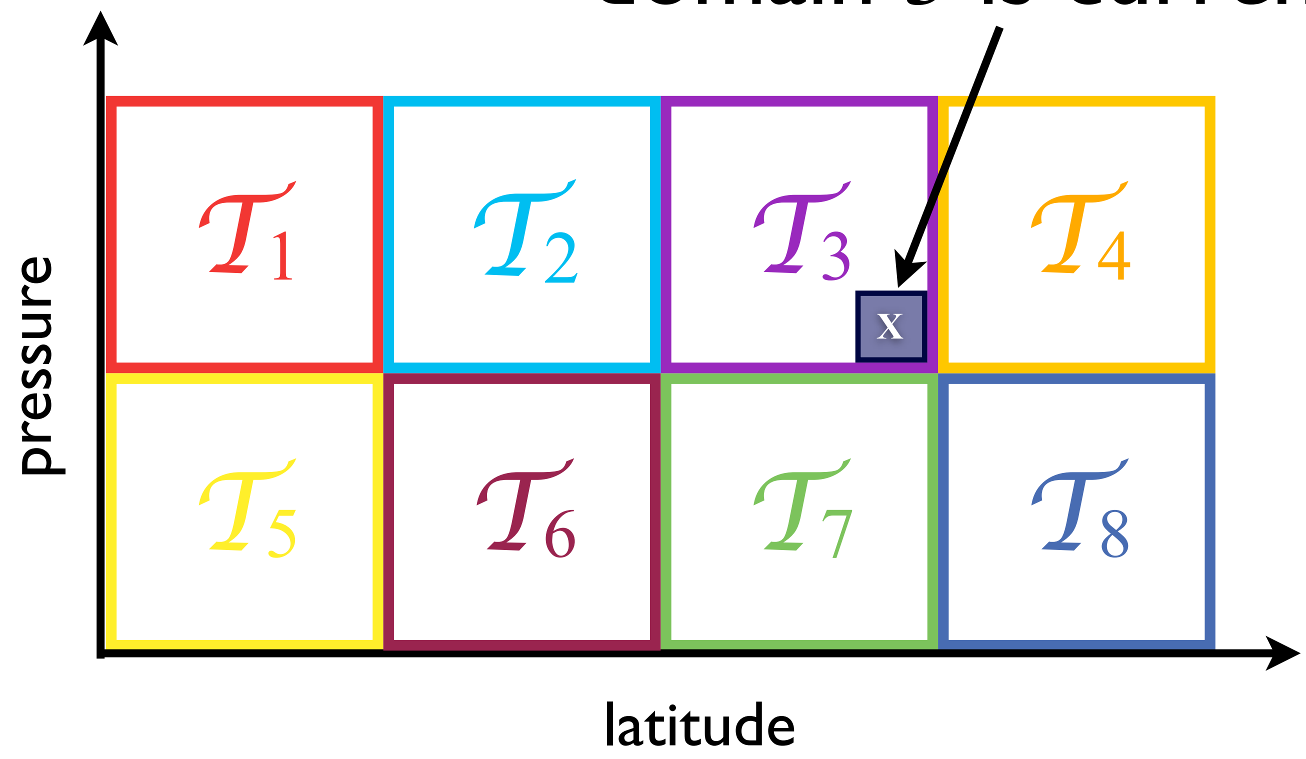


Tracer Formulation

Divide the atmosphere into N zonally axisymmetric tracer domains

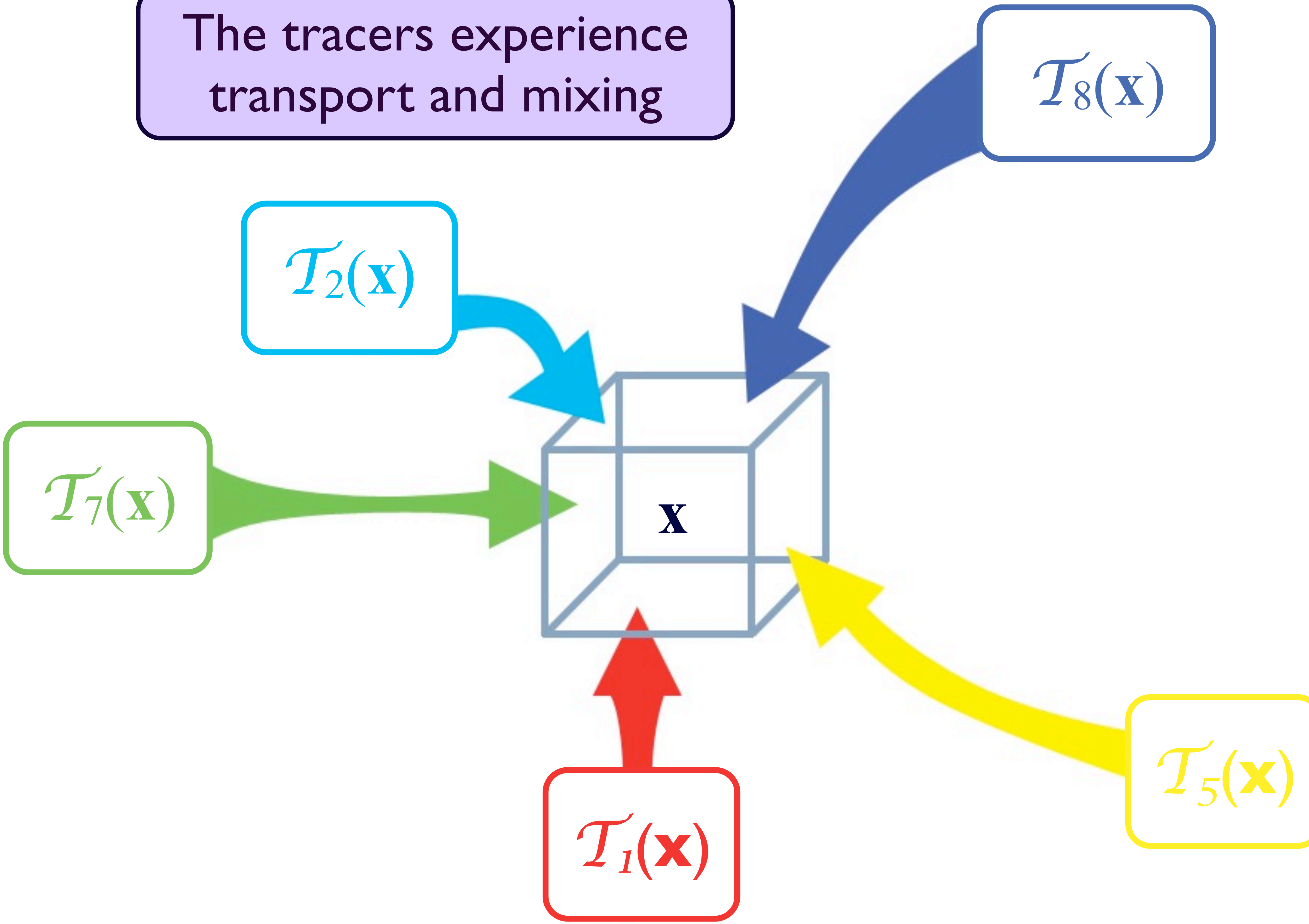
suppose a grid cell $\mathbf{x}$ within tracer domain 3 is currently saturated...



...we would then set the tracer concentration $\mathcal{T}_3(\mathbf{x})$ to 1 and all other tracer concentrations $\mathcal{T}_i(\mathbf{x})|_{i\neq 3}$ to 0 at $\mathbf{x}$

Tracer Formulation

The tracers experience transport and mixing



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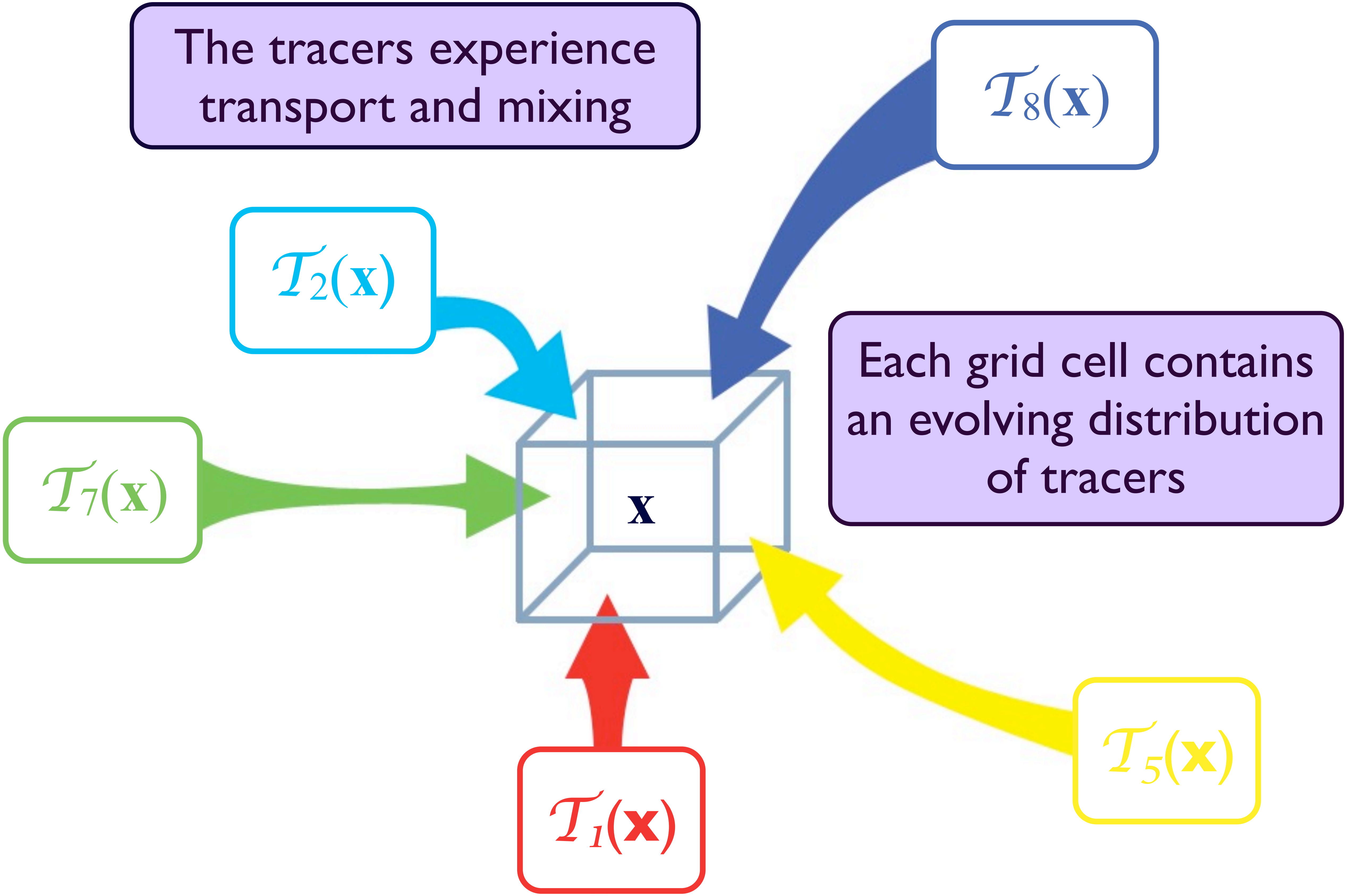

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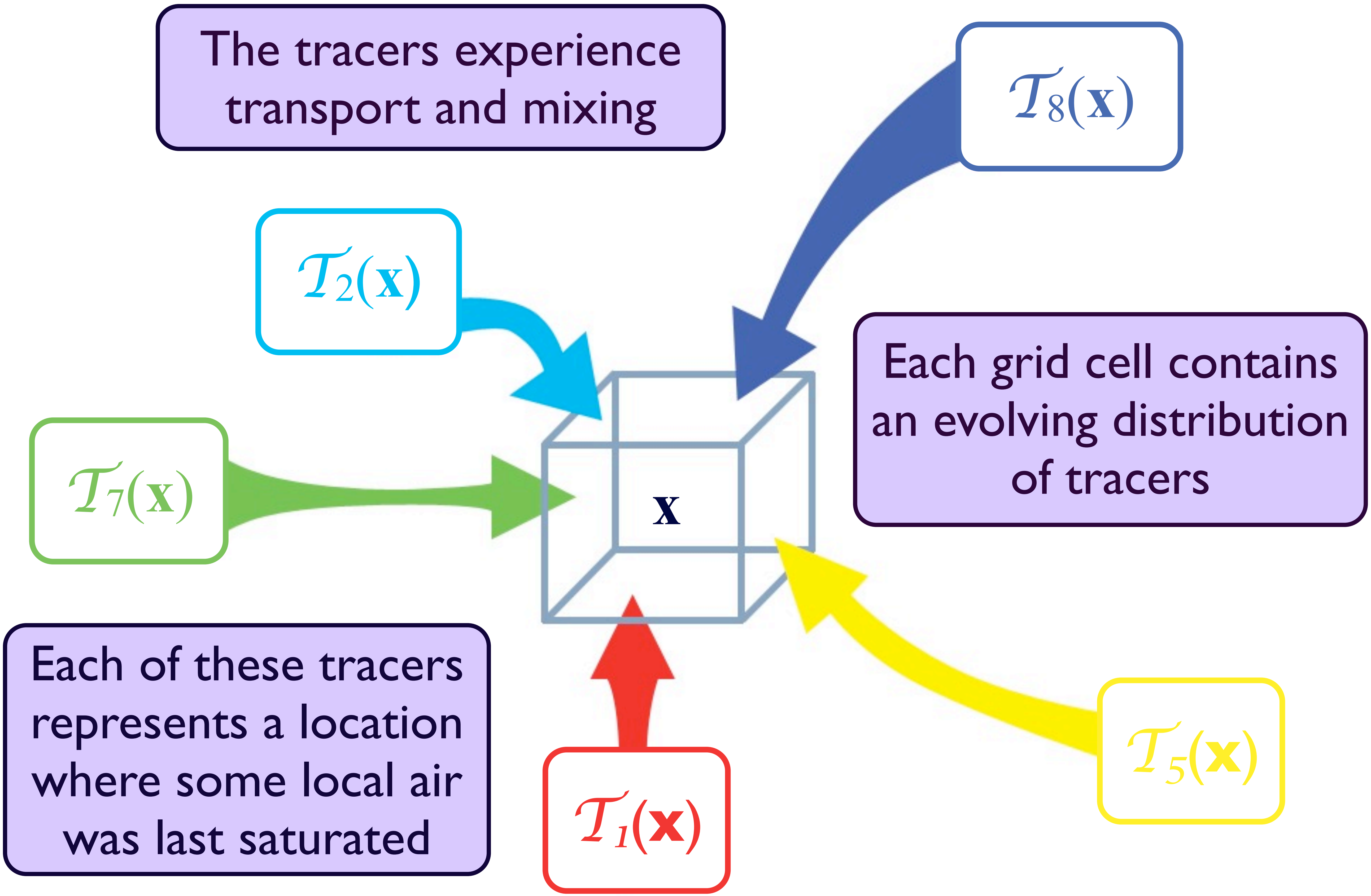


Tracer Formulation

We can then reconstruct the relative humidity for every grid cell $\mathbf{x}$

$\mathcal{T}_i(\mathbf{x})$ is the local concentration of tracer i

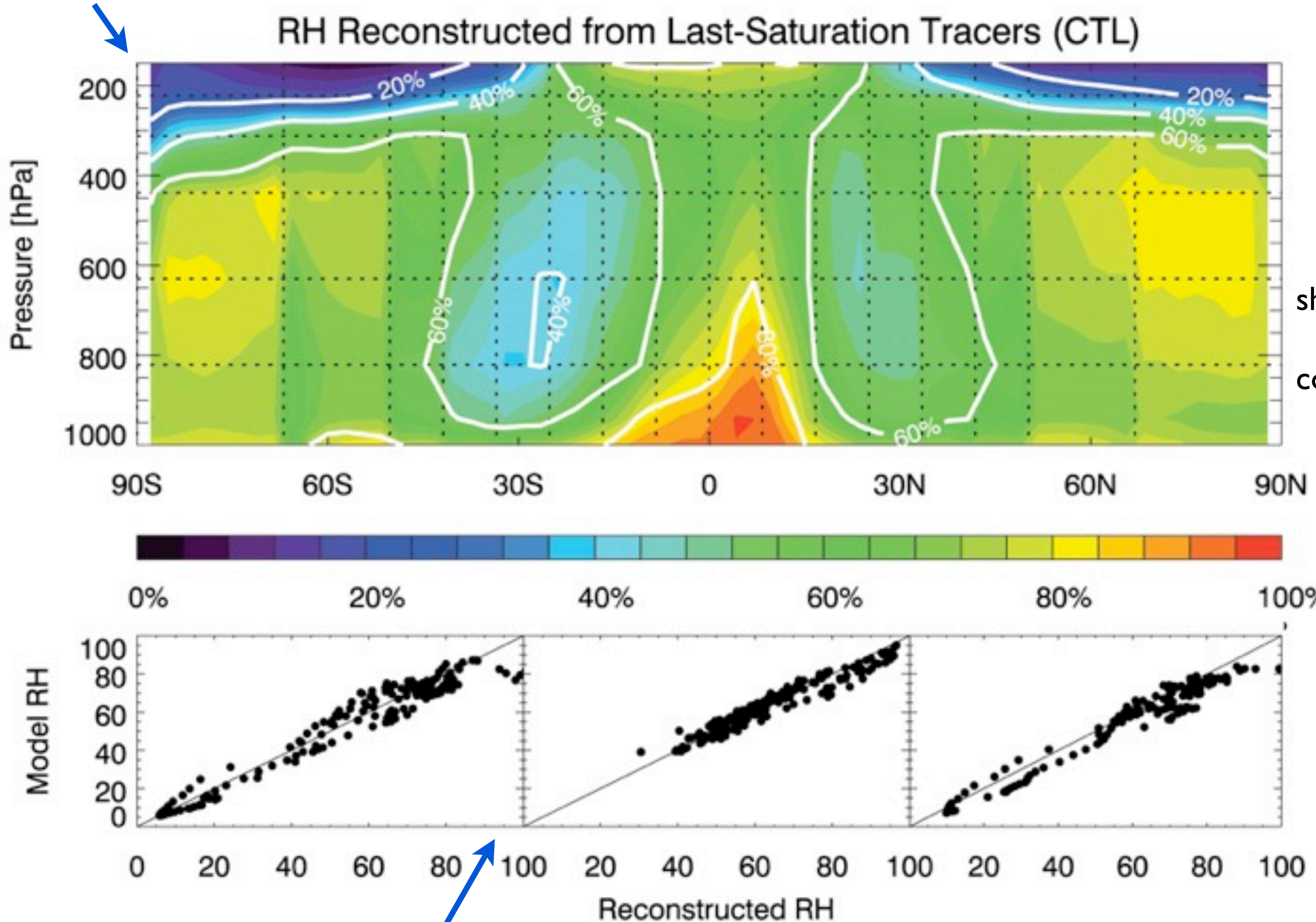
$$RH(\mathbf{x}) = \frac{\sum_{i=1}^{N} \mathcal{T}_i(\mathbf{x}) \langle q^*(\mathcal{T}_i)\rangle}{q^*(\mathbf{x})}$$

$q^*(\mathbf{x})$ is the local saturation mixing ratio

$\langle q^*(\mathcal{T}_i)\rangle$ is the mean q^* associated with tracer domain i

The tracer-based reconstruction agrees well with model RH

qualitative and quantitative agreement in zonal mean

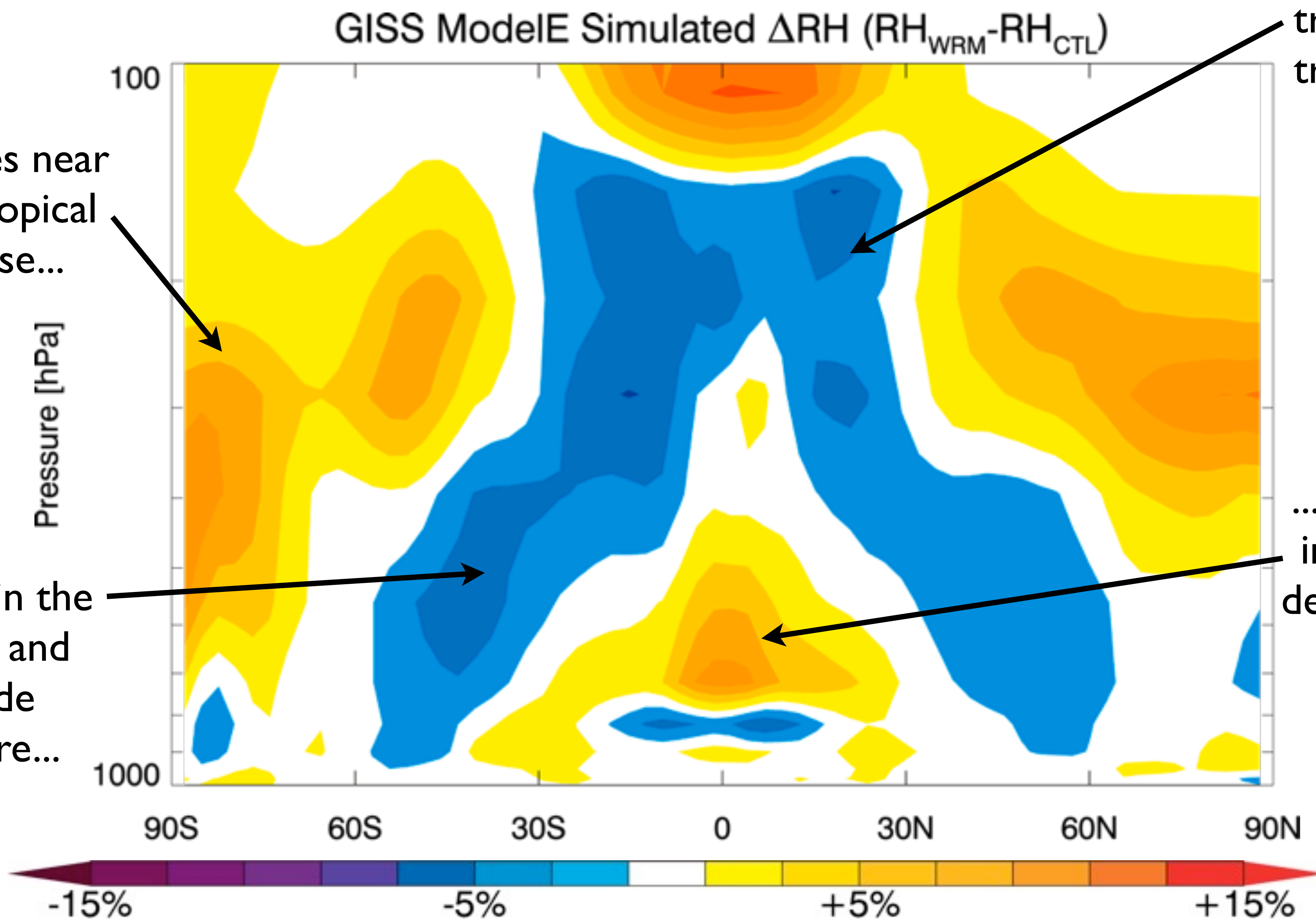


shading: reconstruction
contours: model output

point-to-point comparisons have R^2 > 0.95, with particularly good agreement in the tropics

Wright et al. 2010

Is the GISS ModelE Representative?



RH increases near the extratropical tropopause…

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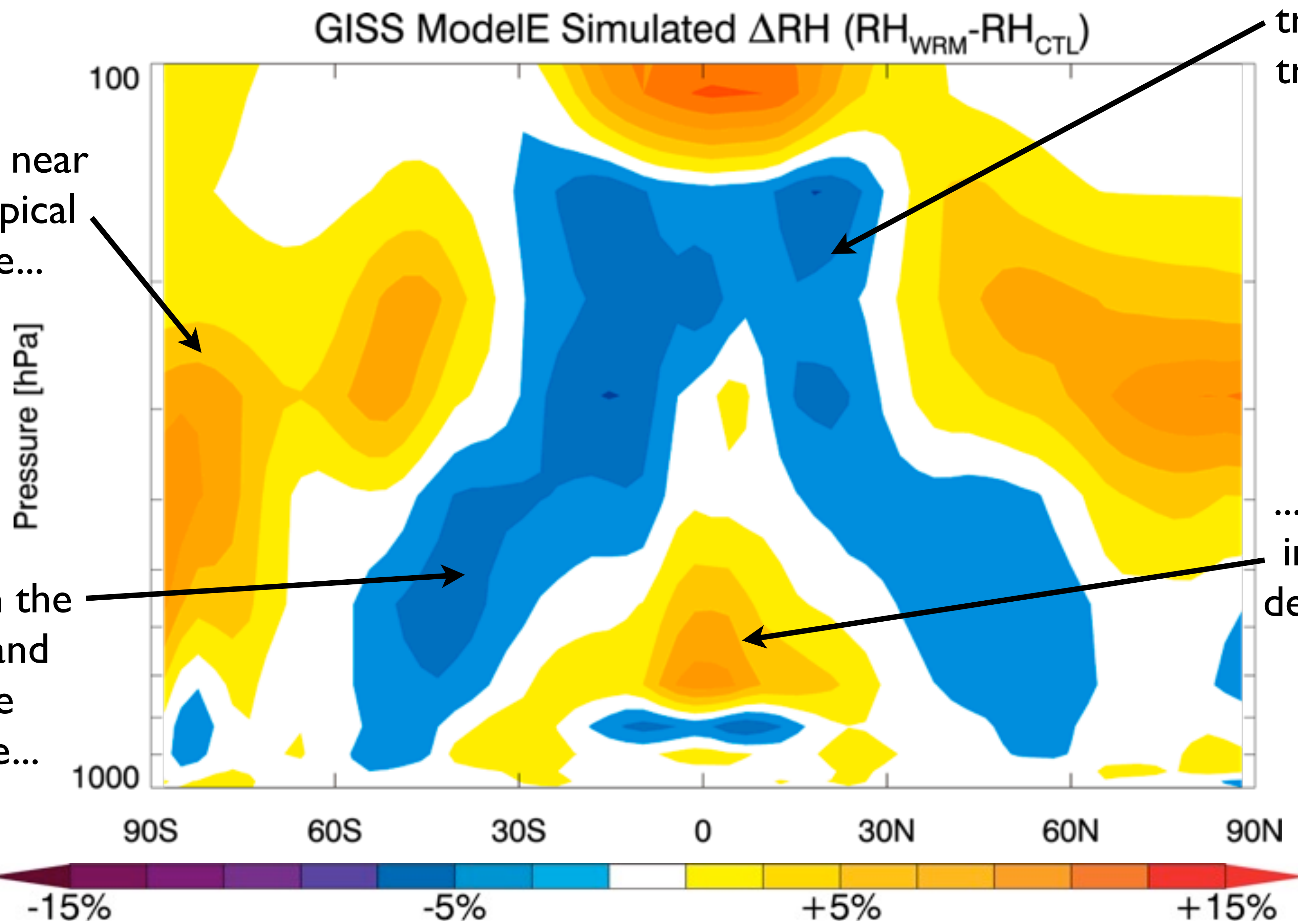

...decreases in the tropical upper troposphere...

