Influences of Microphysical Processes on Atmospheric Humidity: Observations and Model Results

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with contributions from
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