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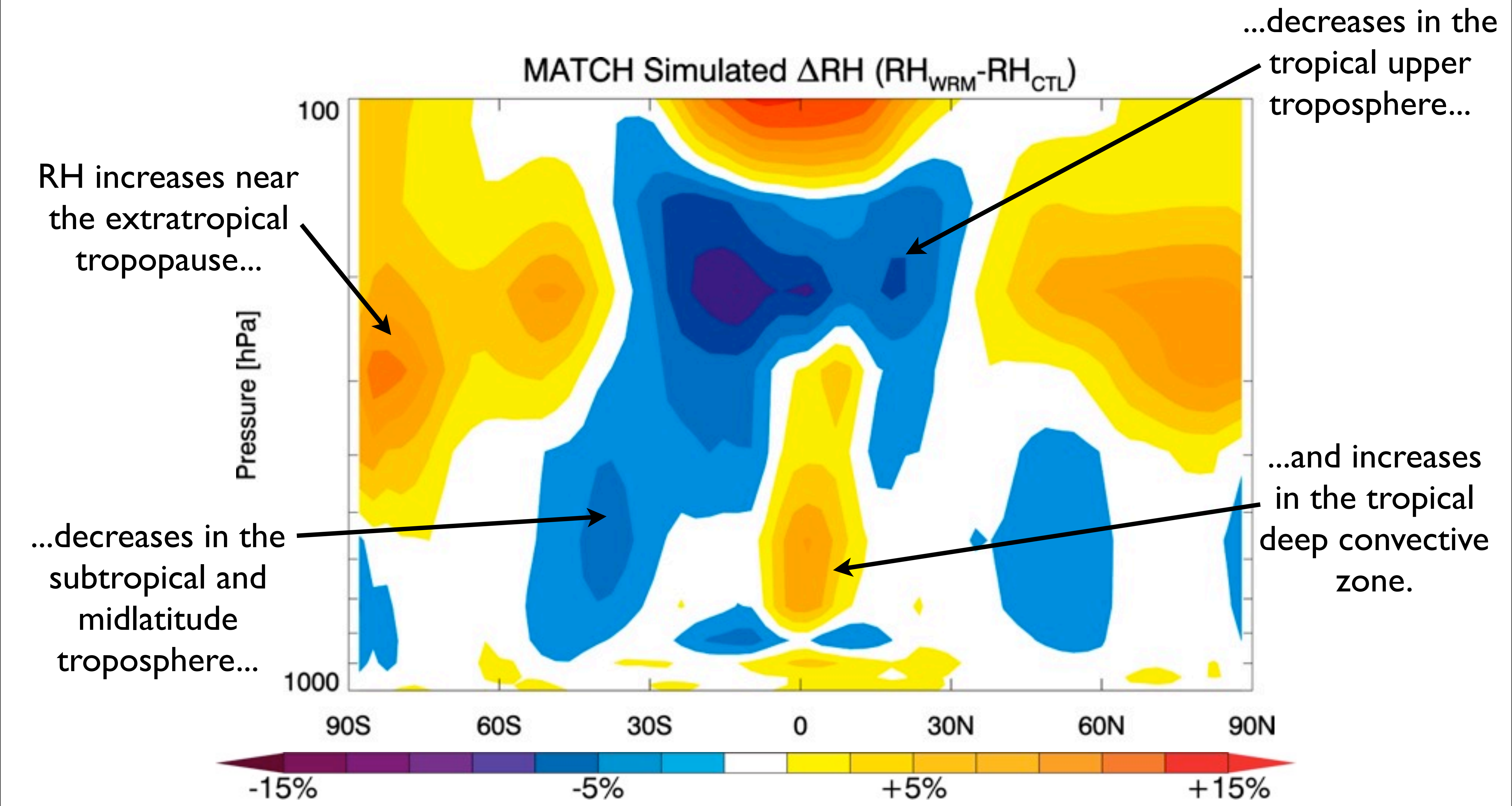
The pattern of RH change in the ModelE is consistent with the multi-model mean

Wright et al. 2010

Is the MATCH Hydrologic Cycle Suitable?



Wright et al. 2010

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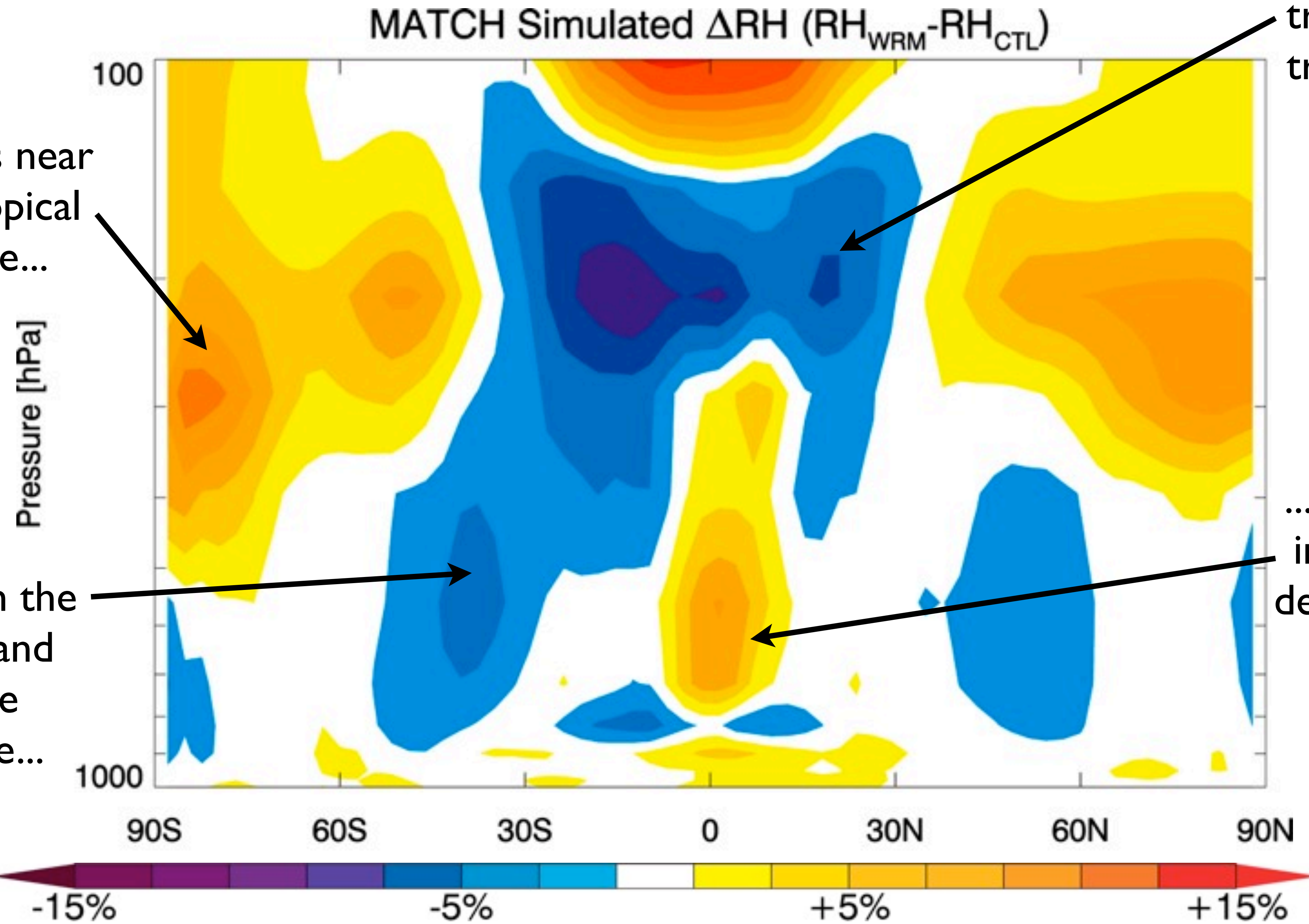
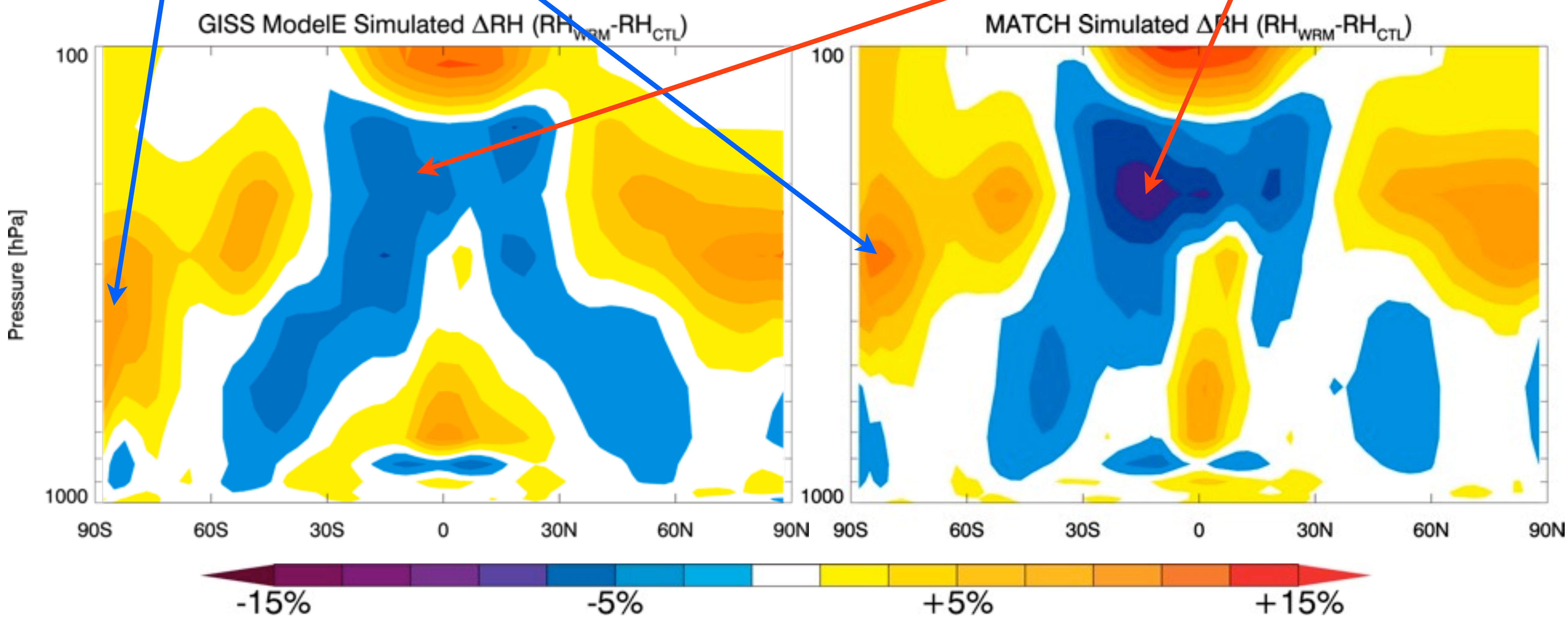


The pattern of RH change simulated by MATCH is qualitatively similar to that simulated by ModelE

Wright et al. 2010

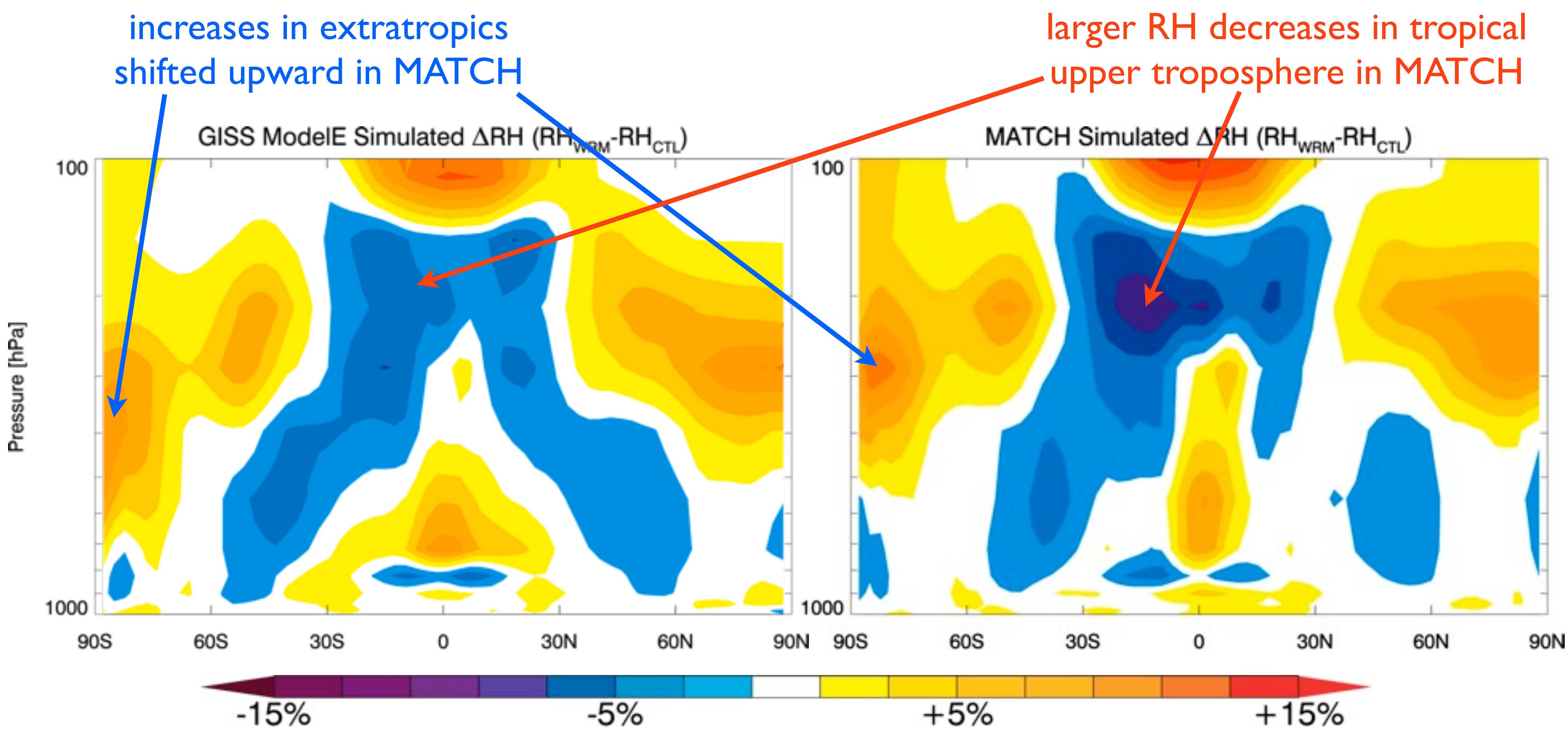
increases in extratropics shifted upward in MATCH

larger RH decreases in tropical upper troposphere in MATCH



Wright et al. 2010

Changes in MATCH are generally smaller at lower altitudes and larger aloft, but these differences are smaller than the differences between ModelE and other CMIP3 GCMs



Wright et al. 2010

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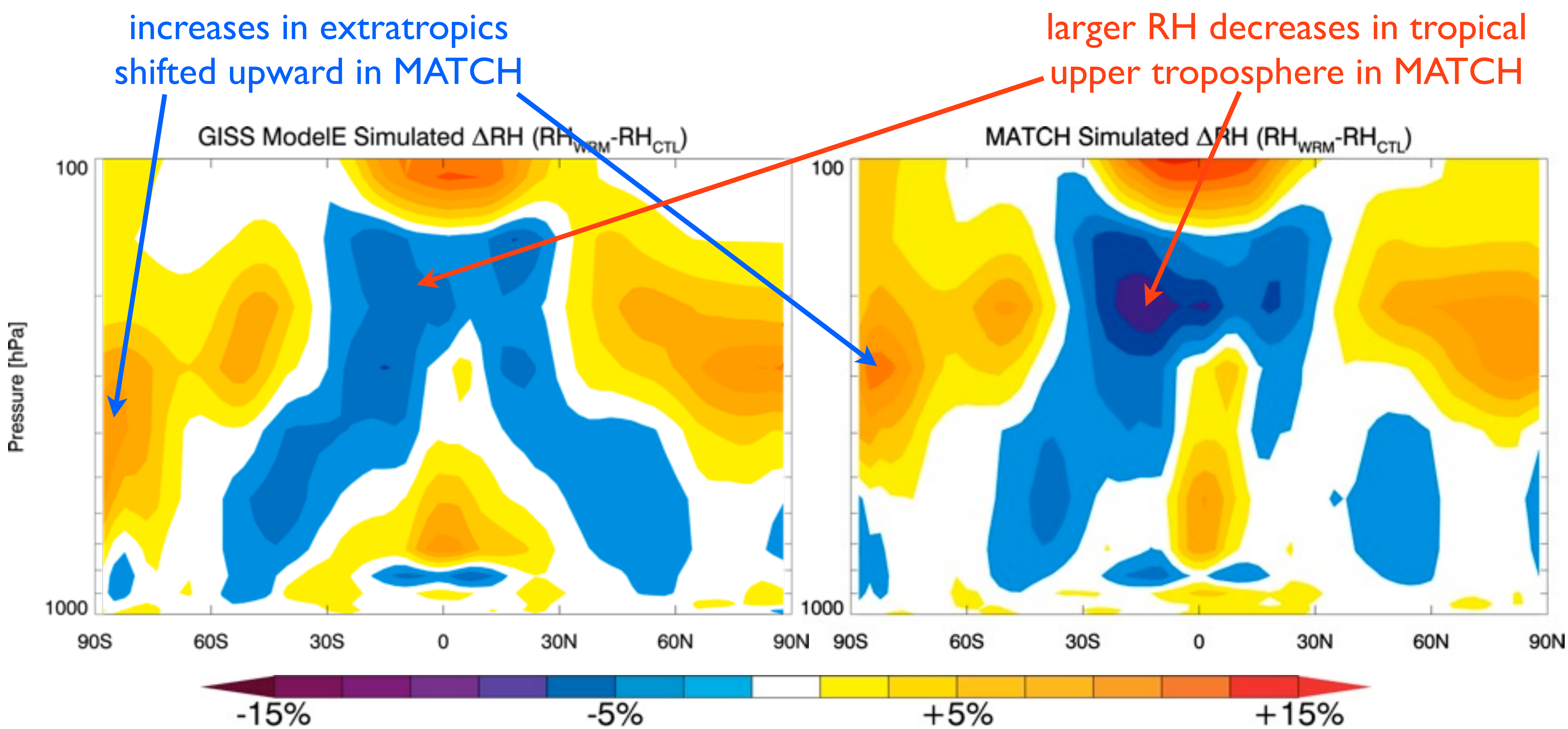
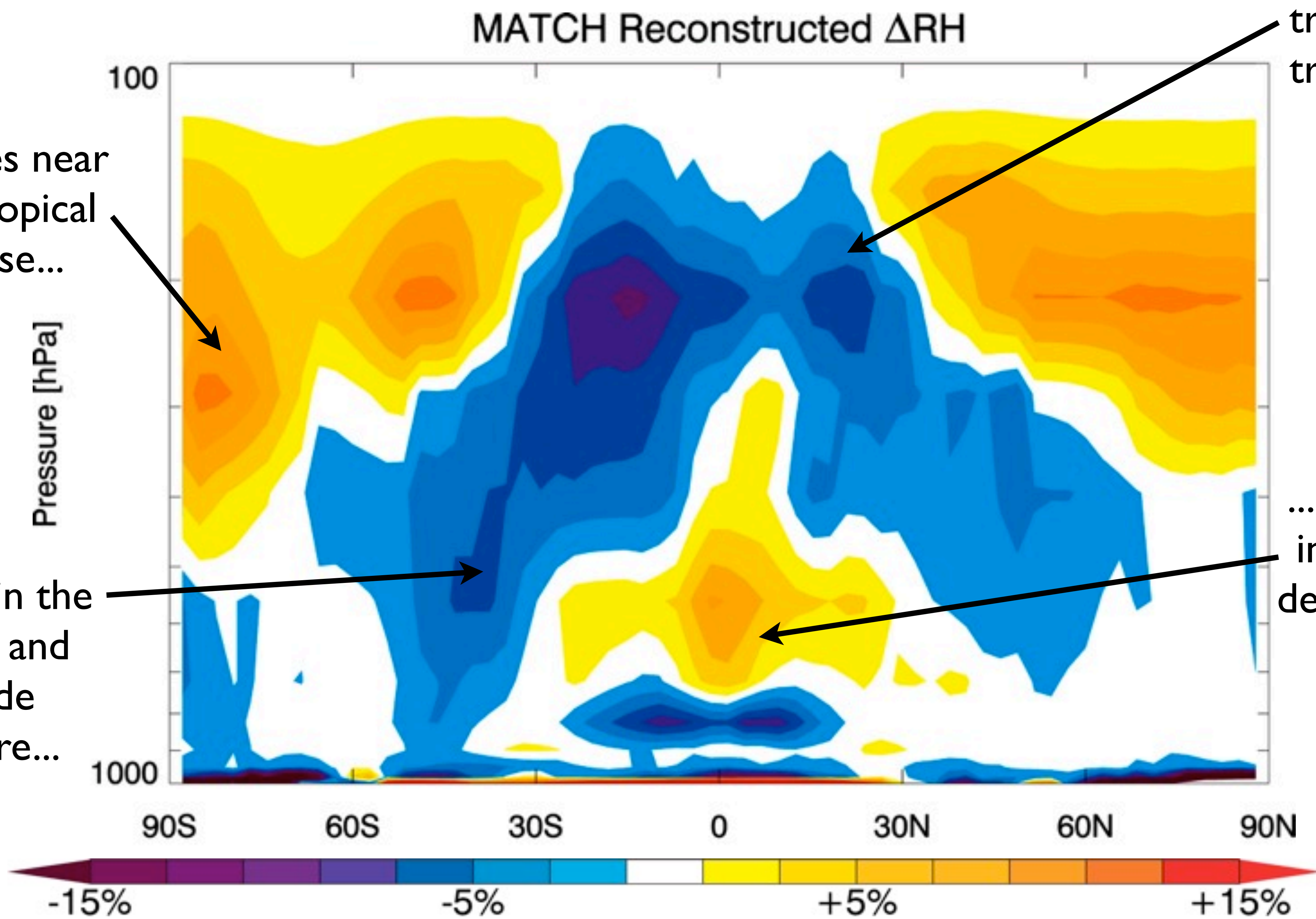


Suggests that RH sensitivity depends mainly on temperature and circulation, not the details of hydrologic cycle parameterizations

Wright et al. 2010

Is the tracer method suitable?



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Wright et al. 2010

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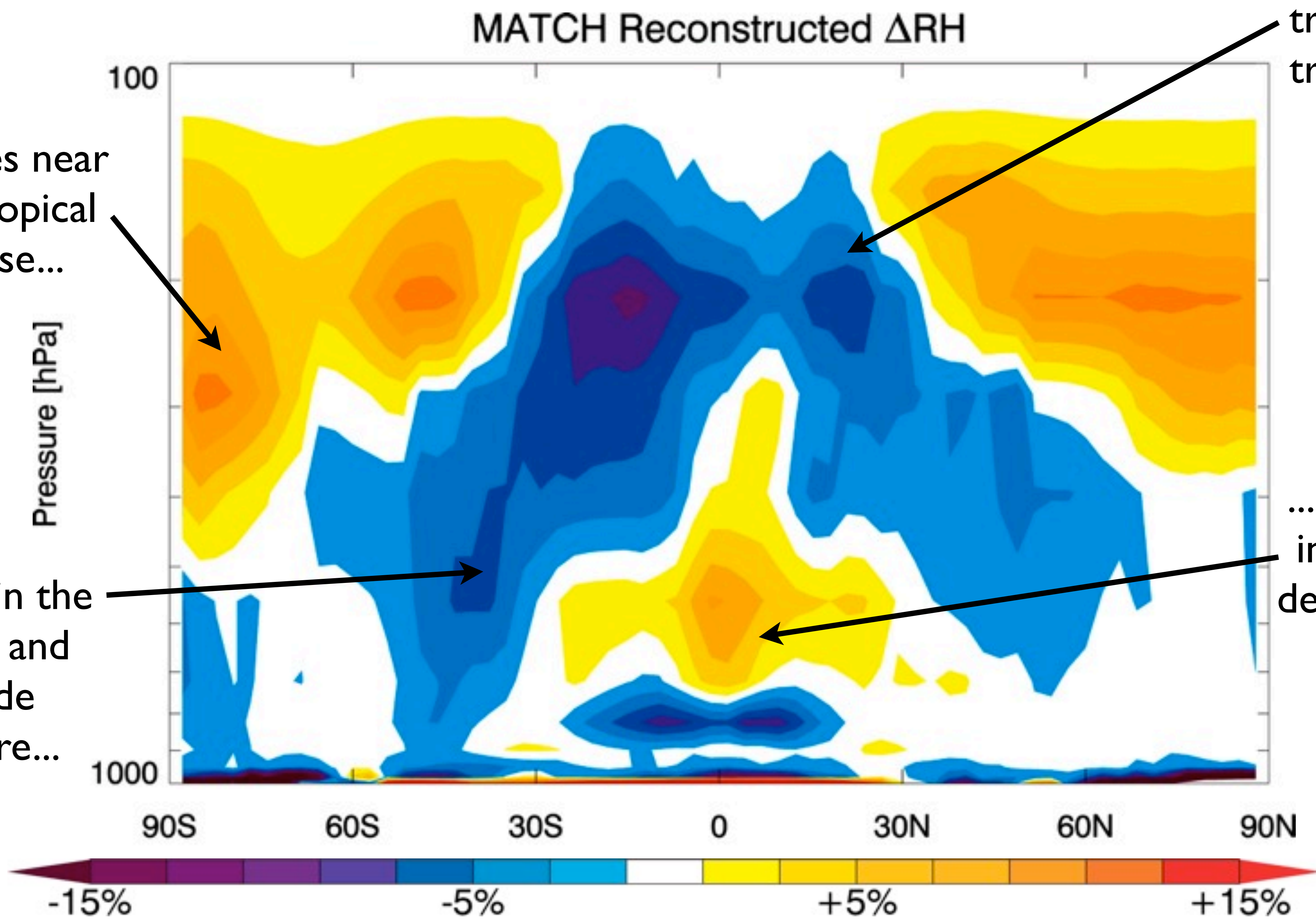


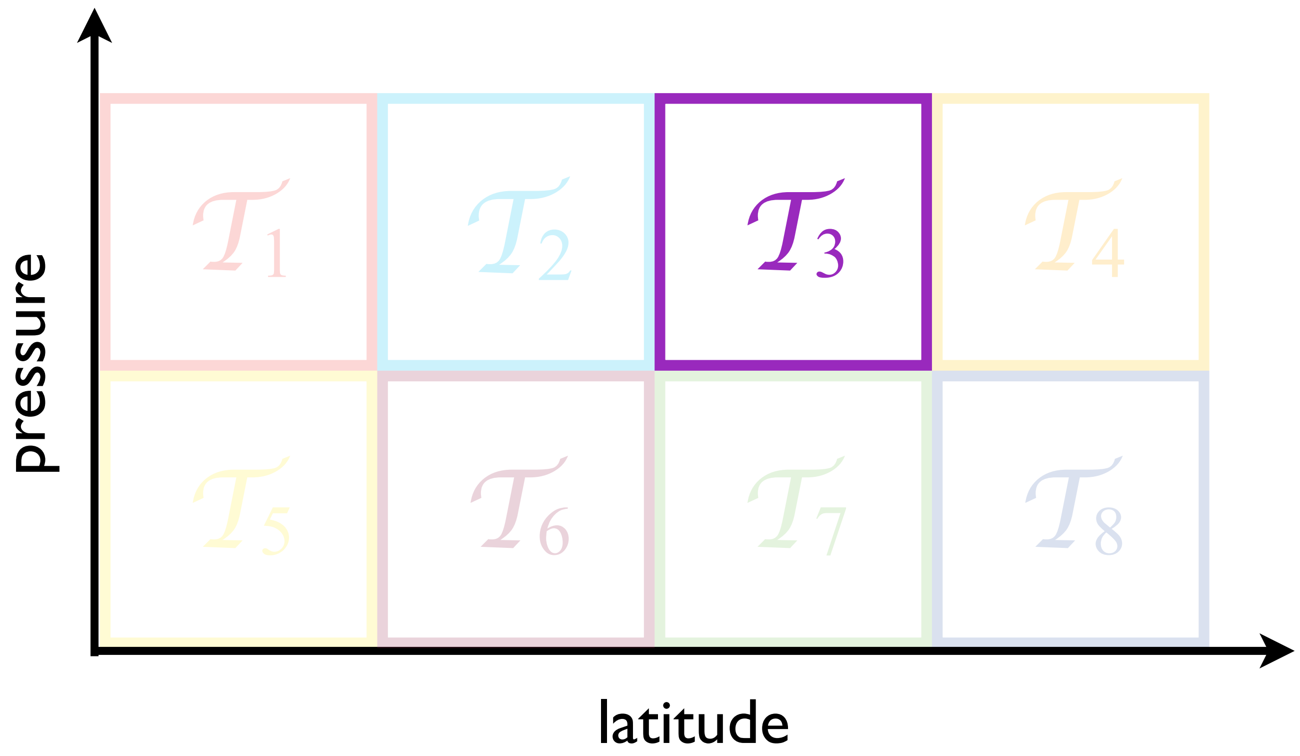
...decreases in the tropical upper troposphere...

...and increases in the tropical deep convective zone.

The tracer reconstruction also matches well, suggesting that the tracers capture the relevant physical processes

Wright et al. 2010

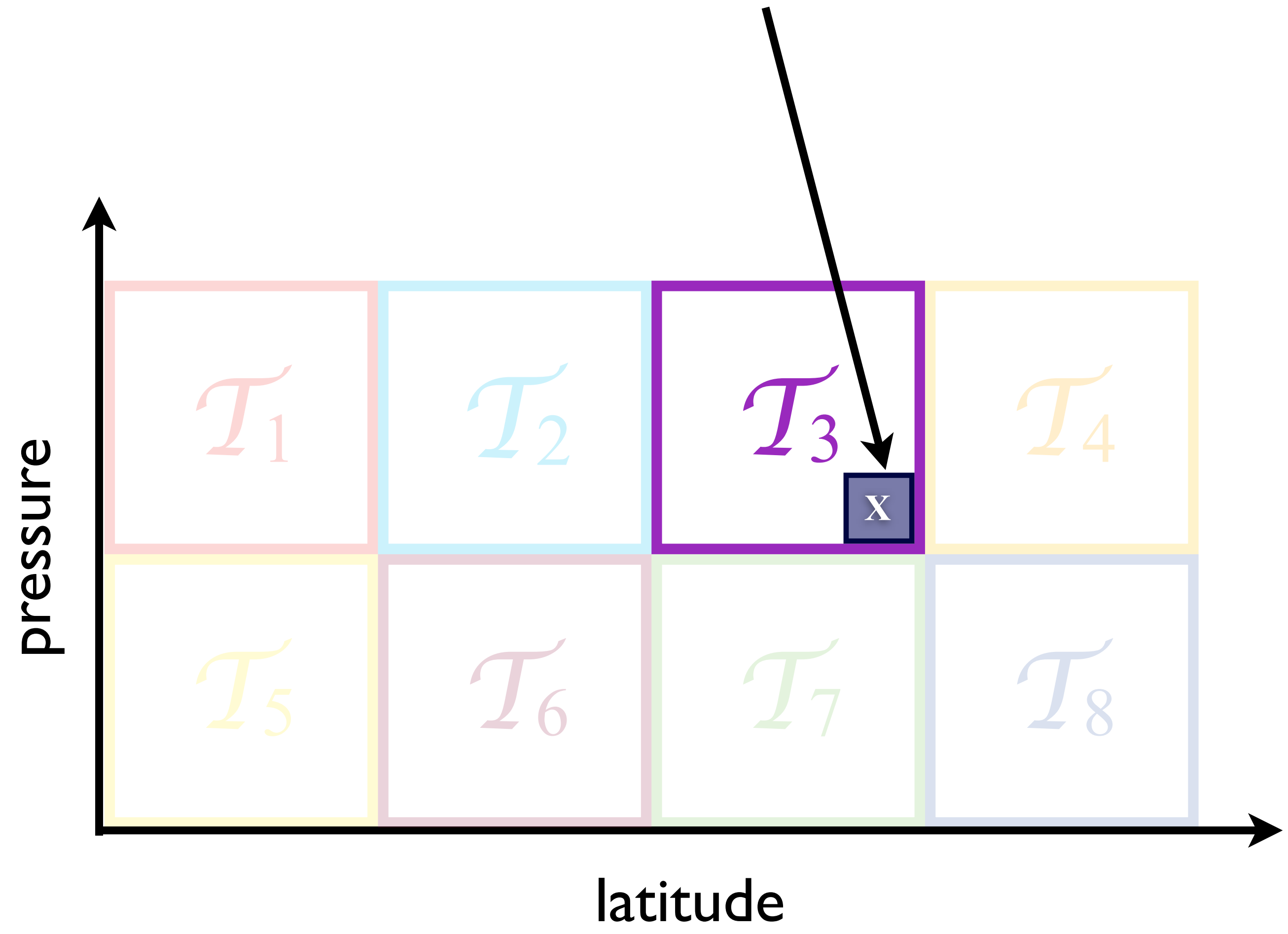
Tracer Formulation: Terminology



All other tracers are **nonlocal tracers** at grid cell $\mathbf{x}$

Tracer Formulation: Terminology

$\mathcal{T}_3$ is the **local tracer** for grid cell $\mathbf{x}$
because $\mathbf{x}$ is inside tracer domain 3



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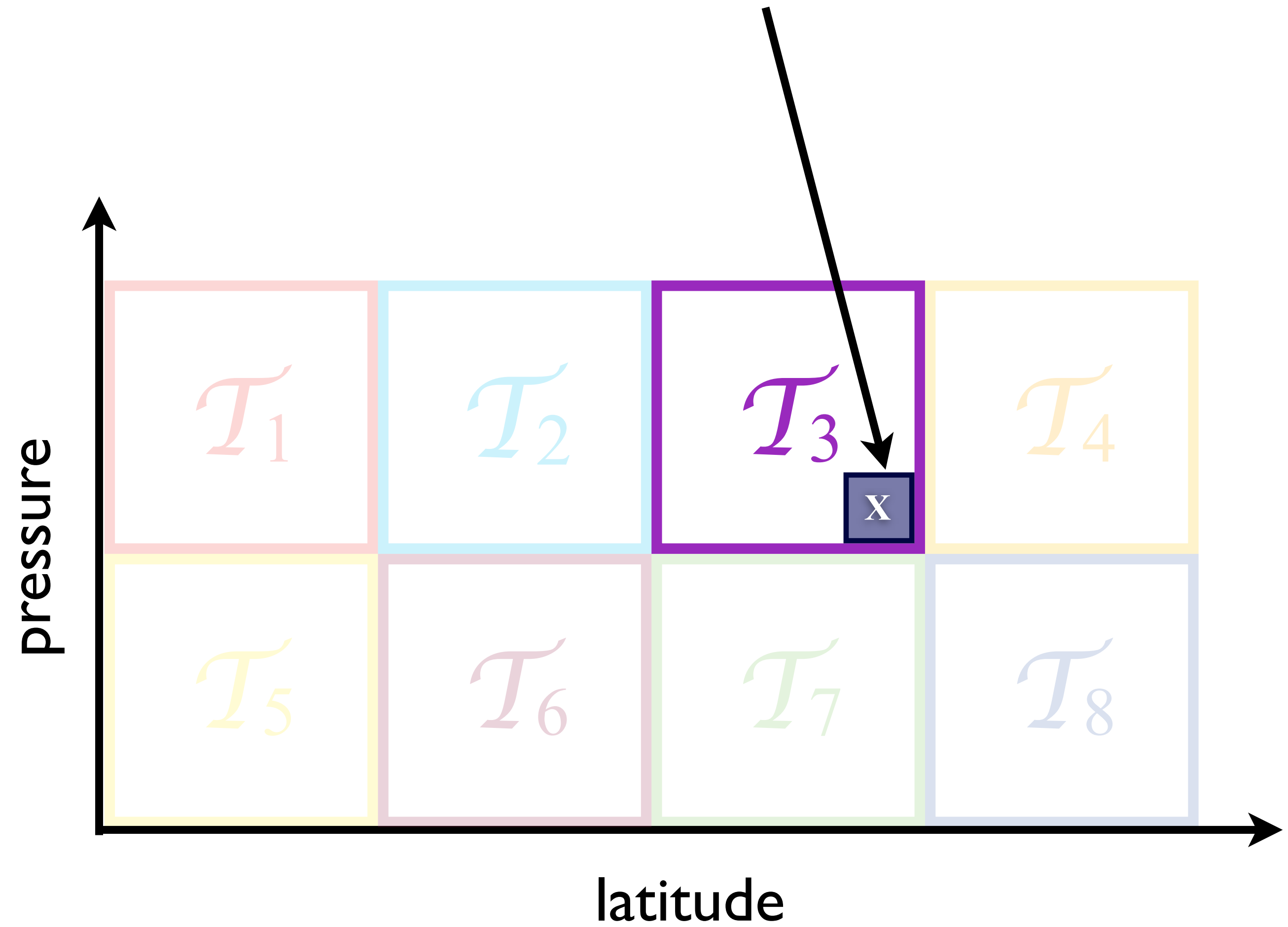

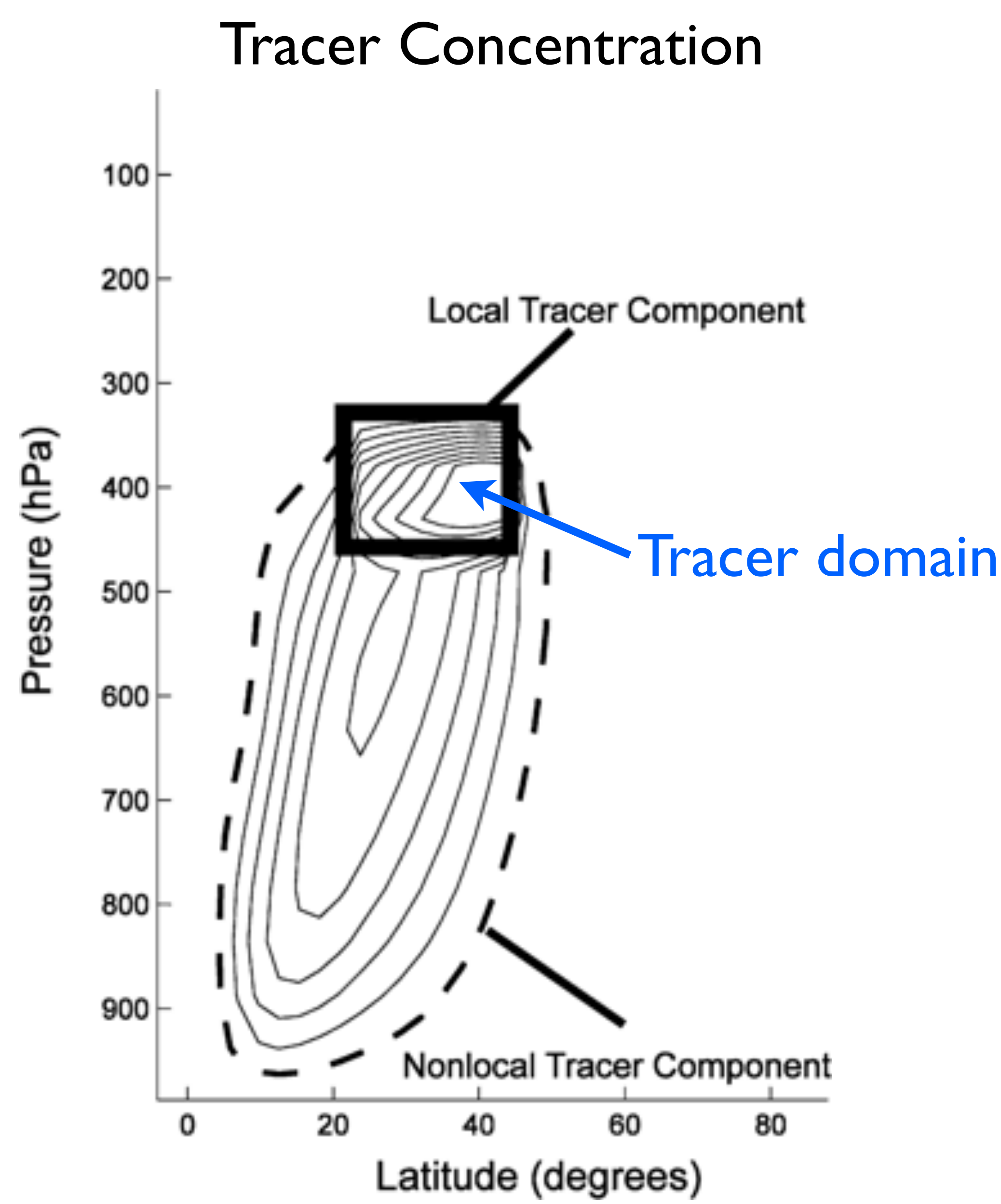

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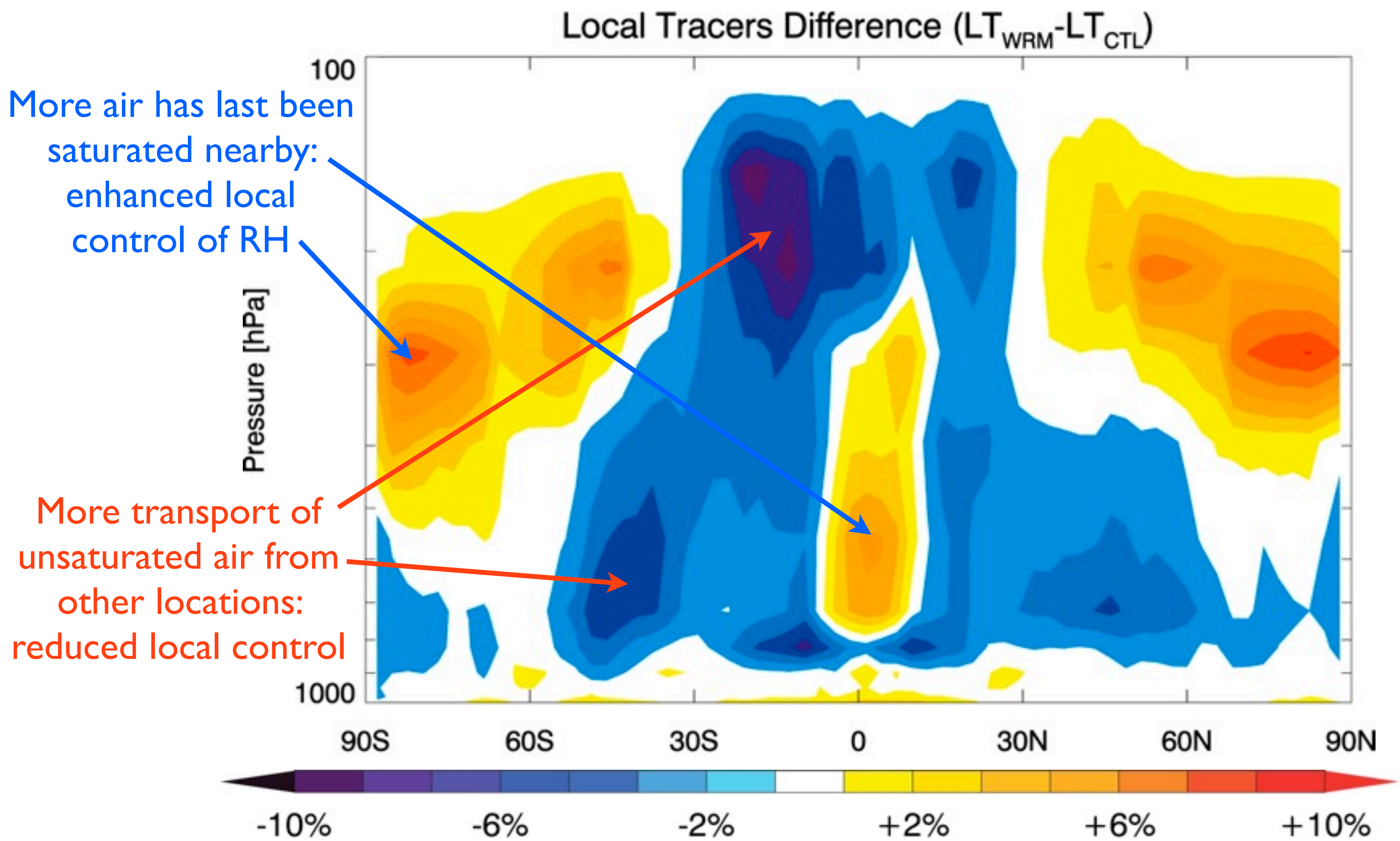
Galewsky et al. 2005

Local and Nonlocal Influences on RH



Wright et al. 2010

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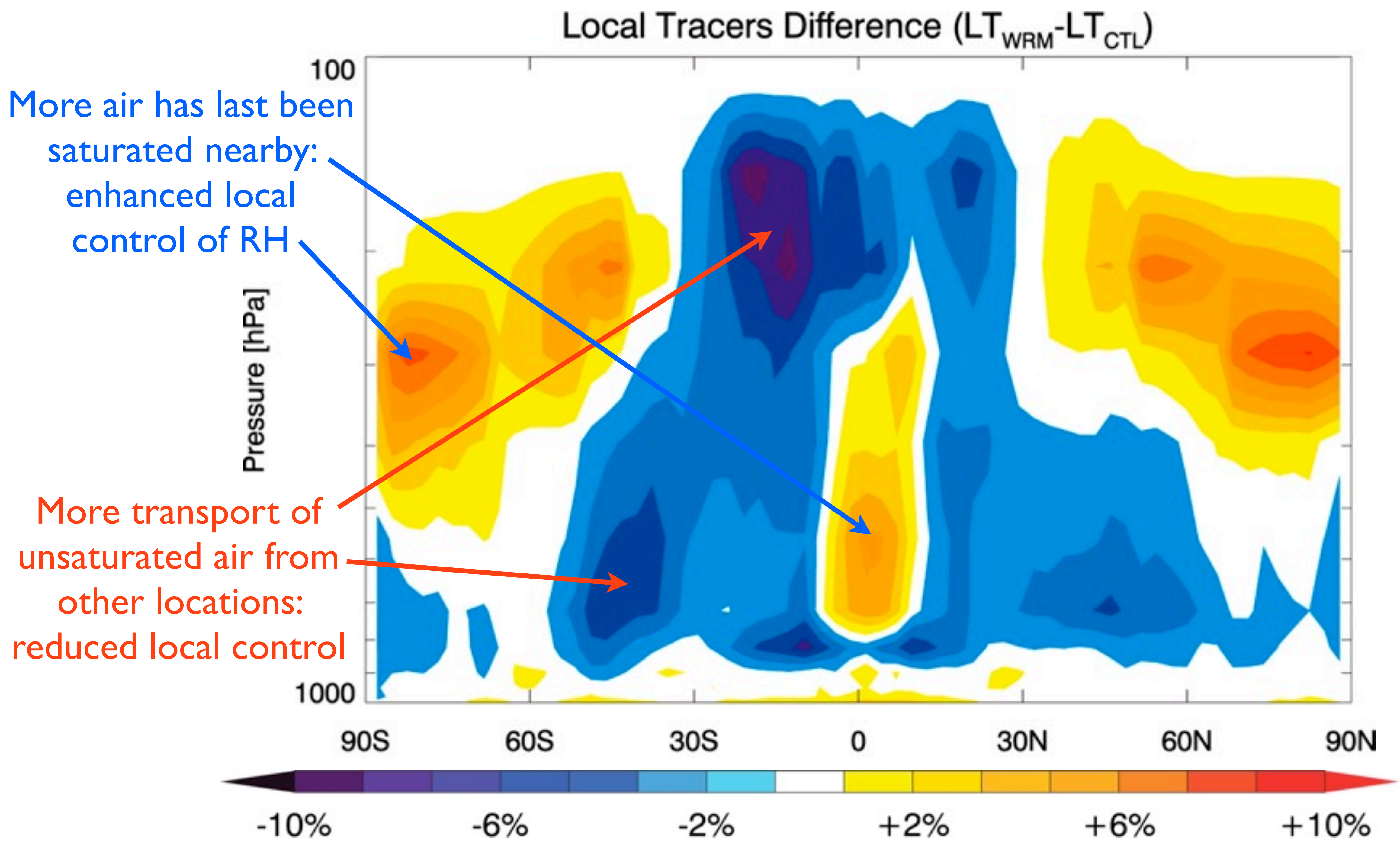
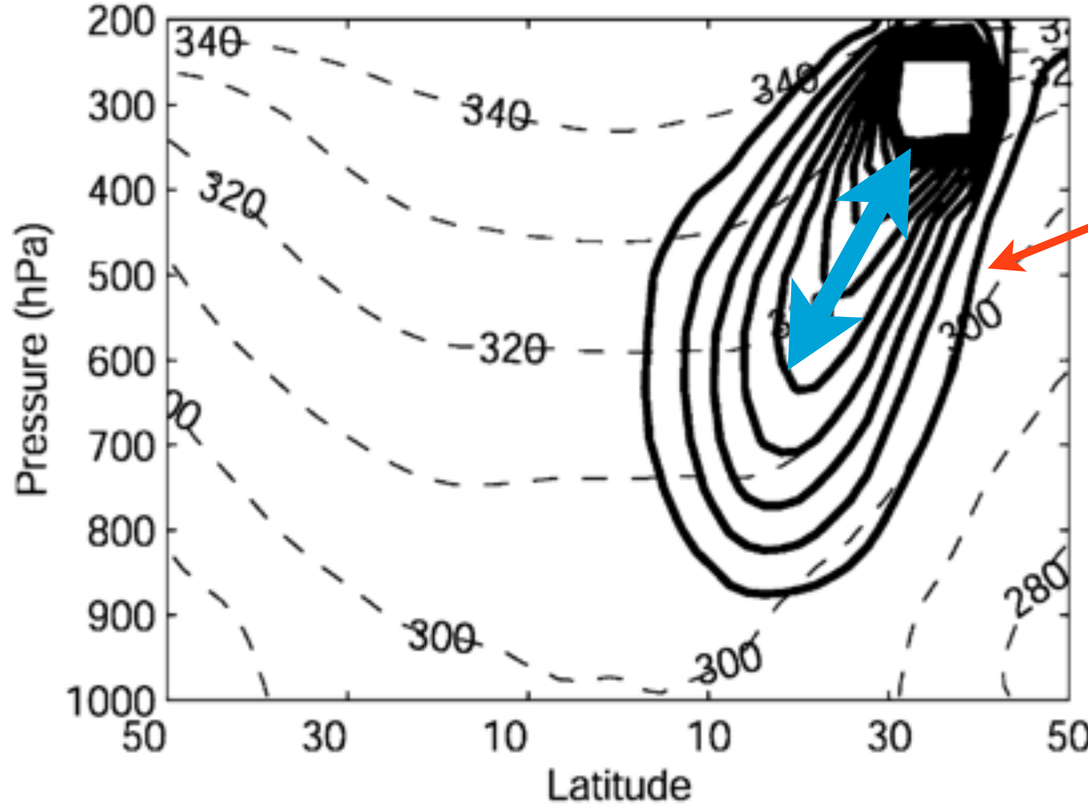


Some changes in RH are locally controlled, while others are dependent on conditions at other locations

Wright et al. 2010

Concentration of a Midlatitude Tracer

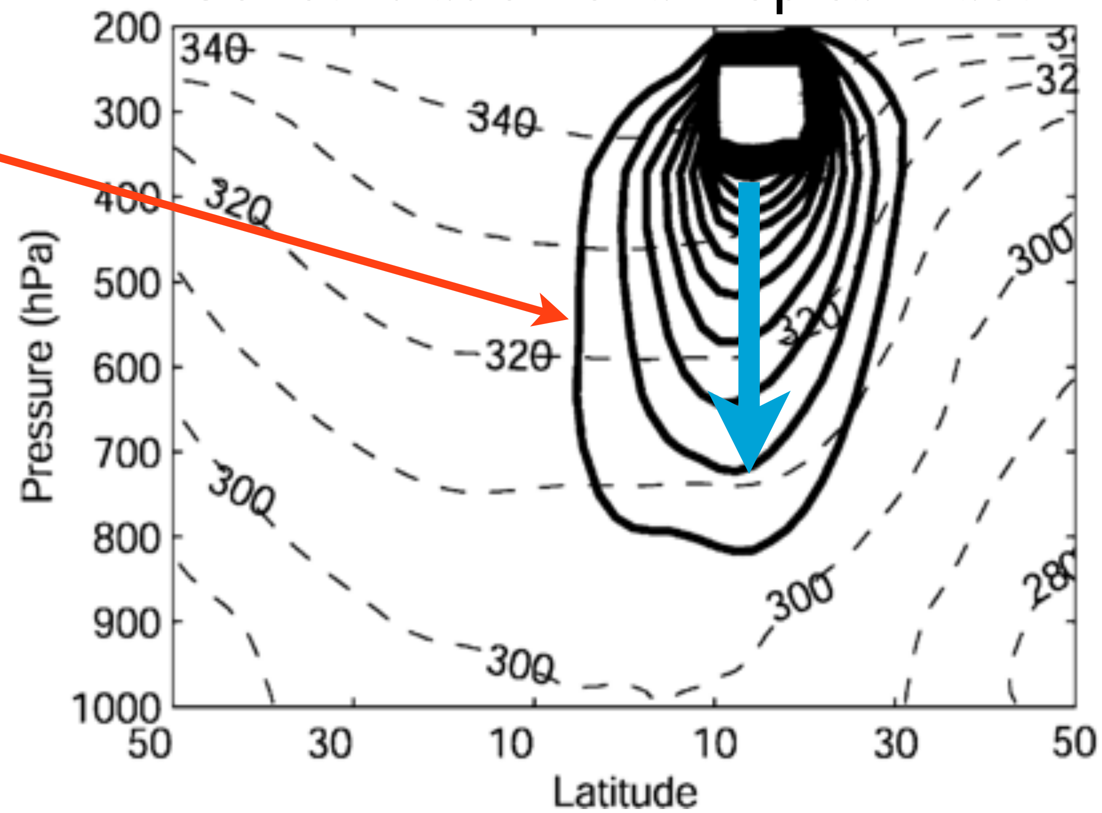


air saturated in the extratropical upper troposphere moves north and south along isentropes

these "isentropic excursions" occur in midlatitude synoptic weather systems

air saturated in tropical deep convective anvils moves downward across isentropes

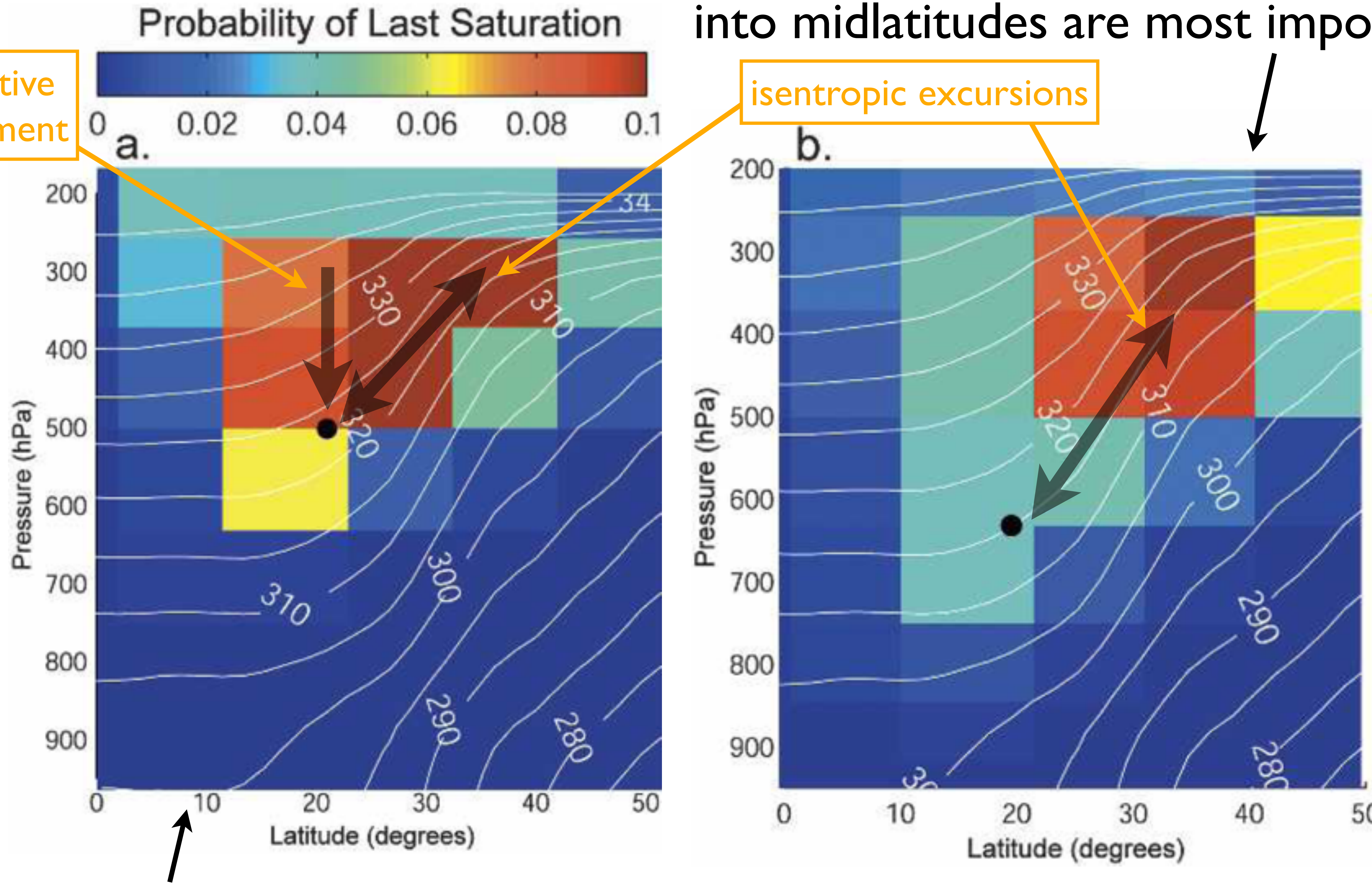
Concentration of a Tropical Tracer



Galewsky et al. 2005

Factors Affecting RH in the Subtropics

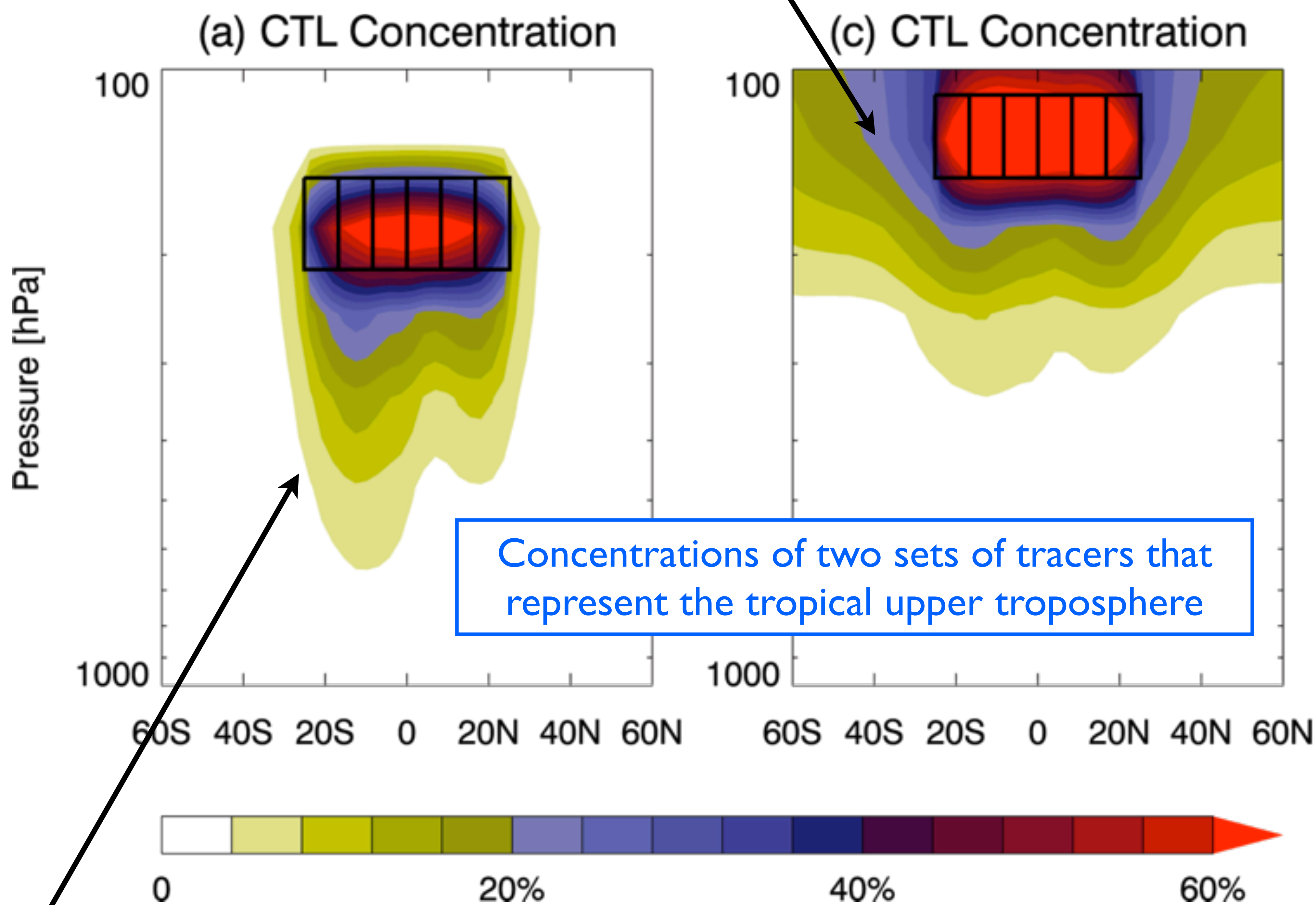
At lower altitudes isentropic excursions into midlatitudes are most important



At higher altitudes both tropical convective detrainment and isentropic excursions are important

Galewsky et al. 2005

Air saturated during slow ascent moves mainly upward and poleward

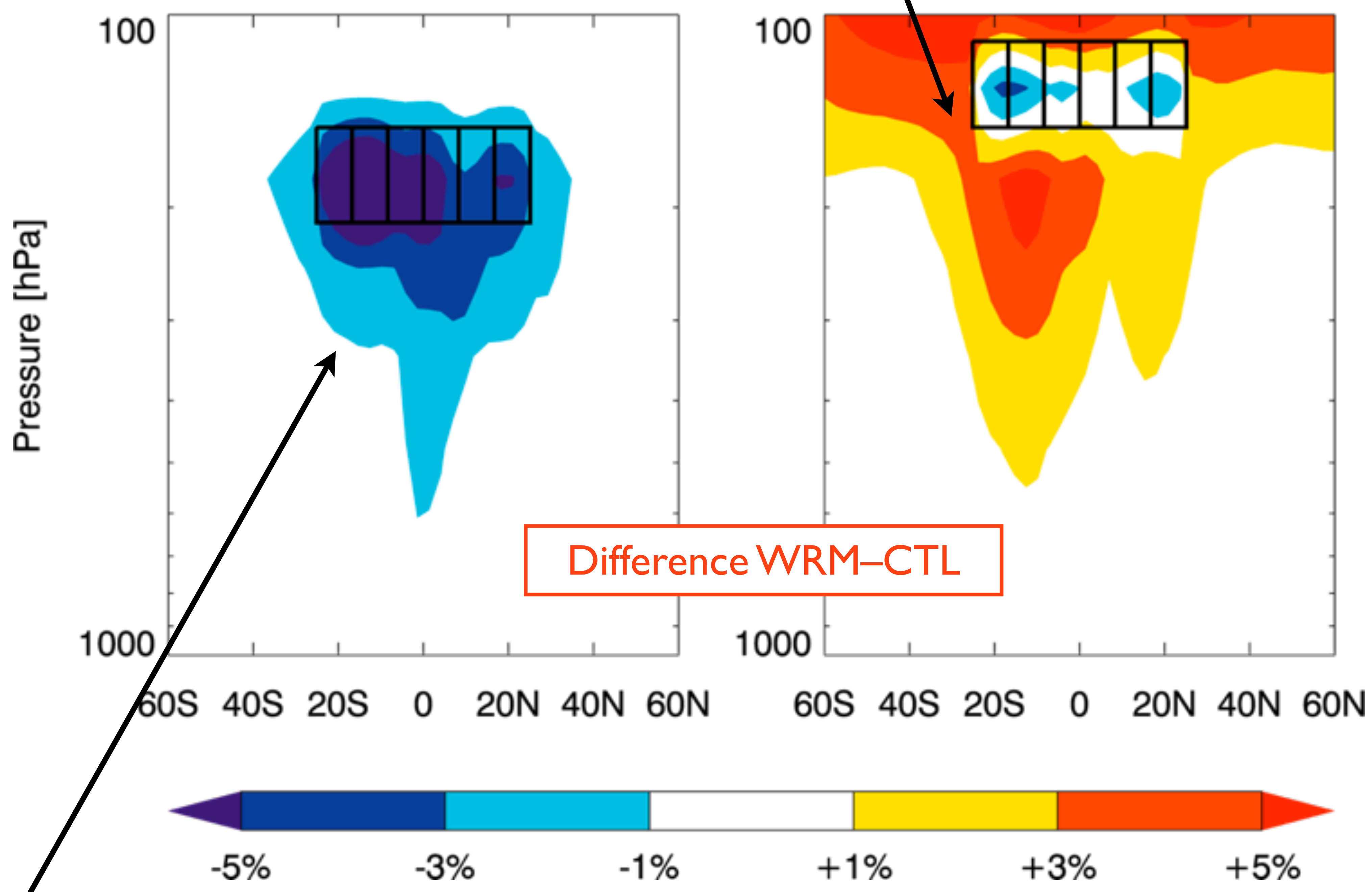


Concentrations of two sets of tracers that represent the tropical upper troposphere

Convectively detrained air moves out and down from the deep tropics

Wright et al. 2010

Deeper convection enhances the convective detrainment contribution (out and down) in the uppermost troposphere...



...while reducing the influence of the layer below

Wright et al. 2010

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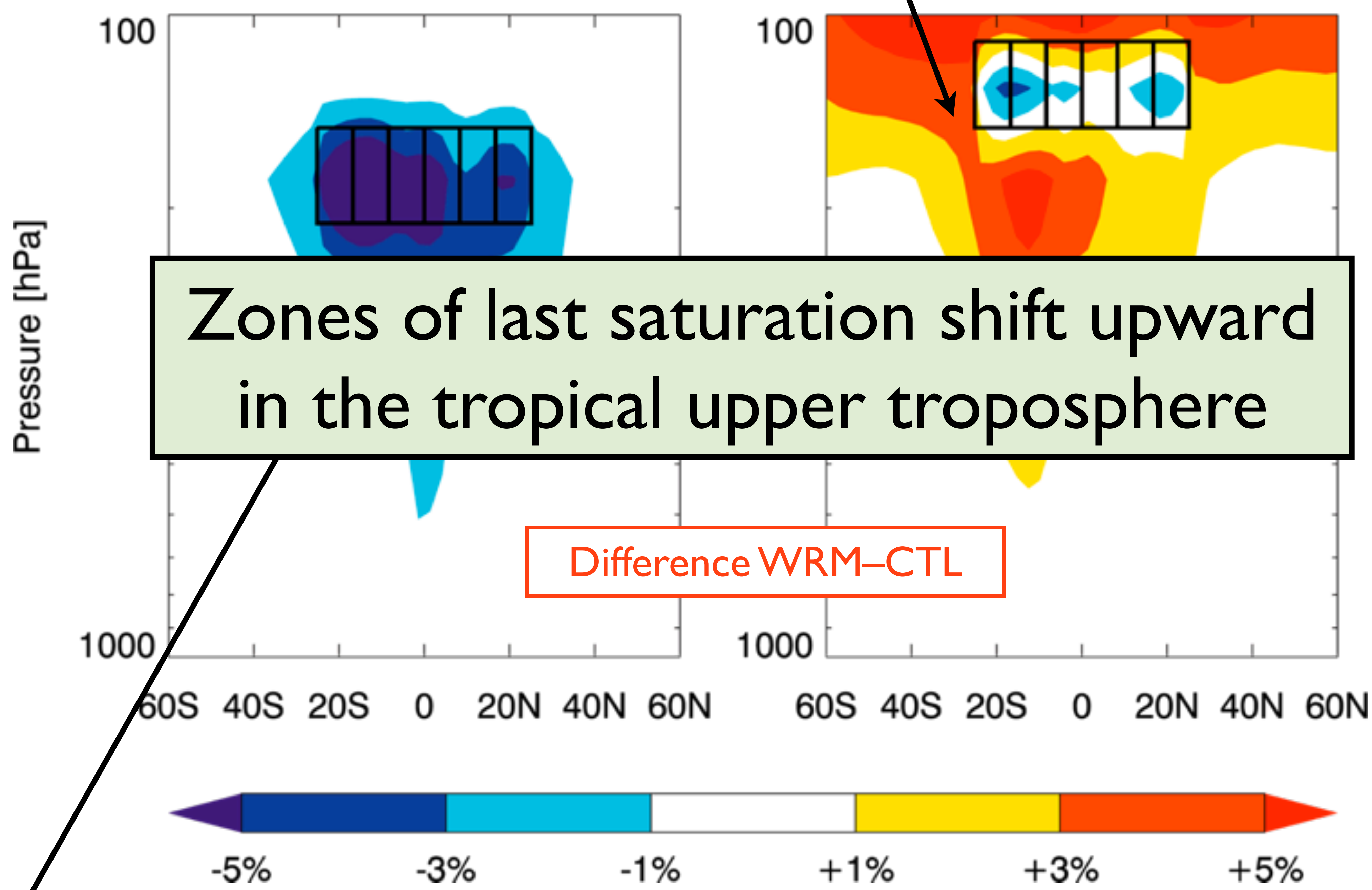
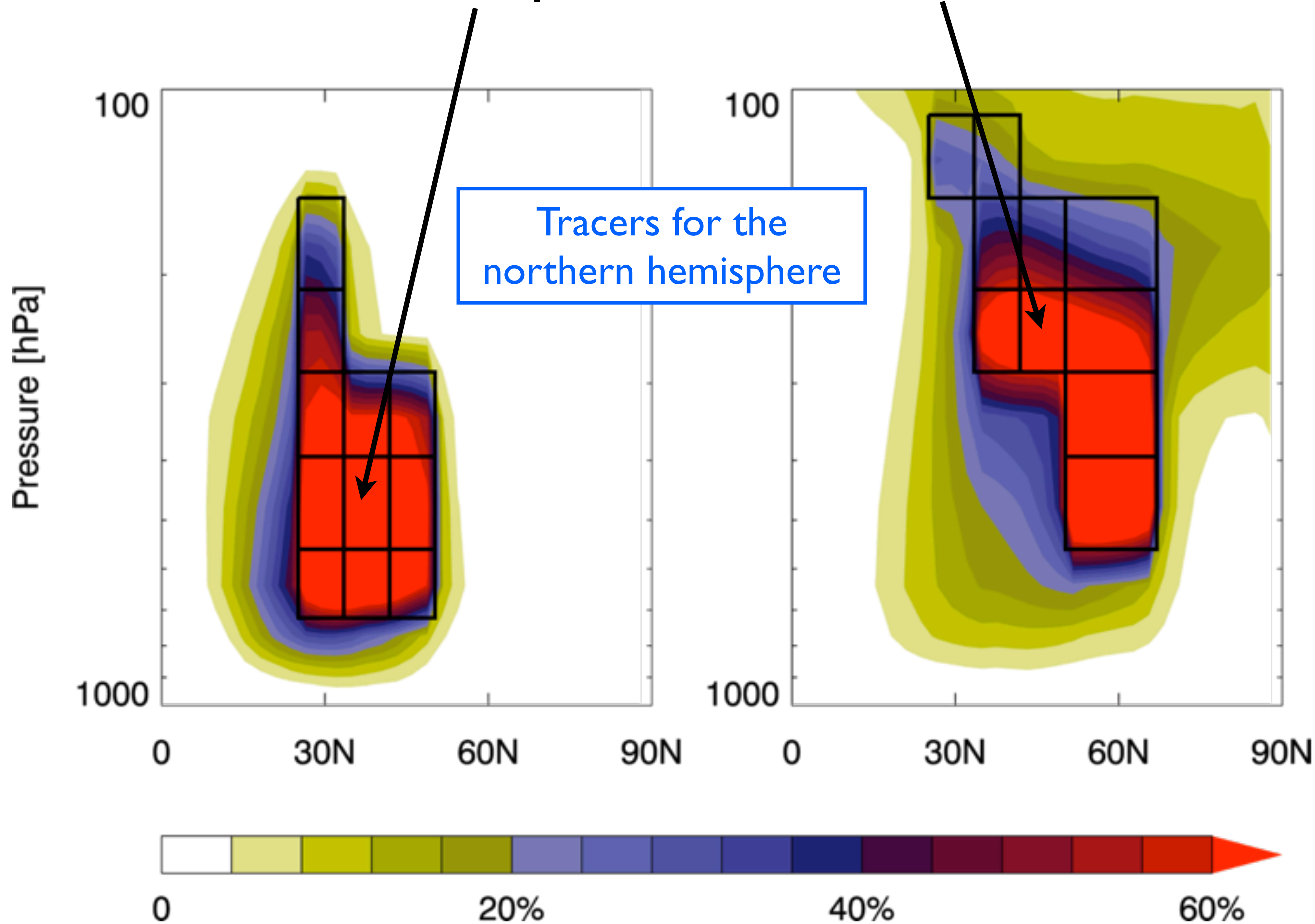


Zones of last saturation shift upward in the tropical upper troposphere

...while reducing the influence of the layer below

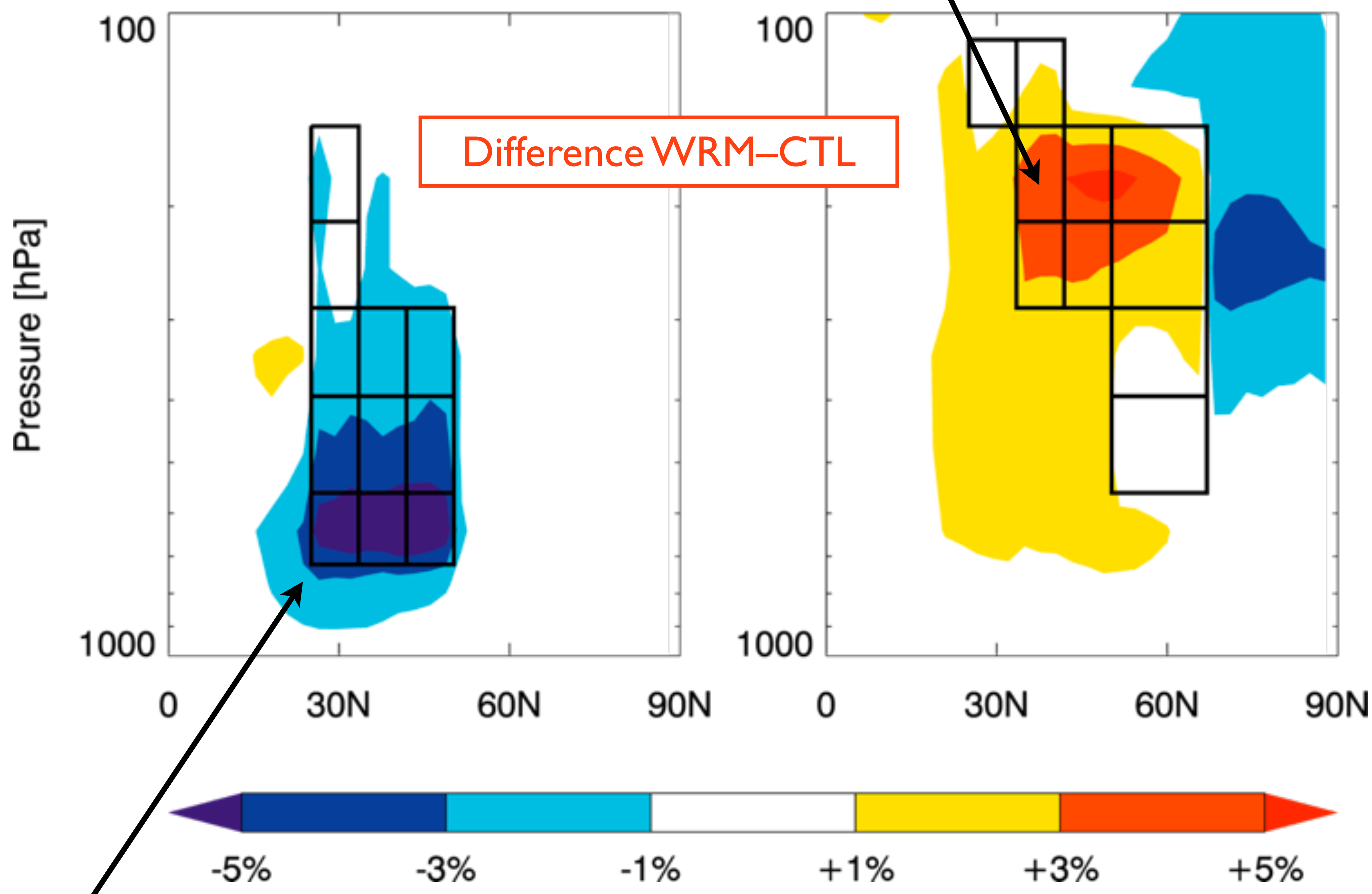
Wright et al. 2010

Saturation mainly follows isentropic surfaces in the subtropics and midlatitudes



Wright et al. 2010

The influence of saturation zones in the midlatitude upper troposphere increases both locally and in the subtropics...



...reducing the importance of saturation zones in the subtropics

Wright et al. 2010

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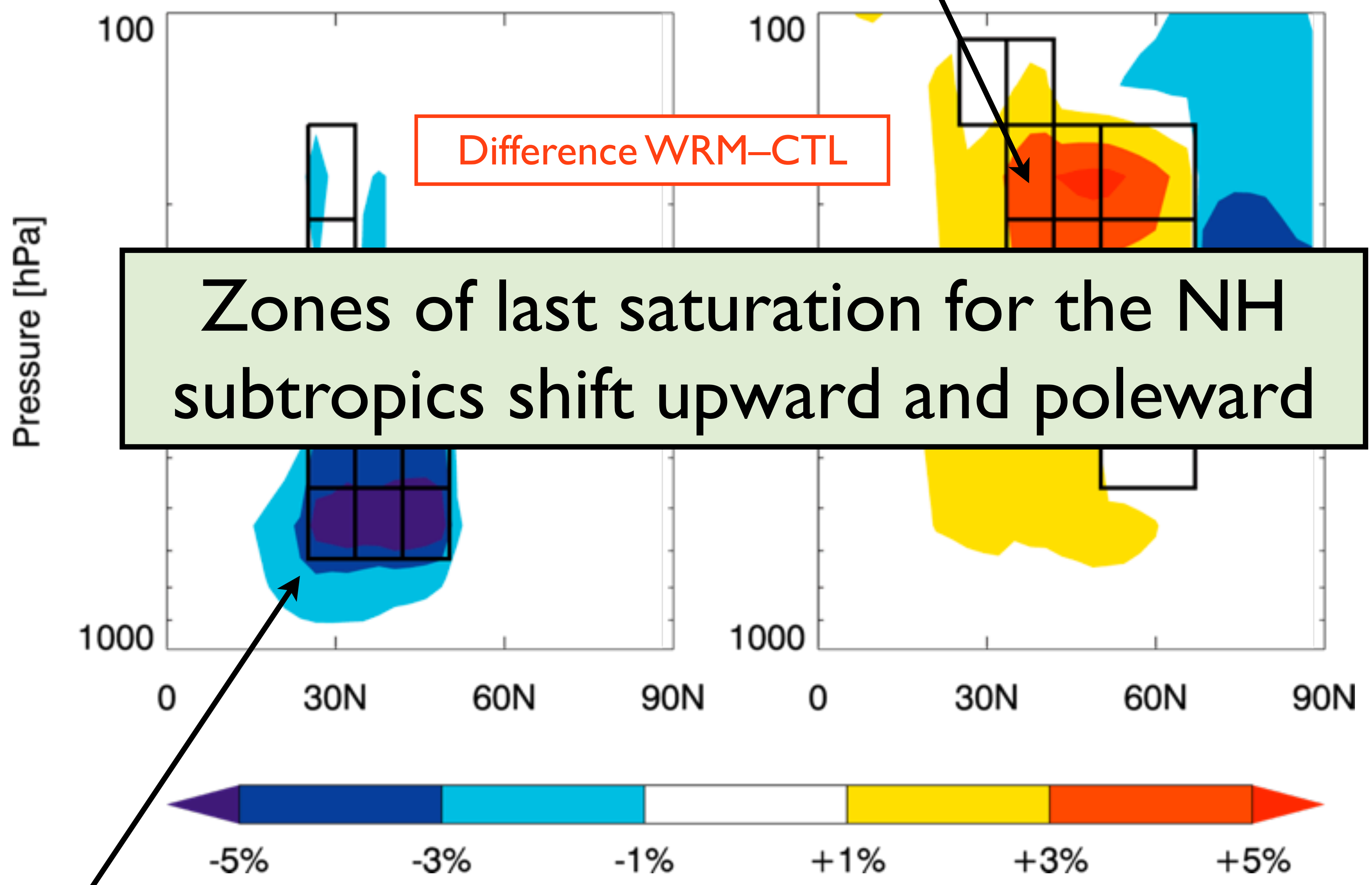

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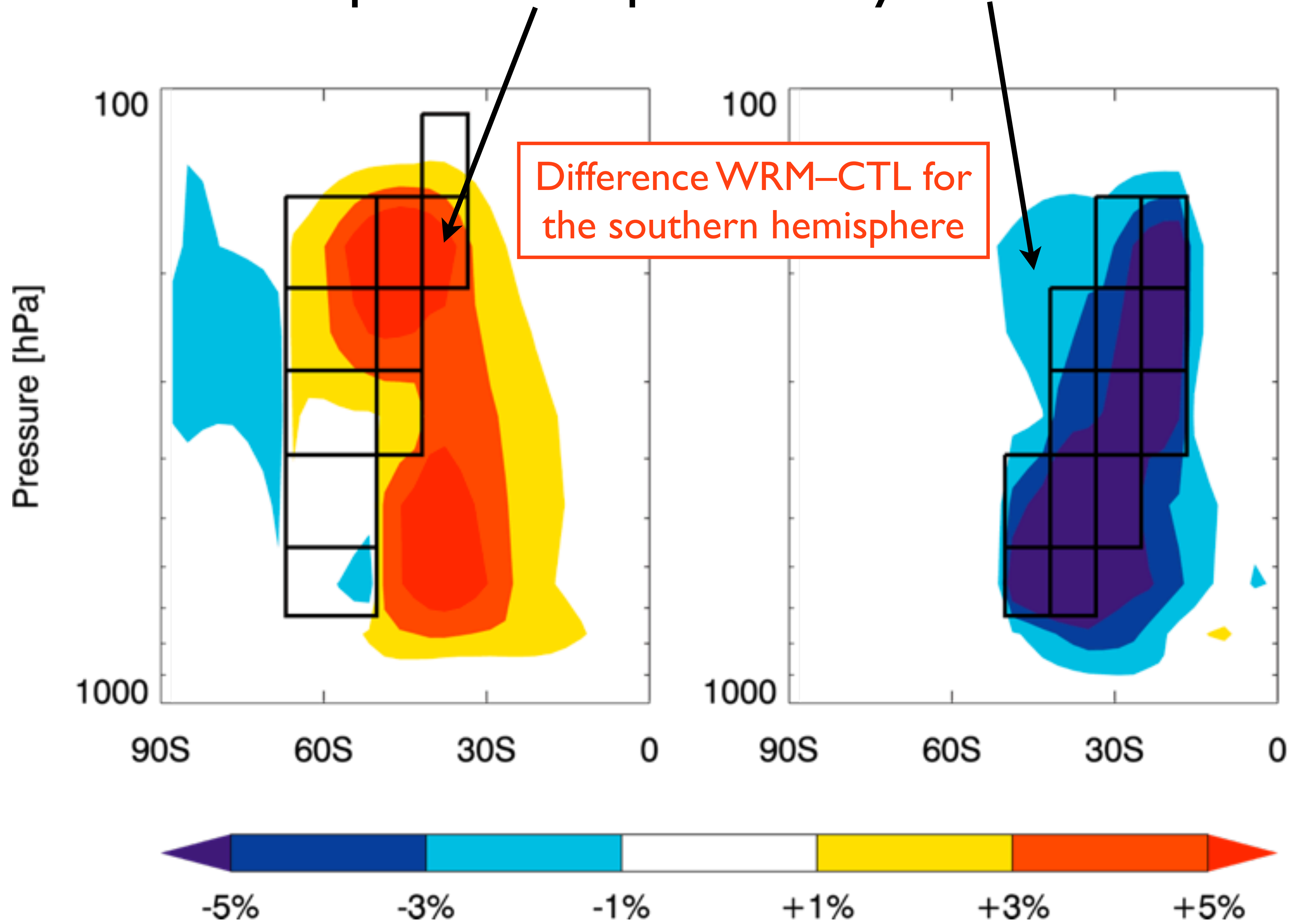
Wright et al. 2010

Changes in similar sets of tracers in the southern hemisphere are qualitatively similar...



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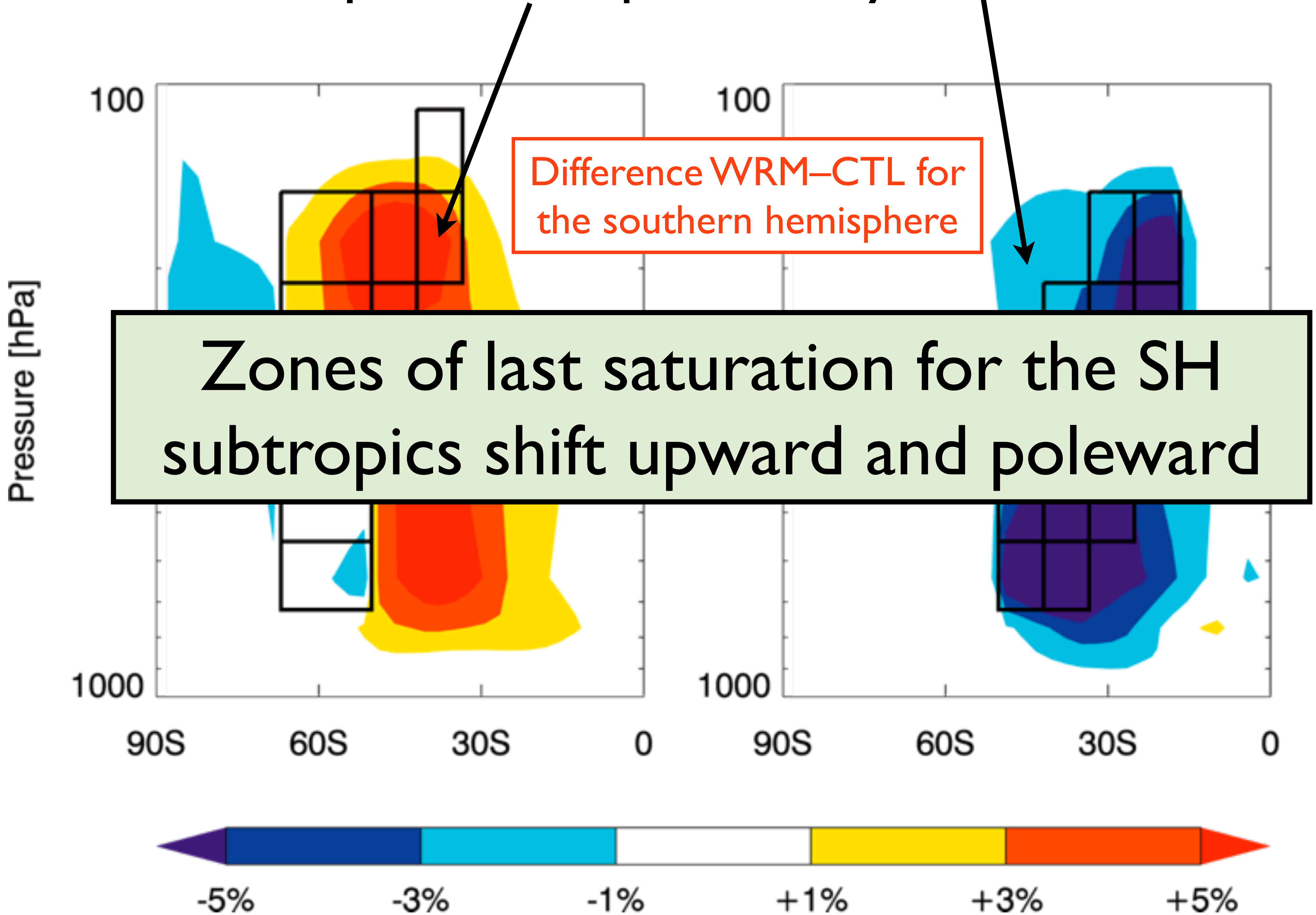

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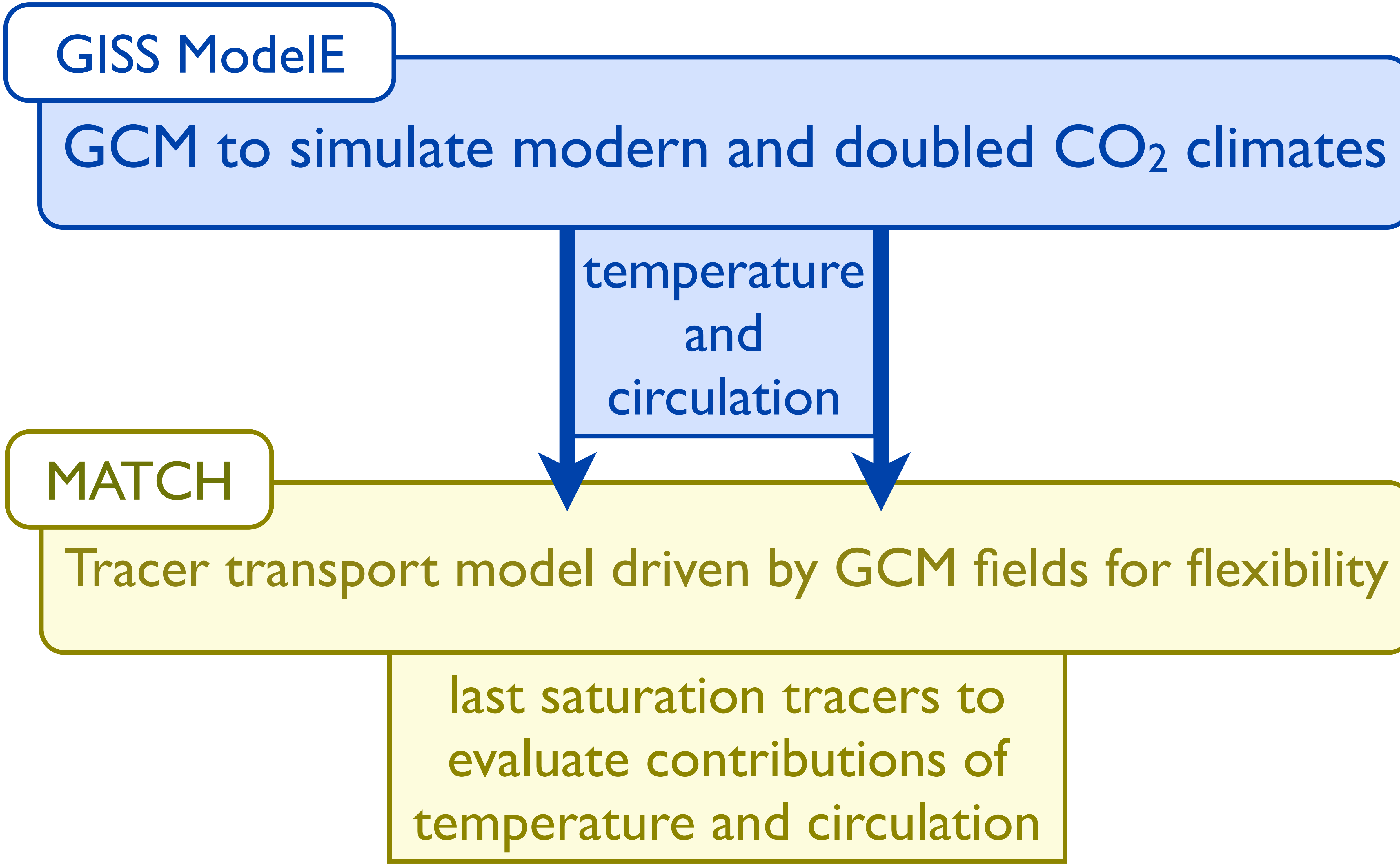
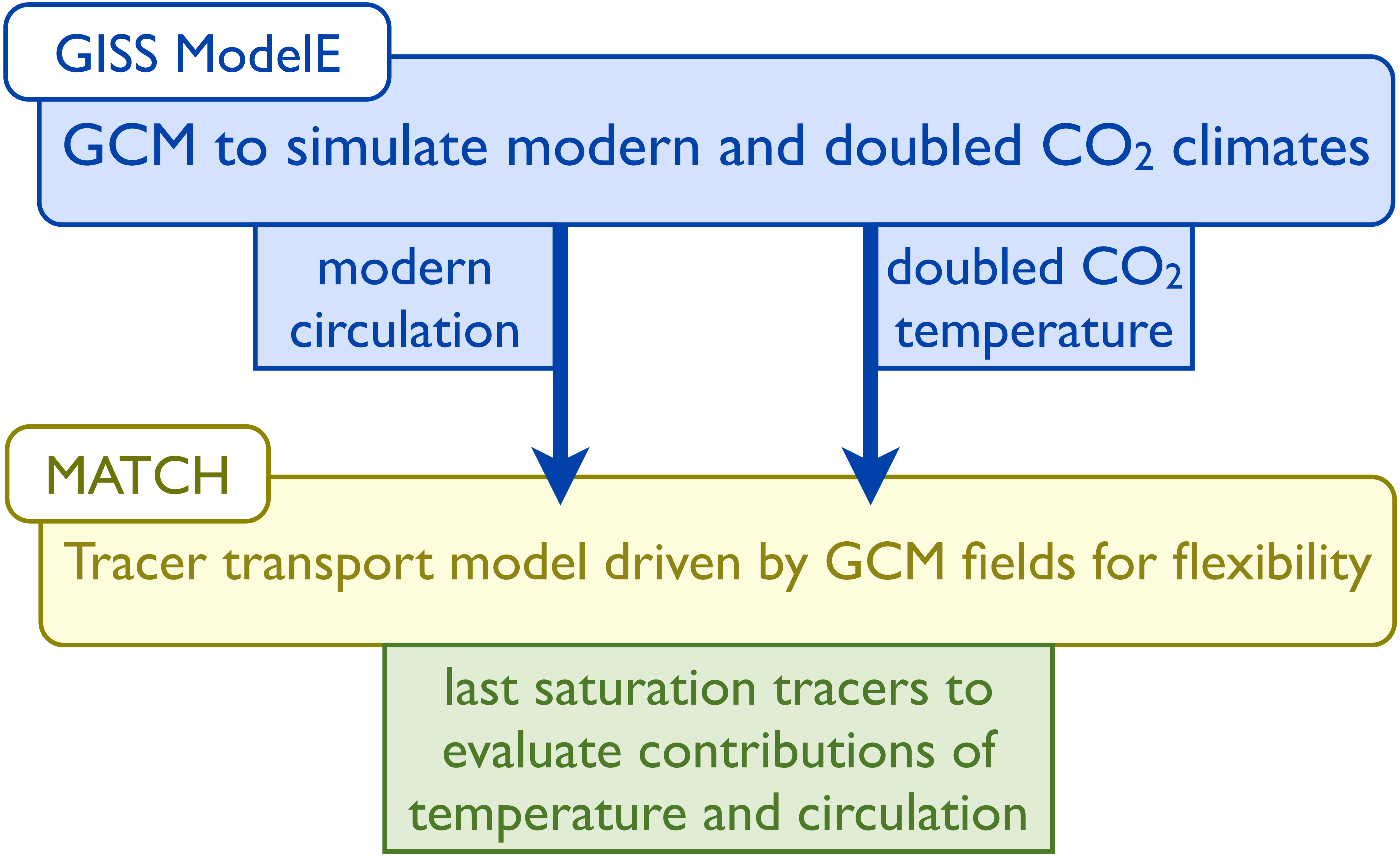


Wright et al. 2010

How do temperature changes affect RH?



Wright et al. 2010

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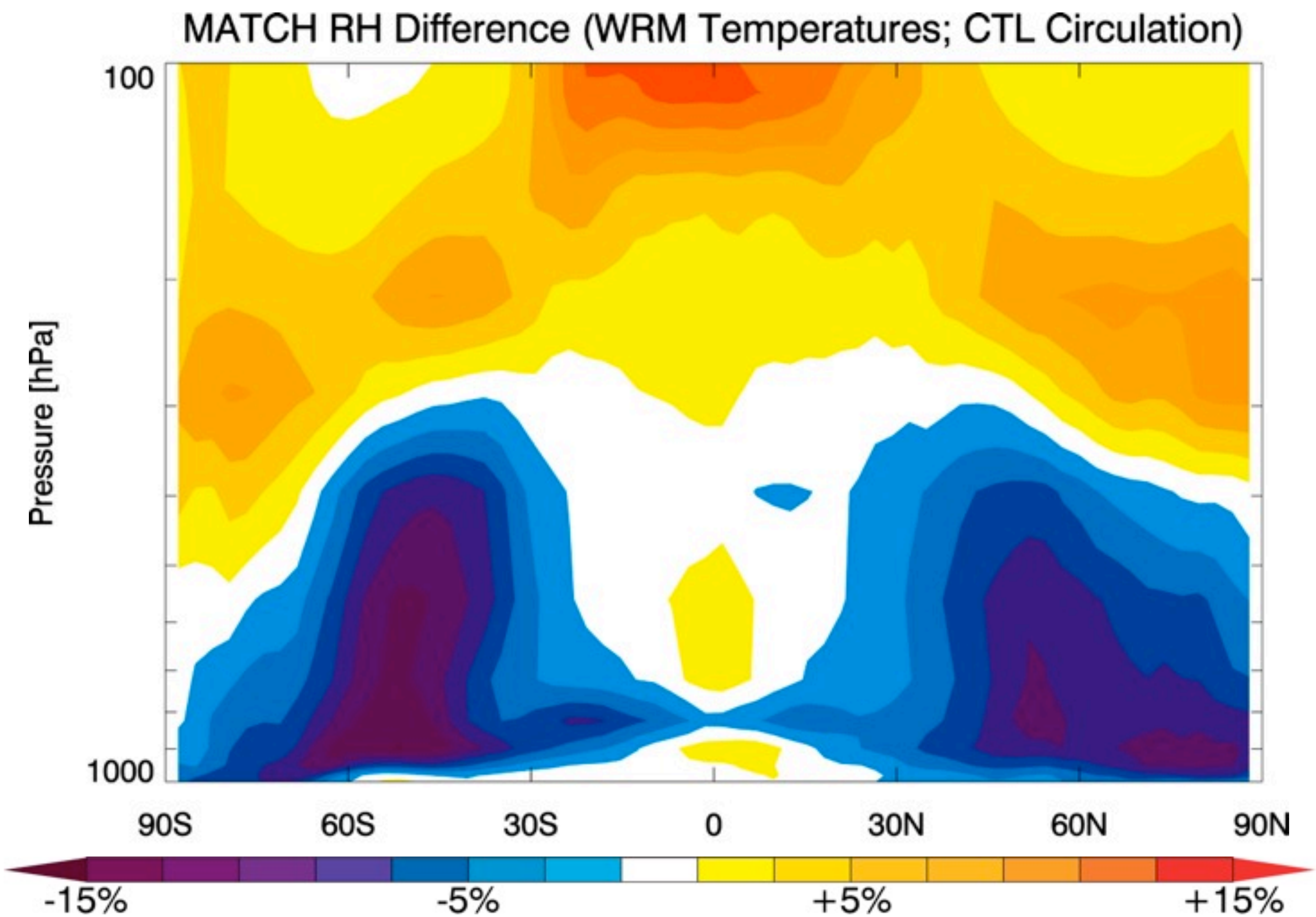
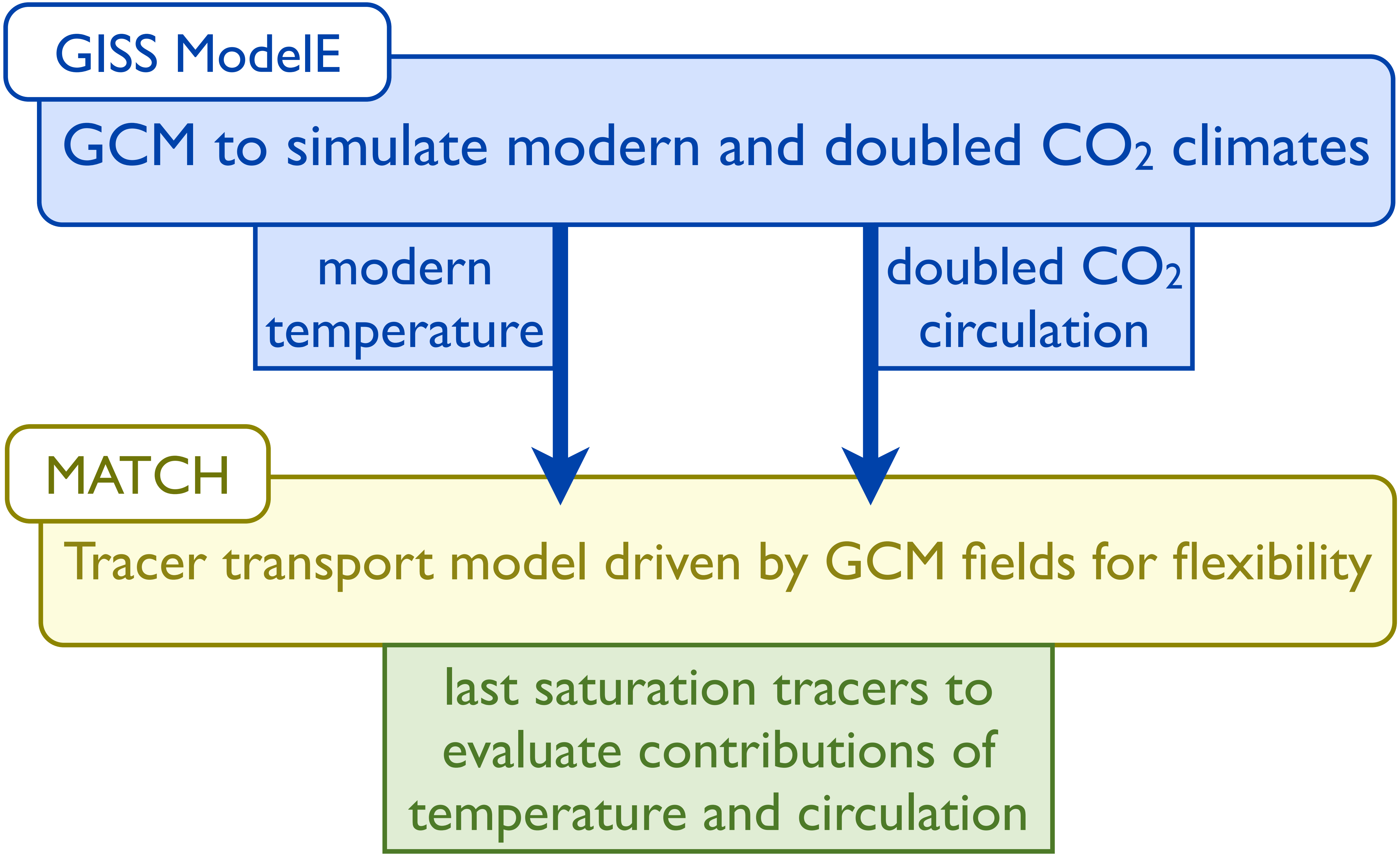


Temperature changes in isolation yield a dipole with increases in RH at high altitudes and decreases below

Wright et al. 2010

How do circulation changes affect RH?



Wright et al. 2010

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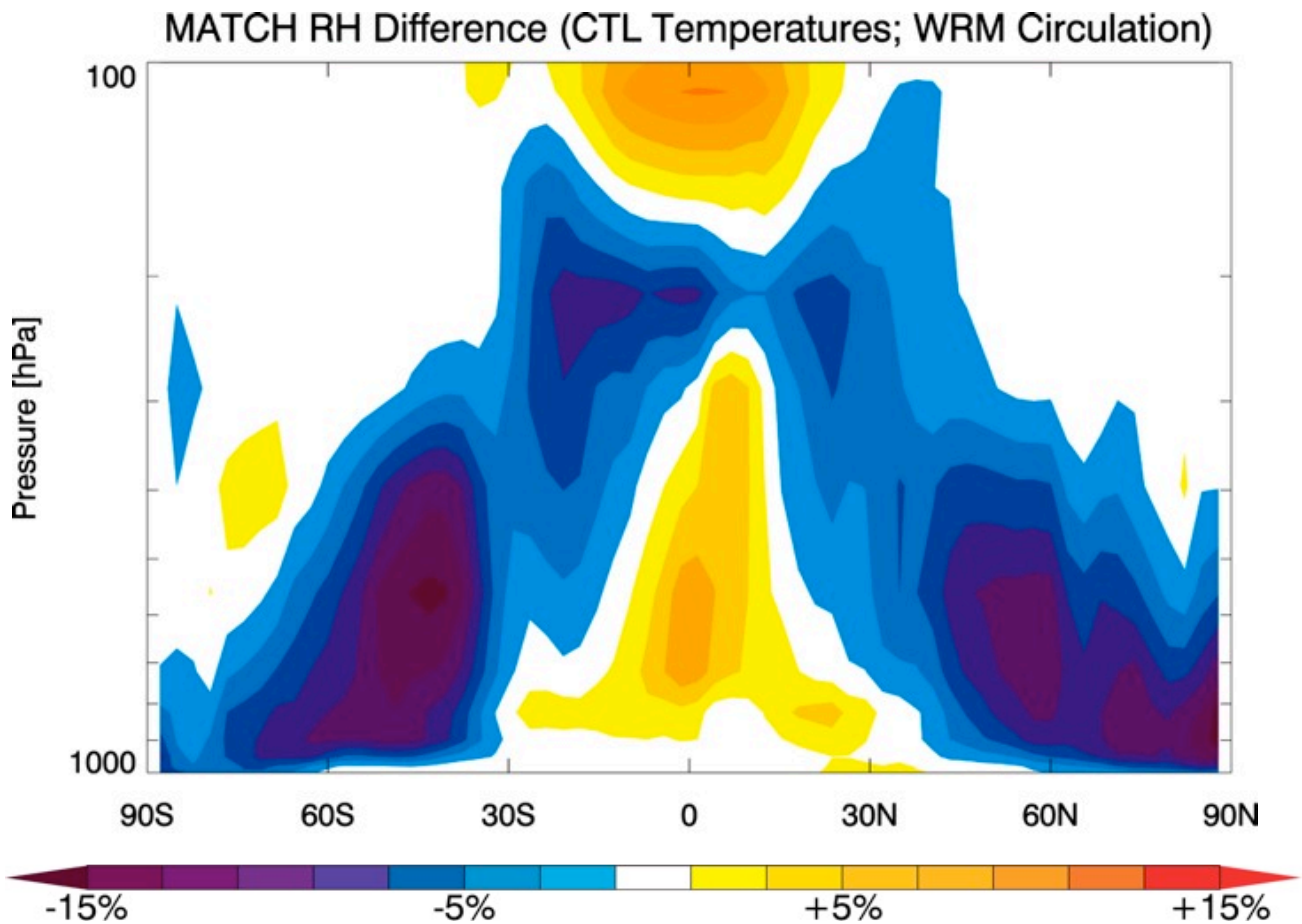
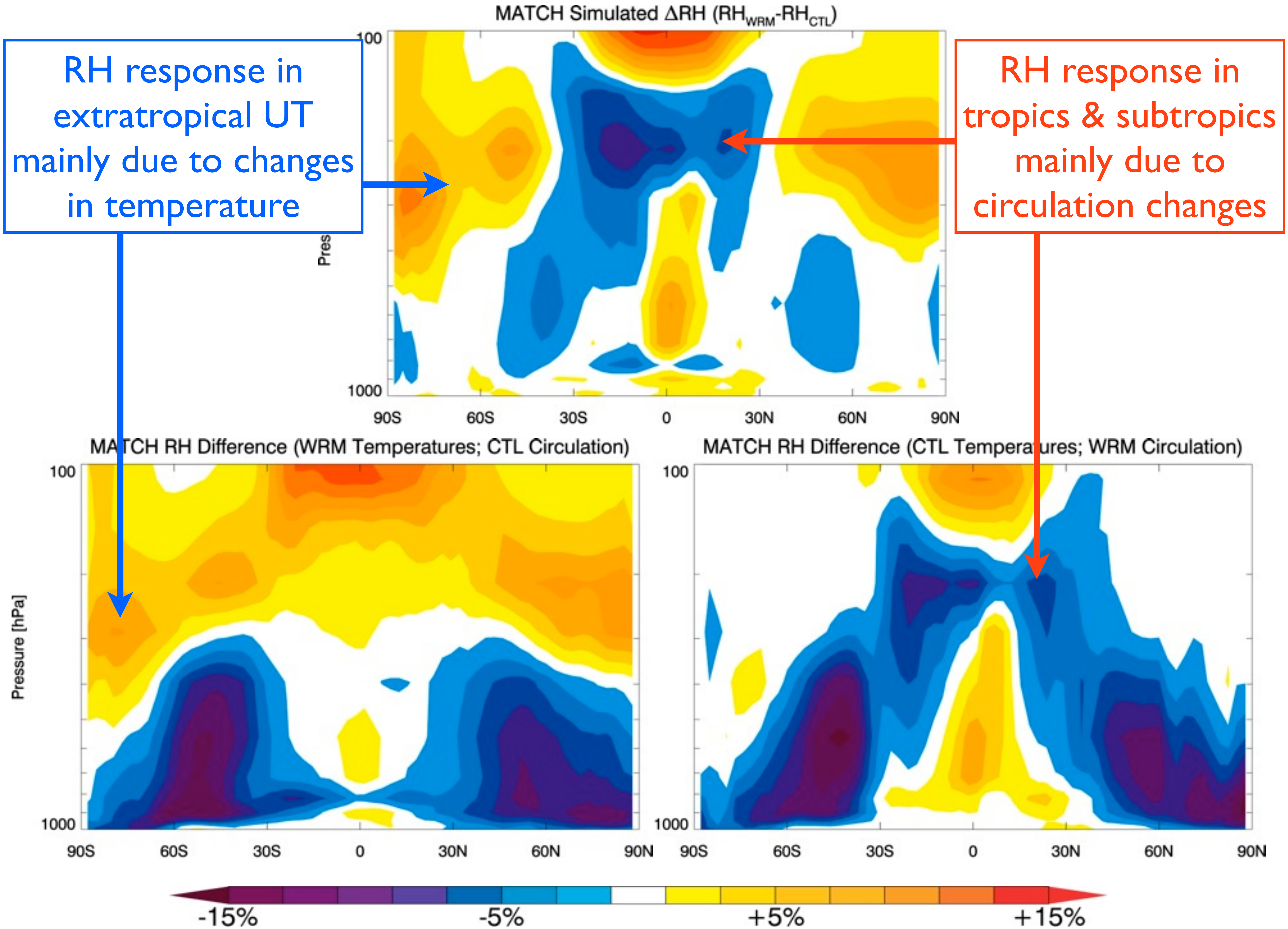


Circulation changes in isolation yield the characteristic horseshoe pattern of RH changes in the tropics

Wright et al. 2010



Wright et al. 2010

Tracer Formulation

The reconstruction of relative humidity offers another means of separating temperature and circulation effects

$\mathcal{T}_i(\mathbf{x})$ is the local concentration of tracer i

tracers represent circulation

Control

$$RH(\mathbf{x}) = \frac{\sum_{i=1}^{N} \mathcal{T}_i(\mathbf{x}) \langle q^*(\mathcal{T}_i) \rangle}{q^*(\mathbf{x})}$$

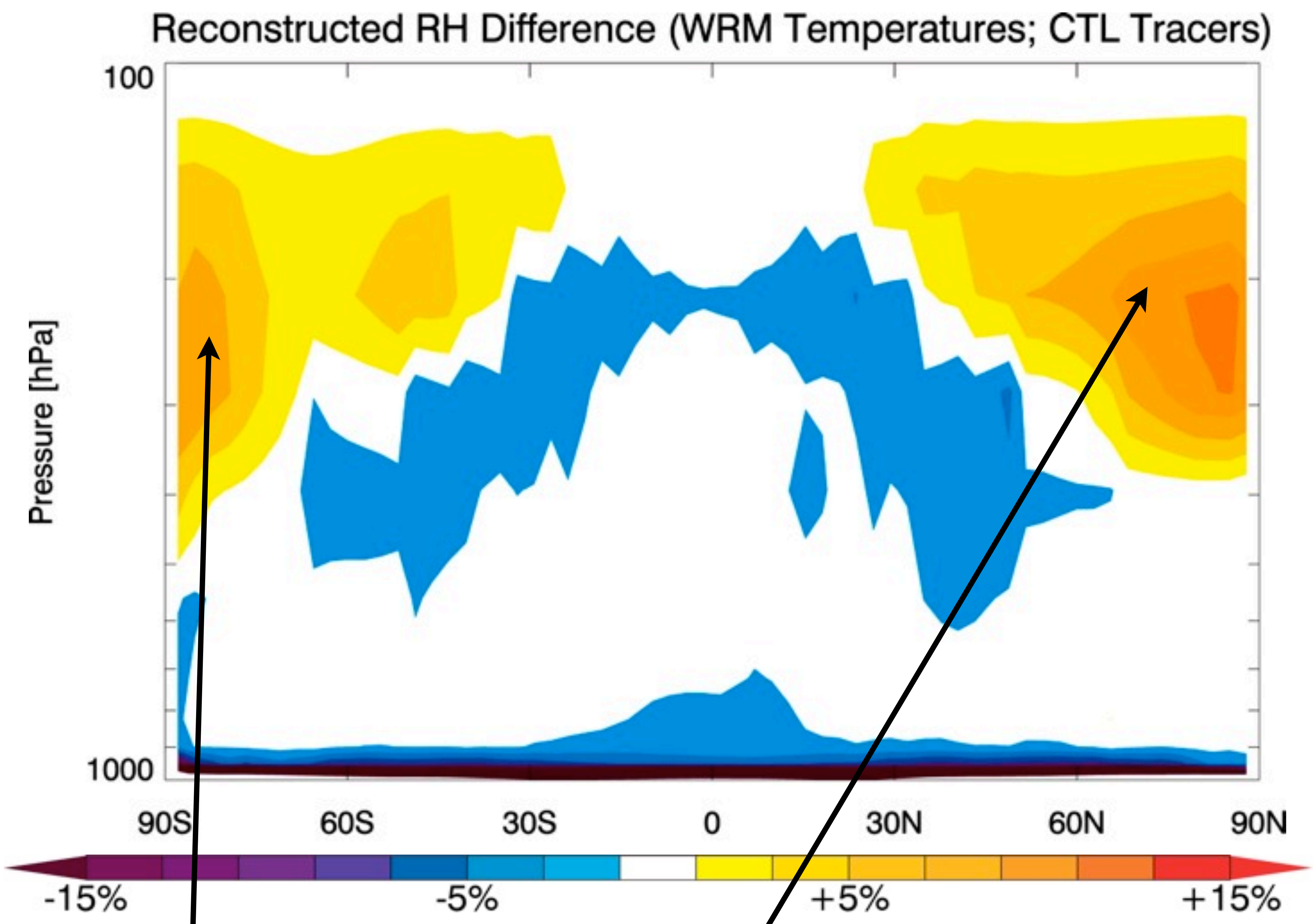
$2\times CO_2$

q^* represents temperature

$q^*(\mathbf{x})$ is the local saturation mixing ratio

$\langle q^*(\mathcal{T}_i) \rangle$ is the mean q^* associated with tracer domain i

How do temperature changes affect RH?



Changes in $q*$ predominantly affect RH near extratropical tropopause

Wright et al. 2010

Tracer Formulation

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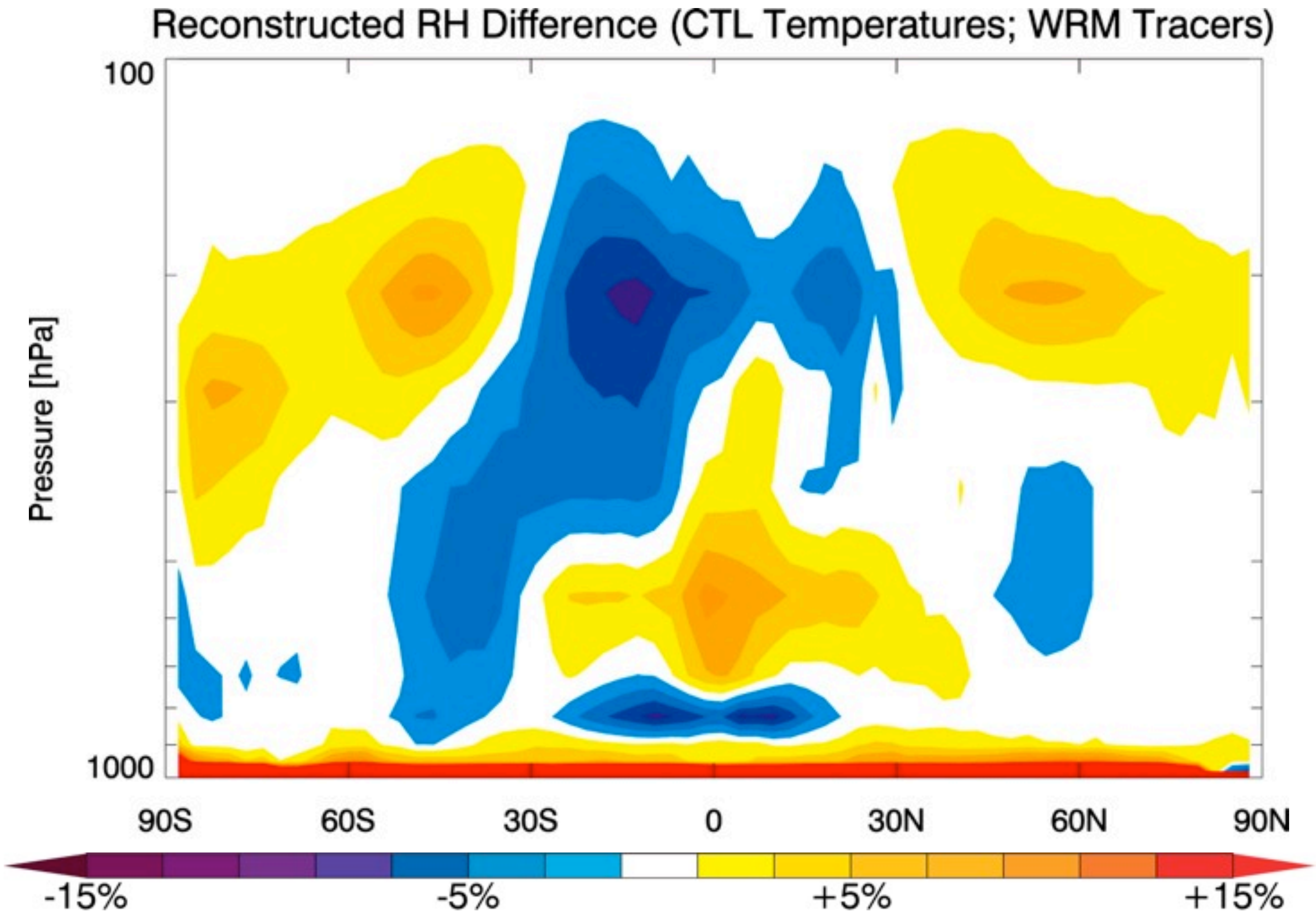
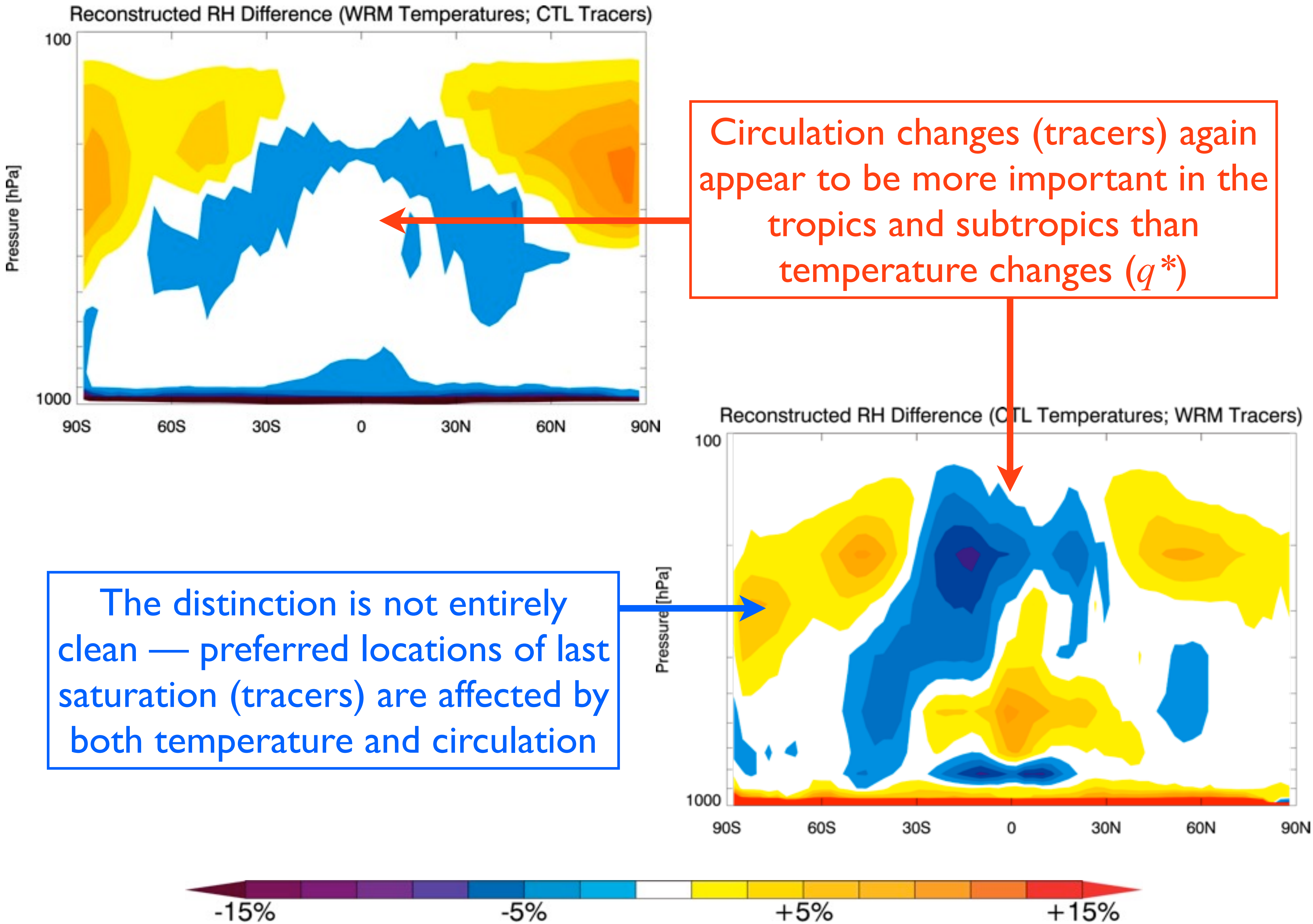


Changing the tracers reproduces the qualitative features of the RH response to warming

Wright et al. 2010

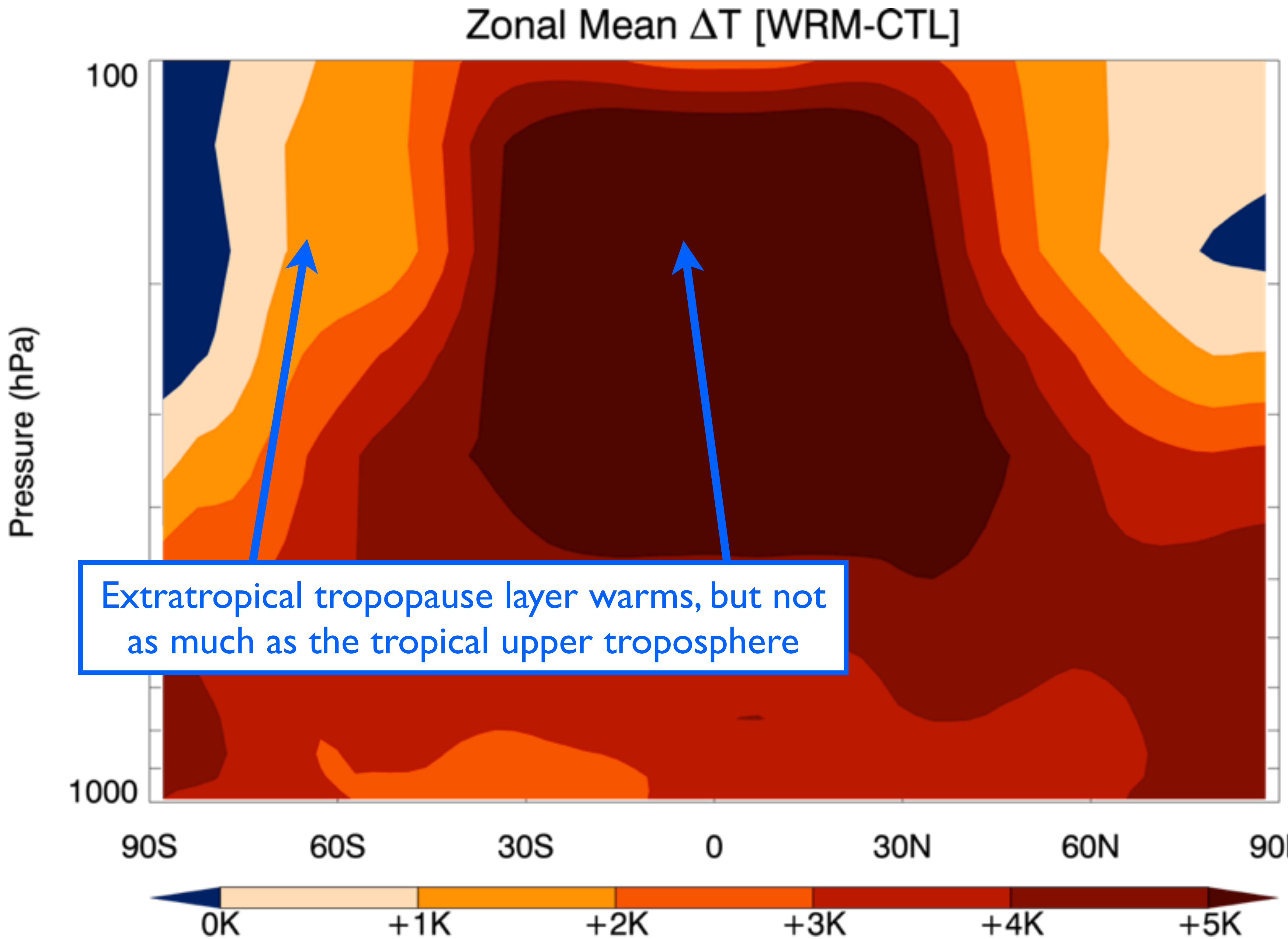


Circulation changes (tracers) again appear to be more important in the tropics and subtropics than temperature changes (q^*)

The distinction is not entirely clean — preferred locations of last saturation (tracers) are affected by both temperature and circulation

Wright et al. 2010

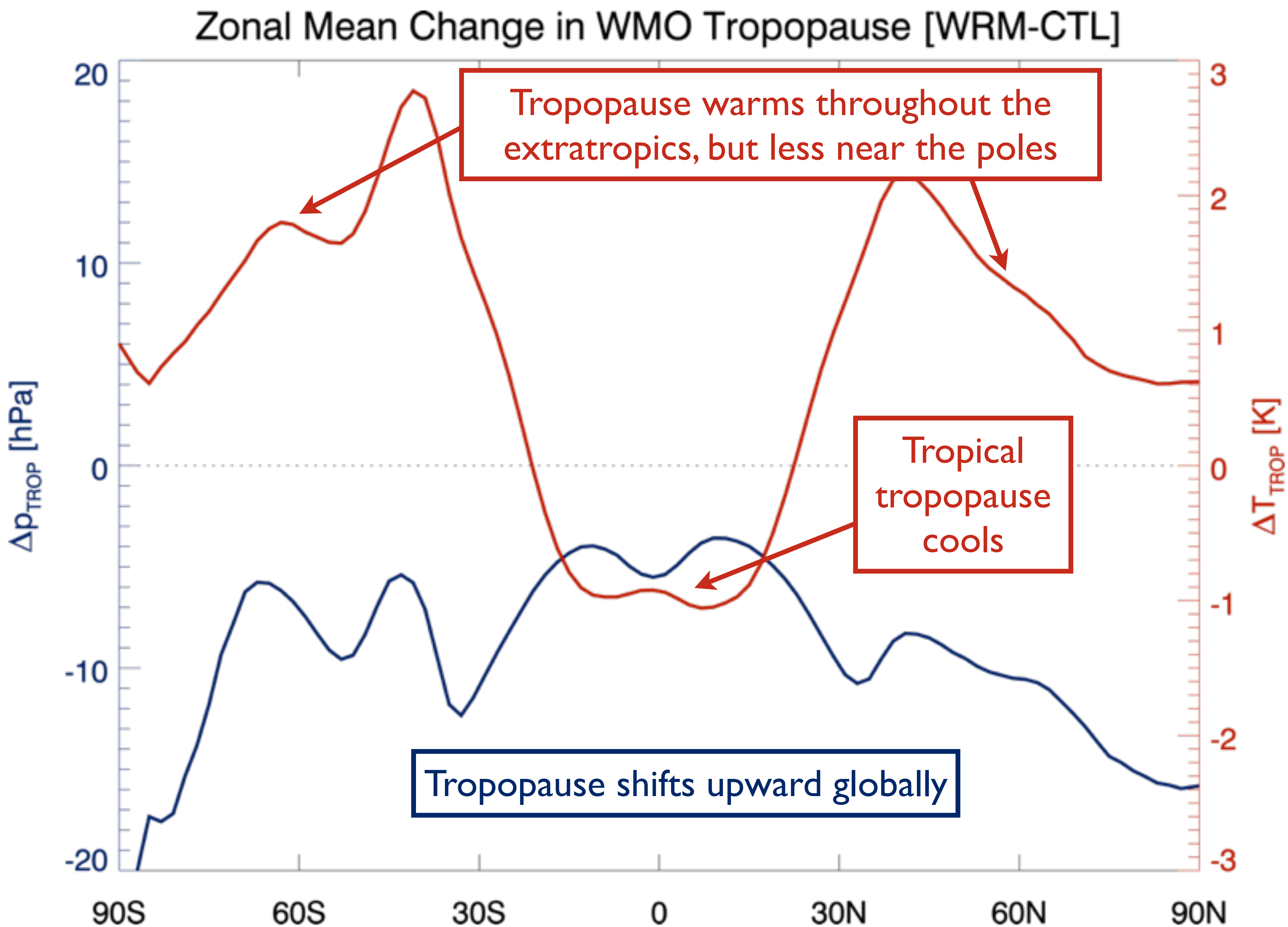
Simulated Changes in Temperature



Temperature changes act to increase RH in the extratropical UT

Wright et al. 2010

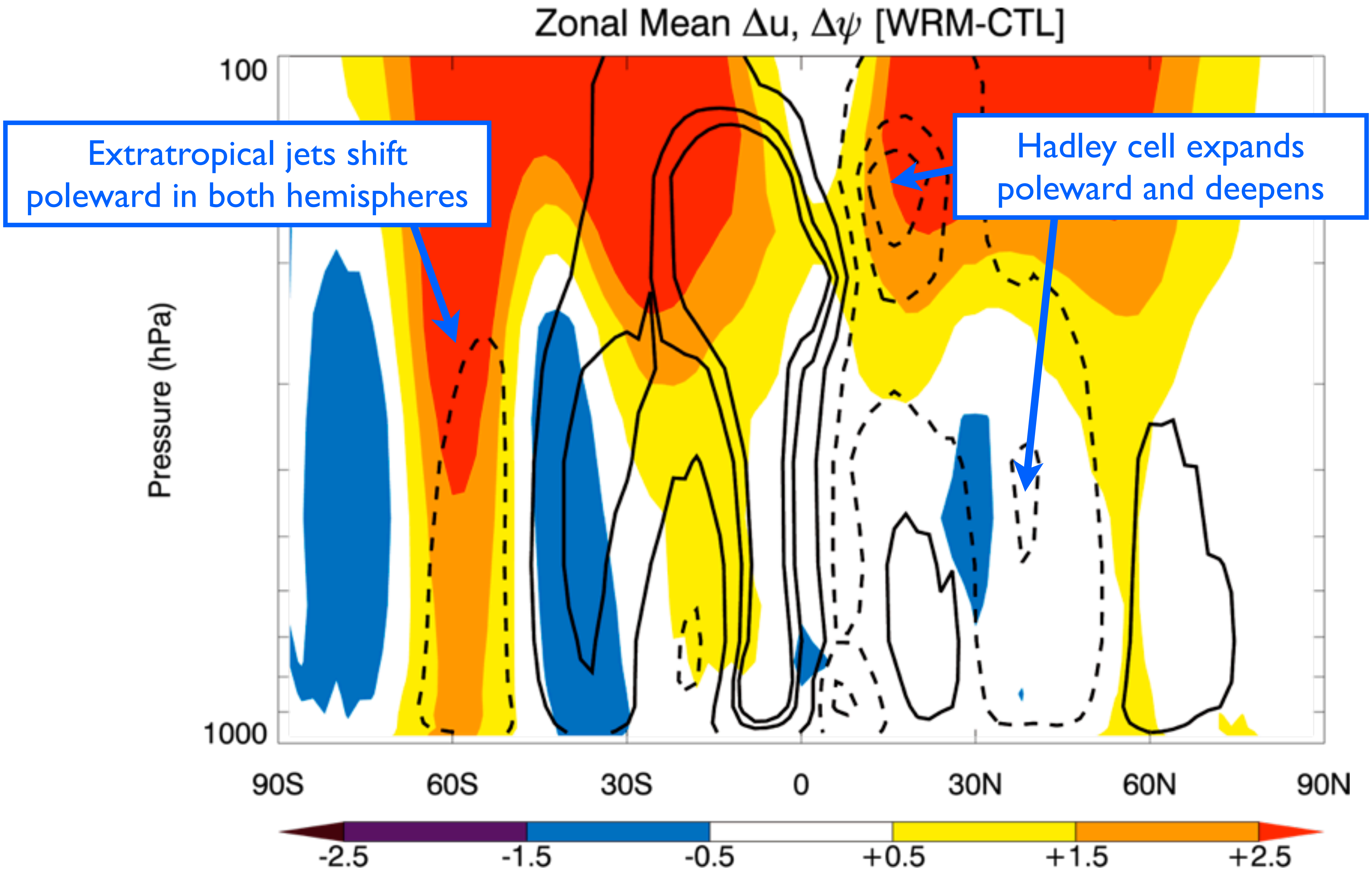
Simulated Changes in the Tropopause



...also promote more frequent saturation in the extratropical UT

Wright et al. 2010

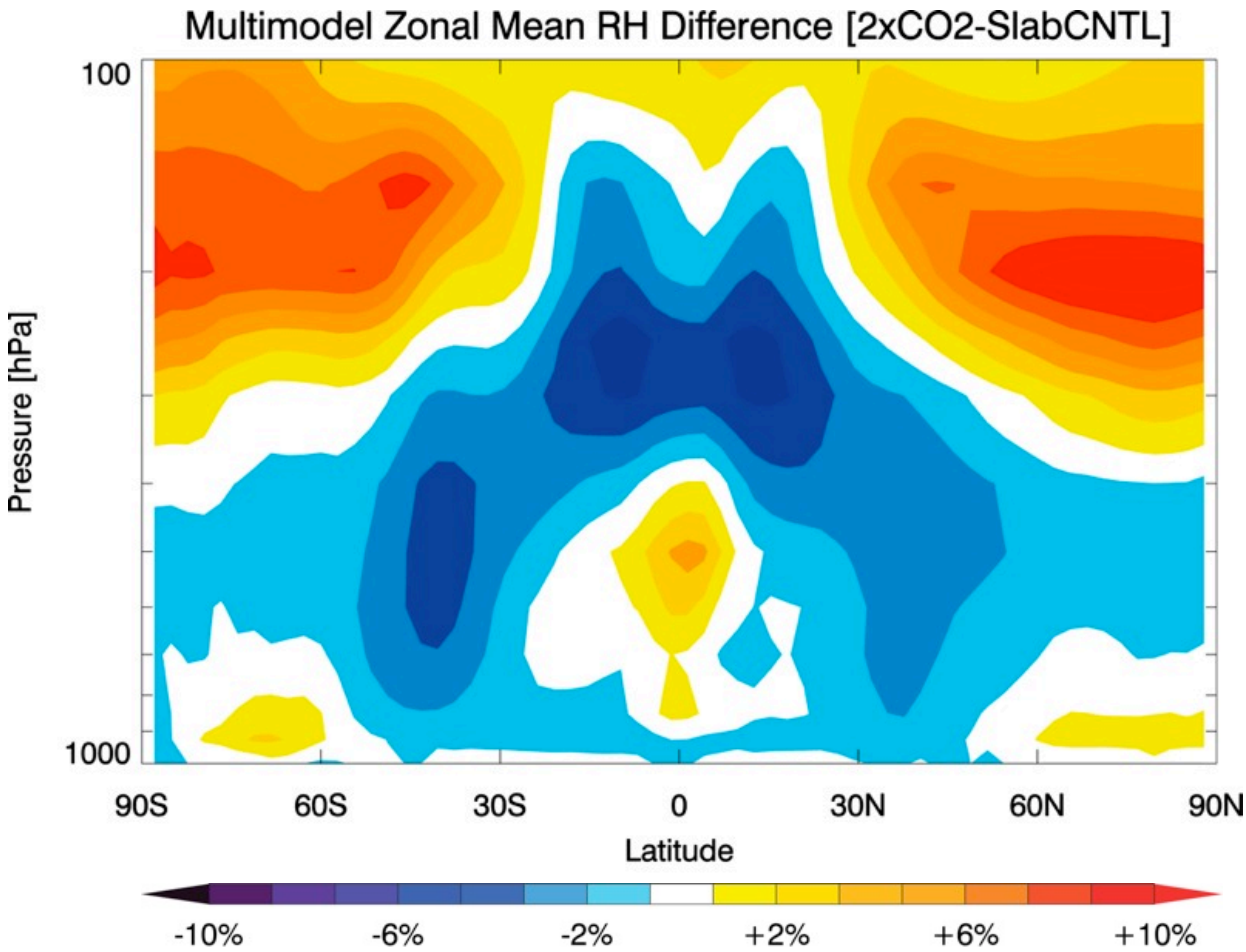
Simulated Changes in the Zonal Mean Circulation



Changes are more pronounced in the southern hemisphere

Wright et al. 2010

Summarizing Changes in Zonal Mean RH



Wright et al. 2010

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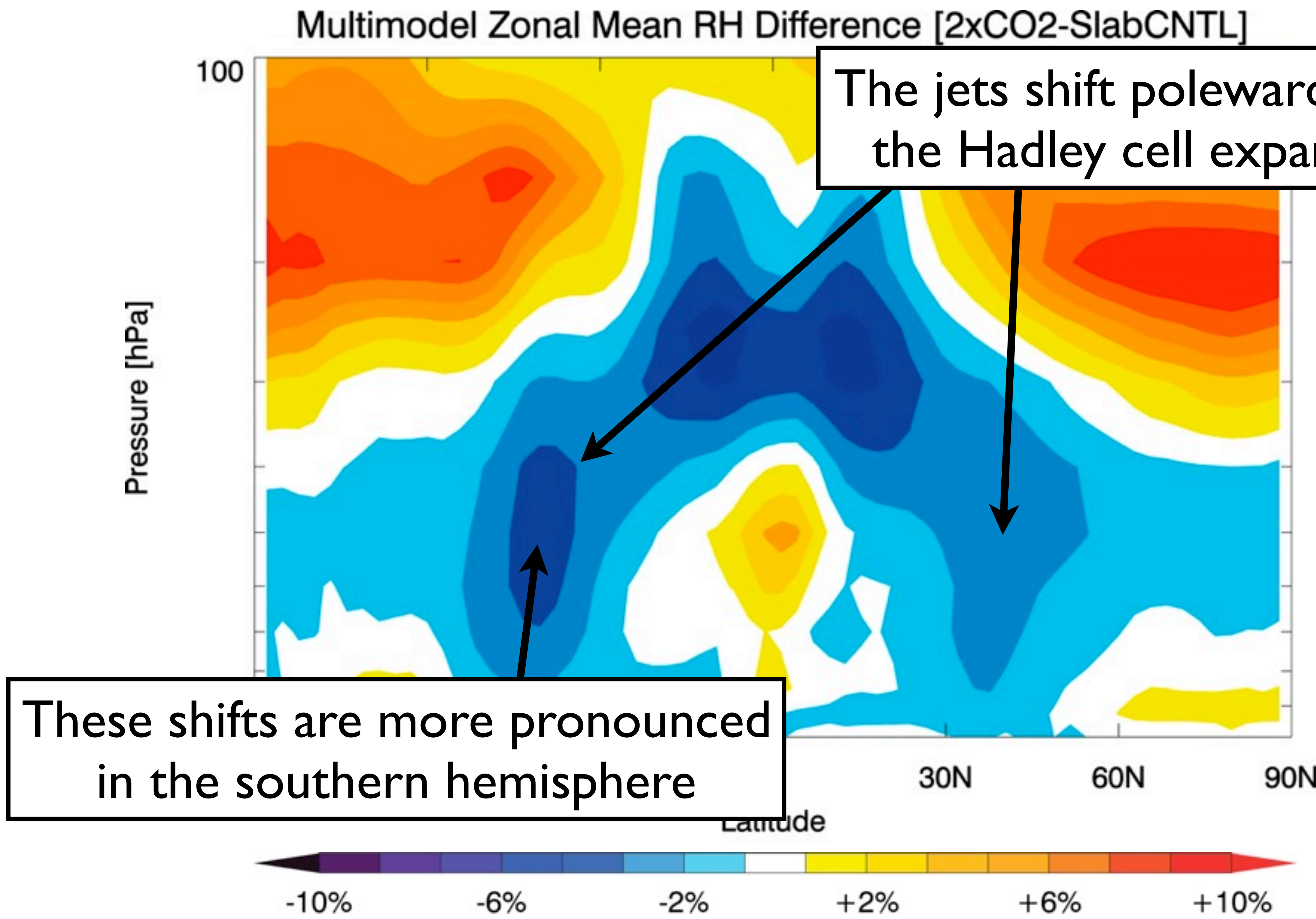
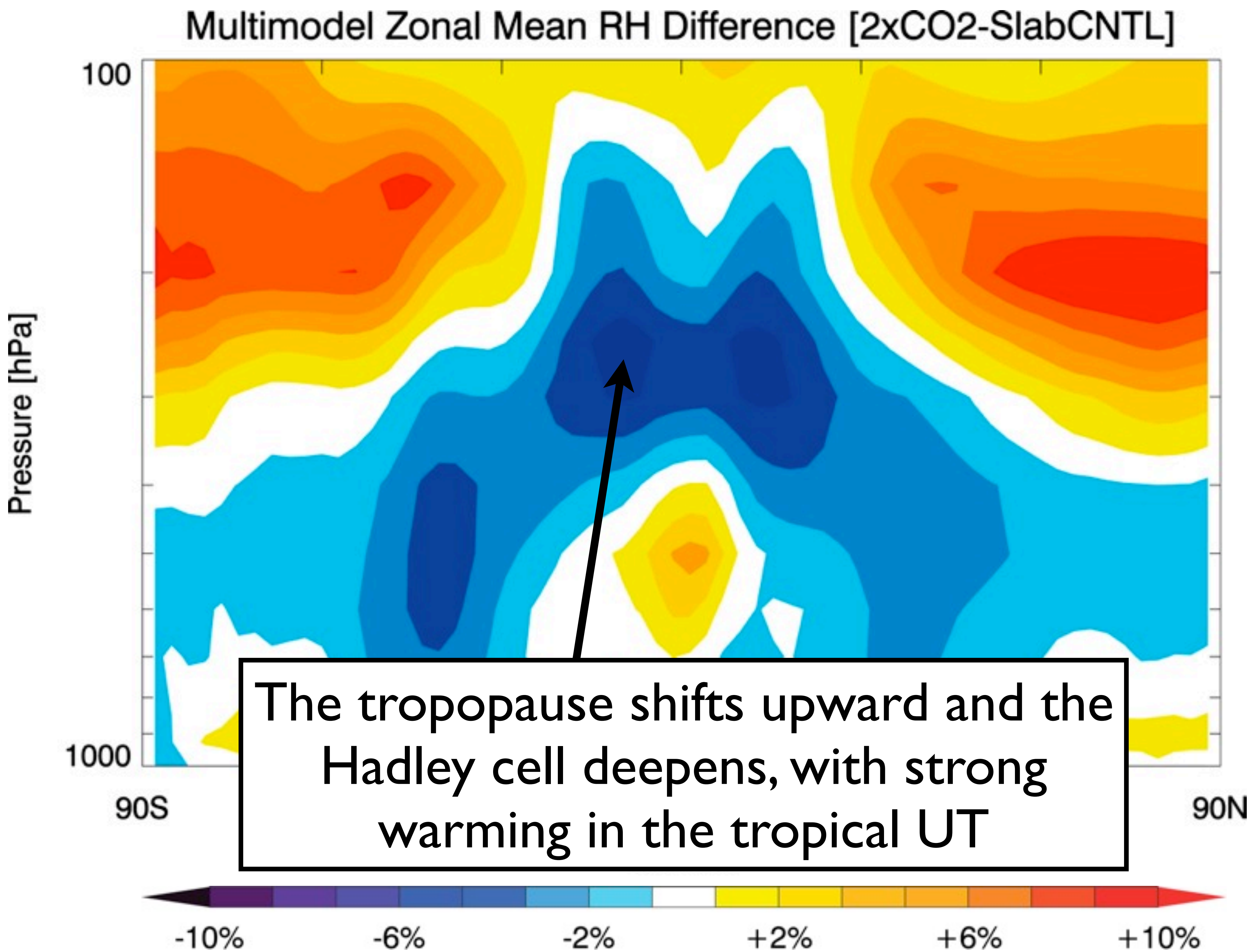


Wright et al. 2010

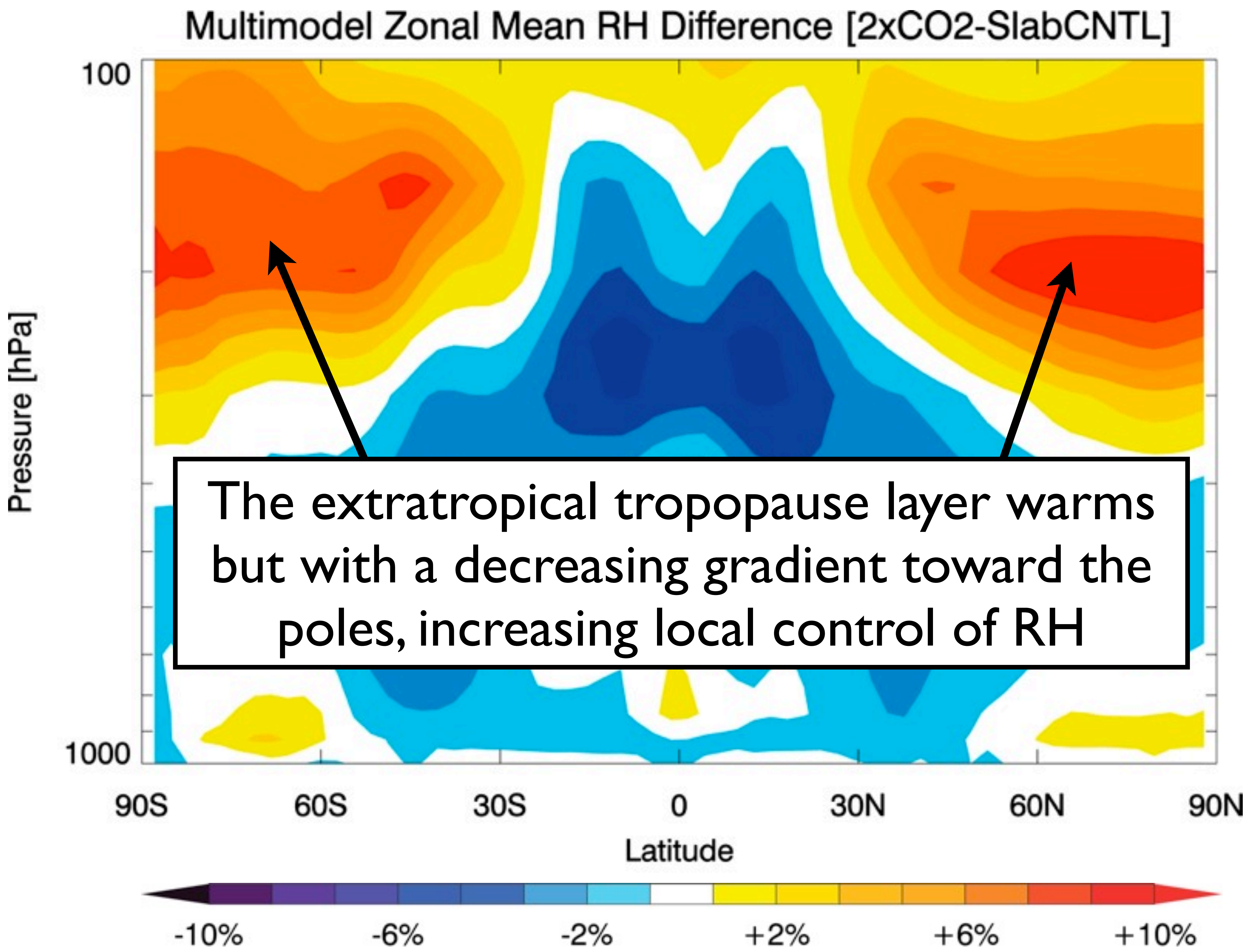
Summarizing Changes in Zonal Mean RH



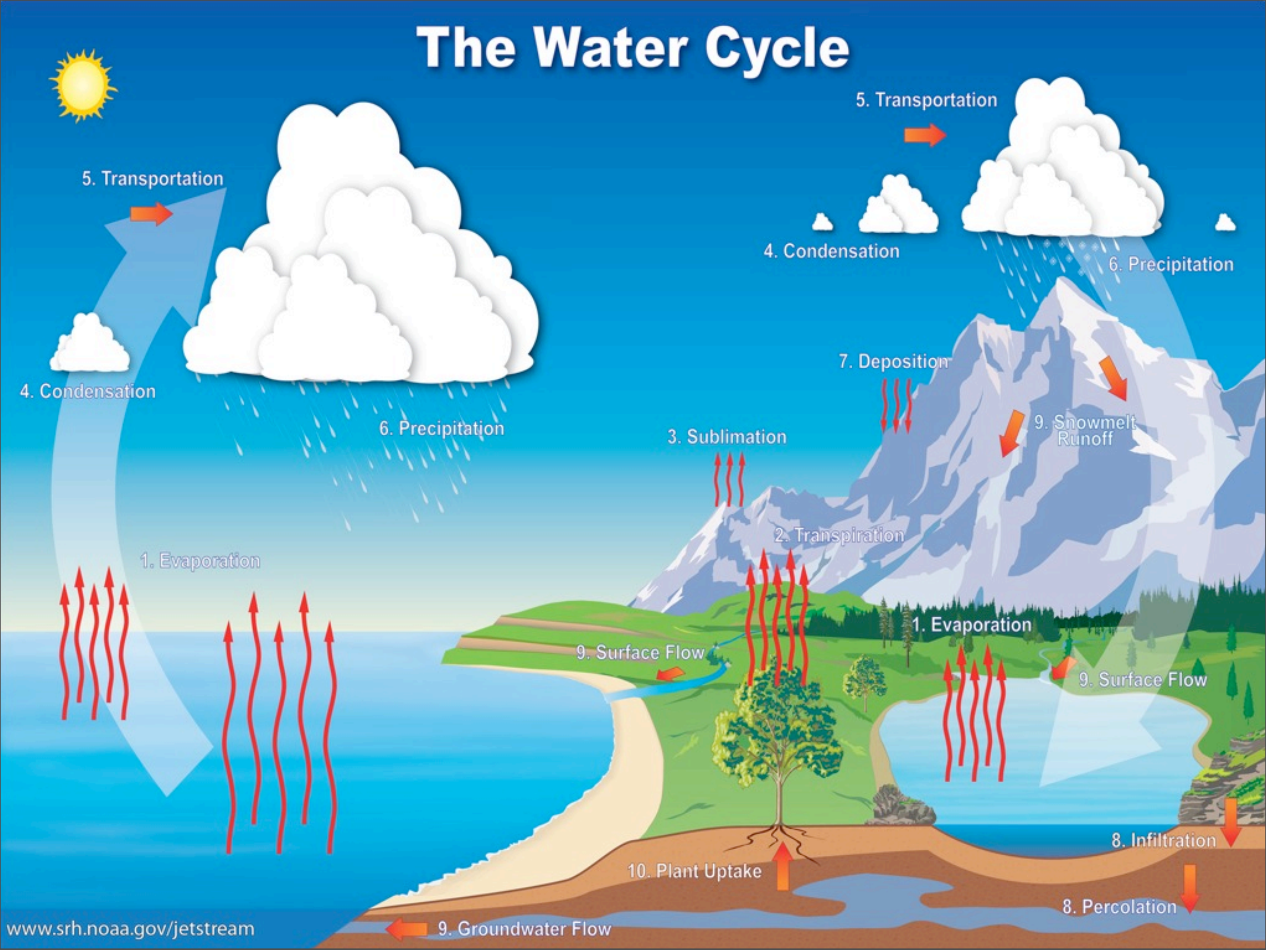
The tropopause shifts upward and the Hadley cell deepens, with strong warming in the tropical UT

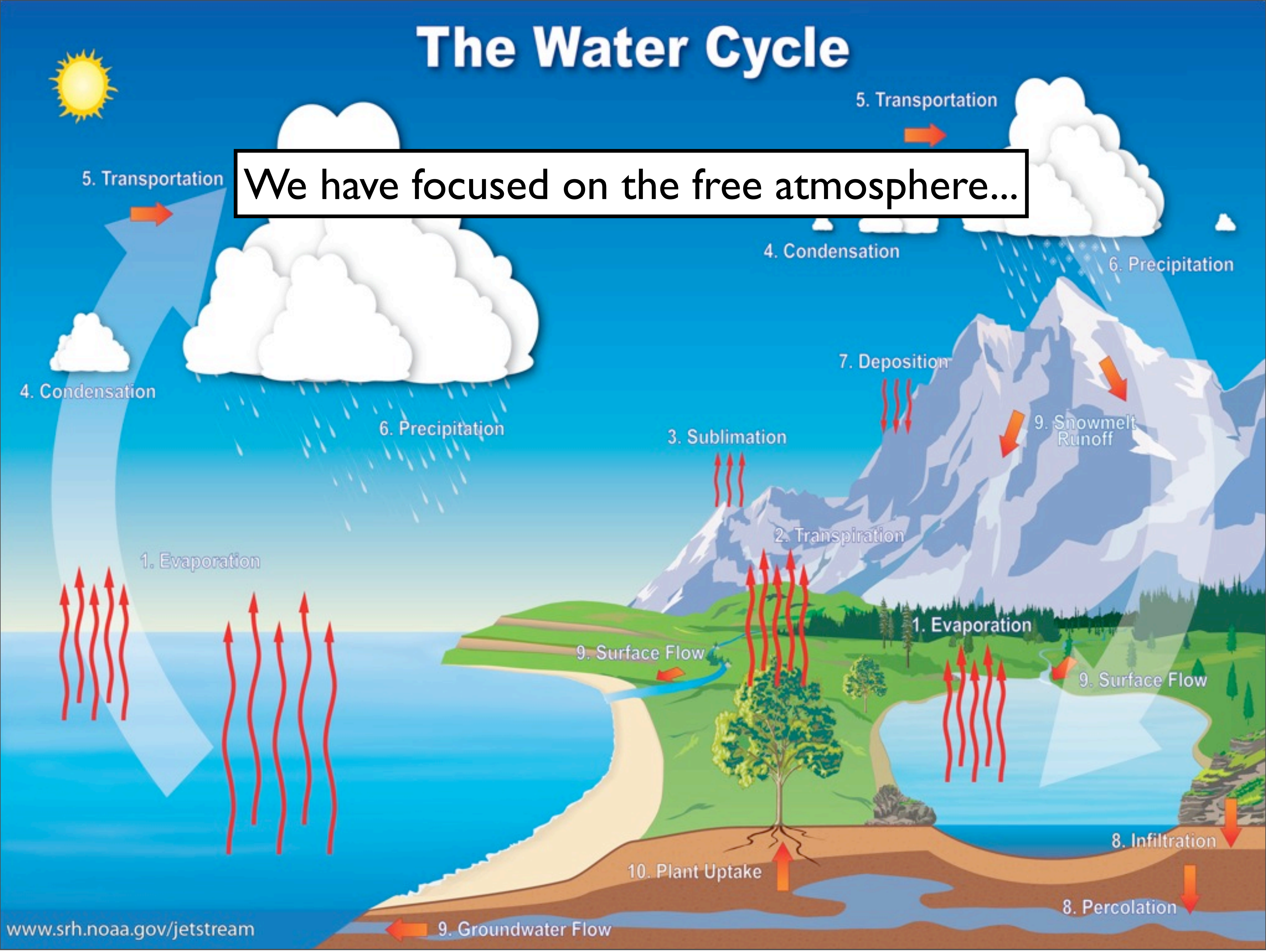
Wright et al. 2010

Summarizing Changes in Zonal Mean RH

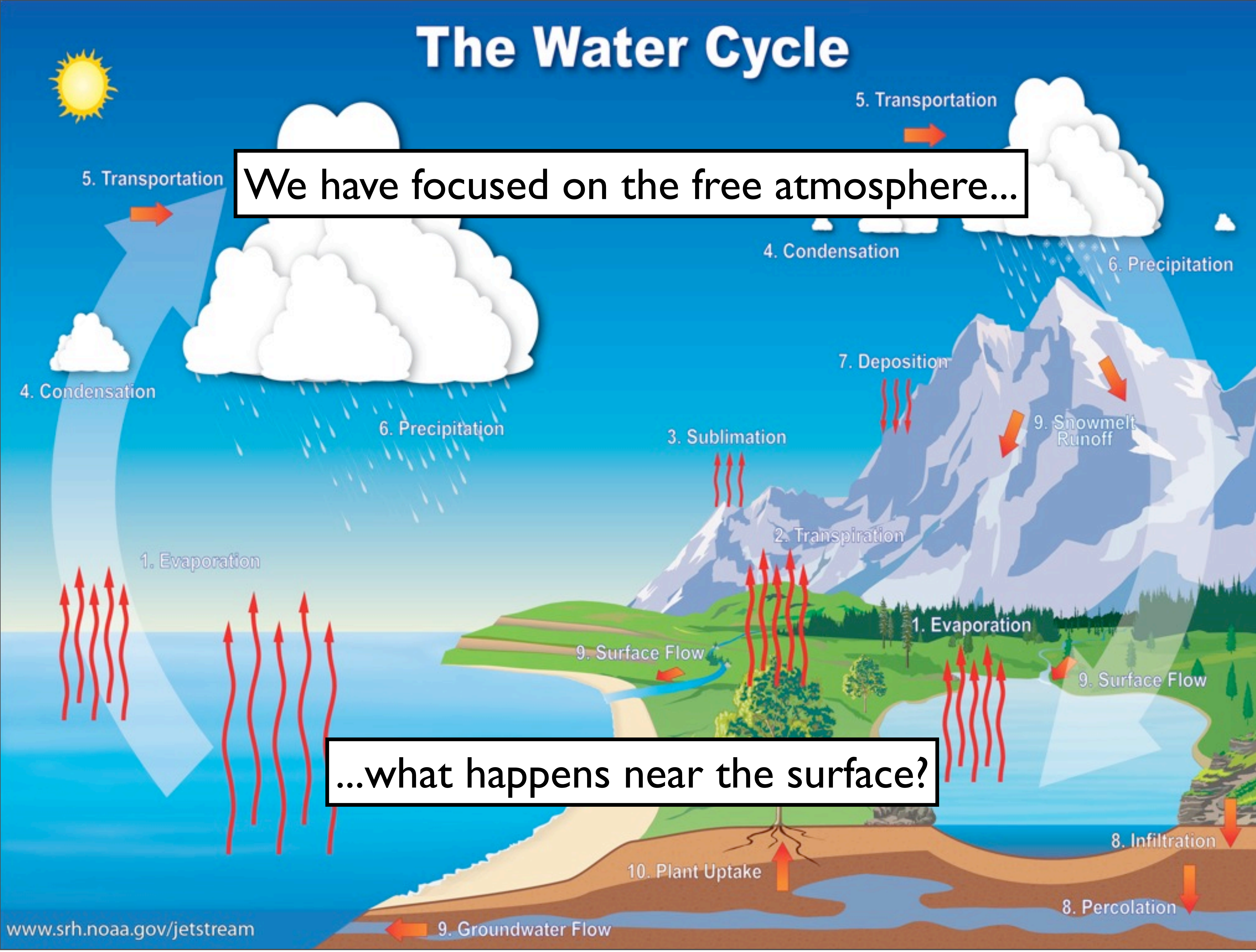


Wright et al. 2010


The Water Cycle
5. Transportation
4. Condensation
6. Precipitation
5. Transportation
4. Condensation
6. Precipitation
7. Deposition
3. Sublimation
9. Snowmelt Runoff
2. Transpiration
1. Evaporation
1. Evaporation
9. Surface Flow
9. Surface Flow
8. Infiltration
10. Plant Uptake
8. Percolation
9. Groundwater Flow
www.srh.noaa.gov/jetstream



We have focused on the free atmosphere...

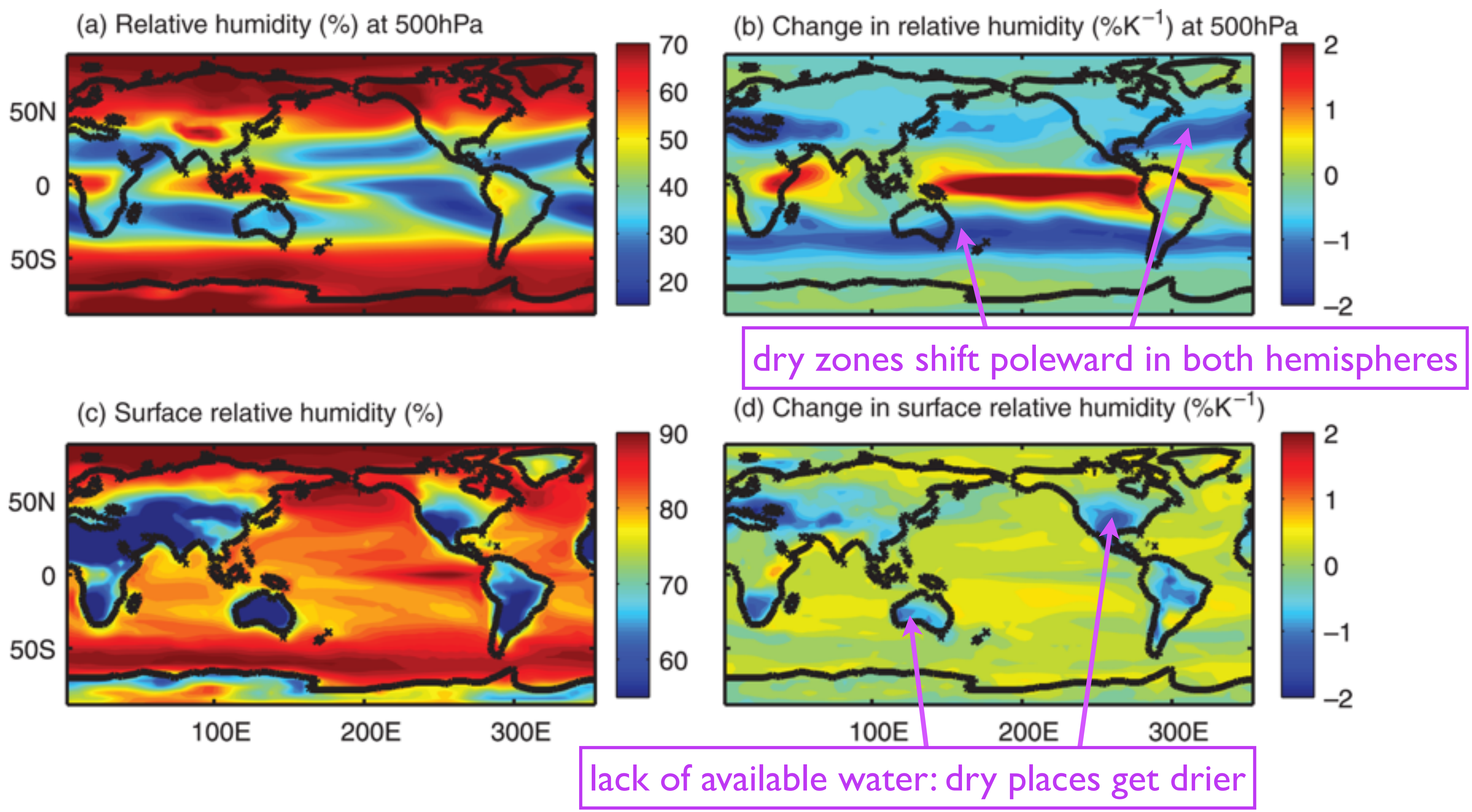


We have focused on the free atmosphere...

...what happens near the surface?

Regional Changes in Relative Humidity

Changes aloft are driven by changes in temperature and circulation



Changes near the surface are driven by changes in evaporation

O'Gorman and Muller 2010

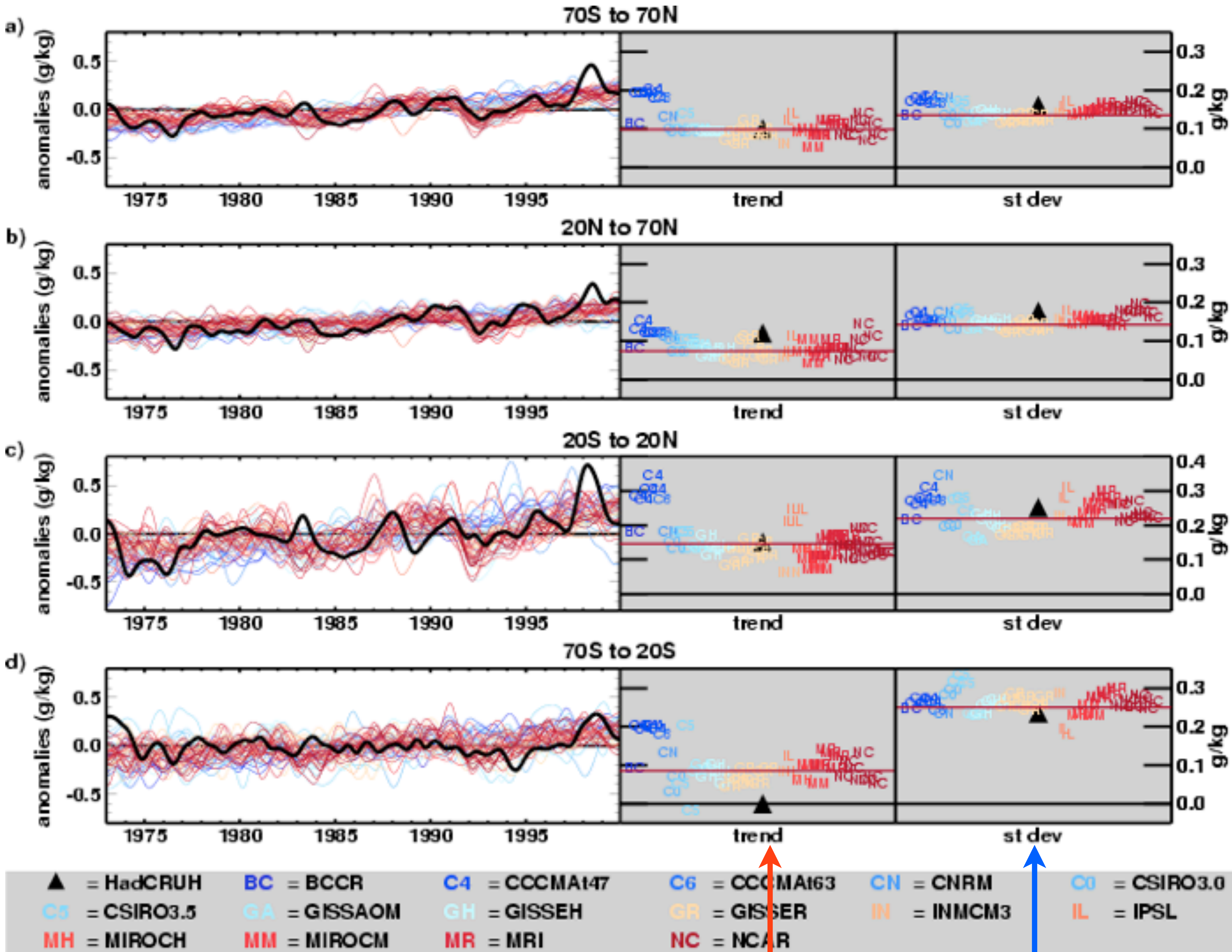
Trends in Near-Surface Humidity

global

northern hemisphere

tropics

southern hemisphere

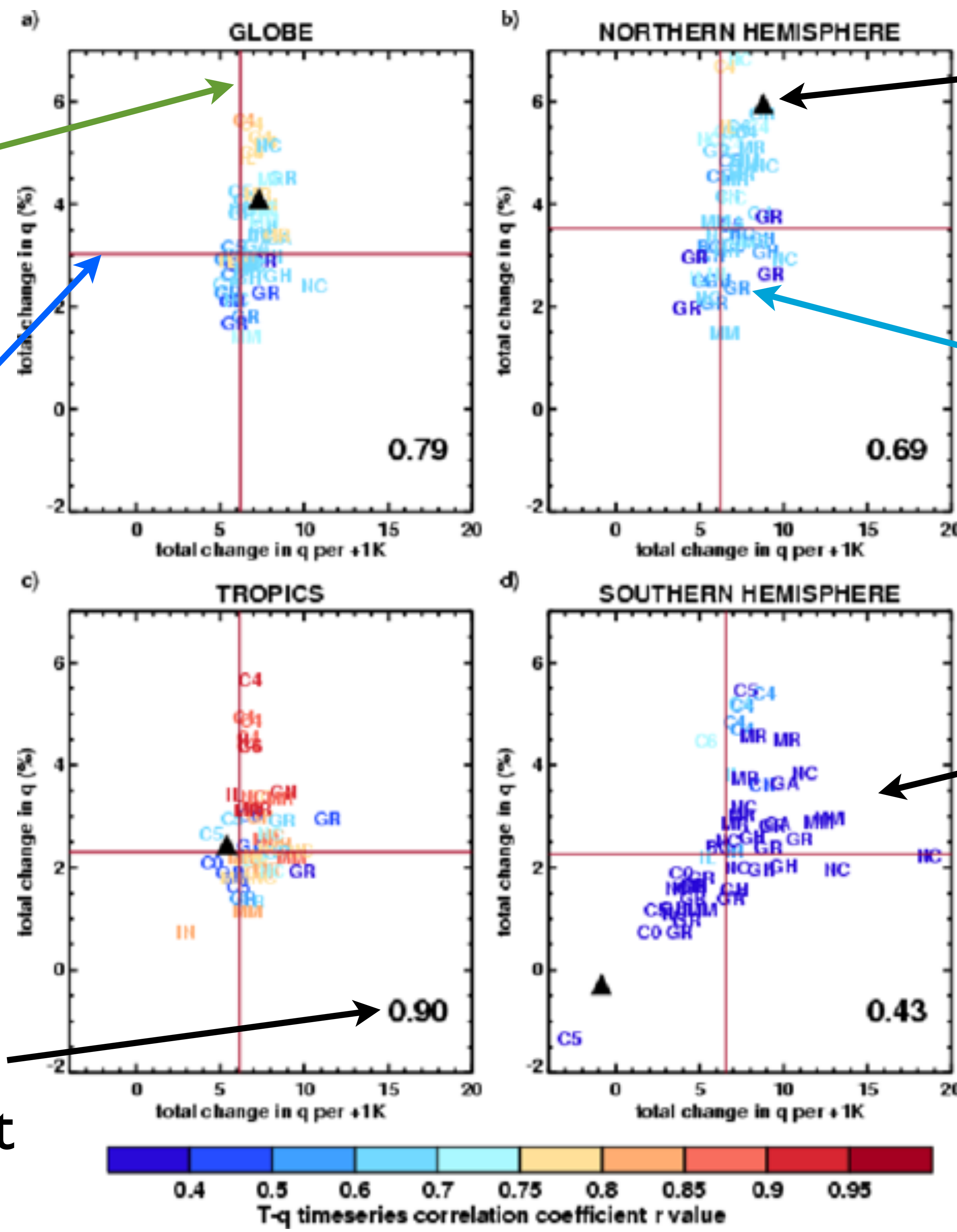


GCMs generally capture observed trends and variability at global and hemispheric scales — the worst agreement is in the SH

Willett et al. 2010

Large-scale Changes in Near-Surface Humidity

T-dependent rates of change in models are robust and realistic, even though total changes vary



observations

climate models (color: correlation between time series of T and q)

Uncertainties are largest in the SH, where observations are relatively scarce and T and q are less tightly coupled

Temperature and humidity are most tightly coupled in the tropics

Willett et al. 2010

Summary

- Changes in global mean water vapor are tightly constrained by changes in temperature
- At leading order, these changes can be understood in terms of constant global mean relative humidity
- Regional changes in water vapor deviate substantially from constant RH, and are not yet well constrained
  - A poleward shift of the jets and a poleward expansion of the Hadley cell shift free tropospheric RH gradients throughout the subtropics and extratropics
  - An upward shift of the tropopause and a deepening of the Hadley cell act to reduce RH in the upper troposphere
  - The spatial pattern of temperature changes leads to enhanced RH near the extratropical tropopause
  - Changes near the surface are driven by changes in evaporation
- Climate model and observational estimates of global changes in water vapor are largely consistent
- Future changes in water vapor will likely be similar to changes in the recent past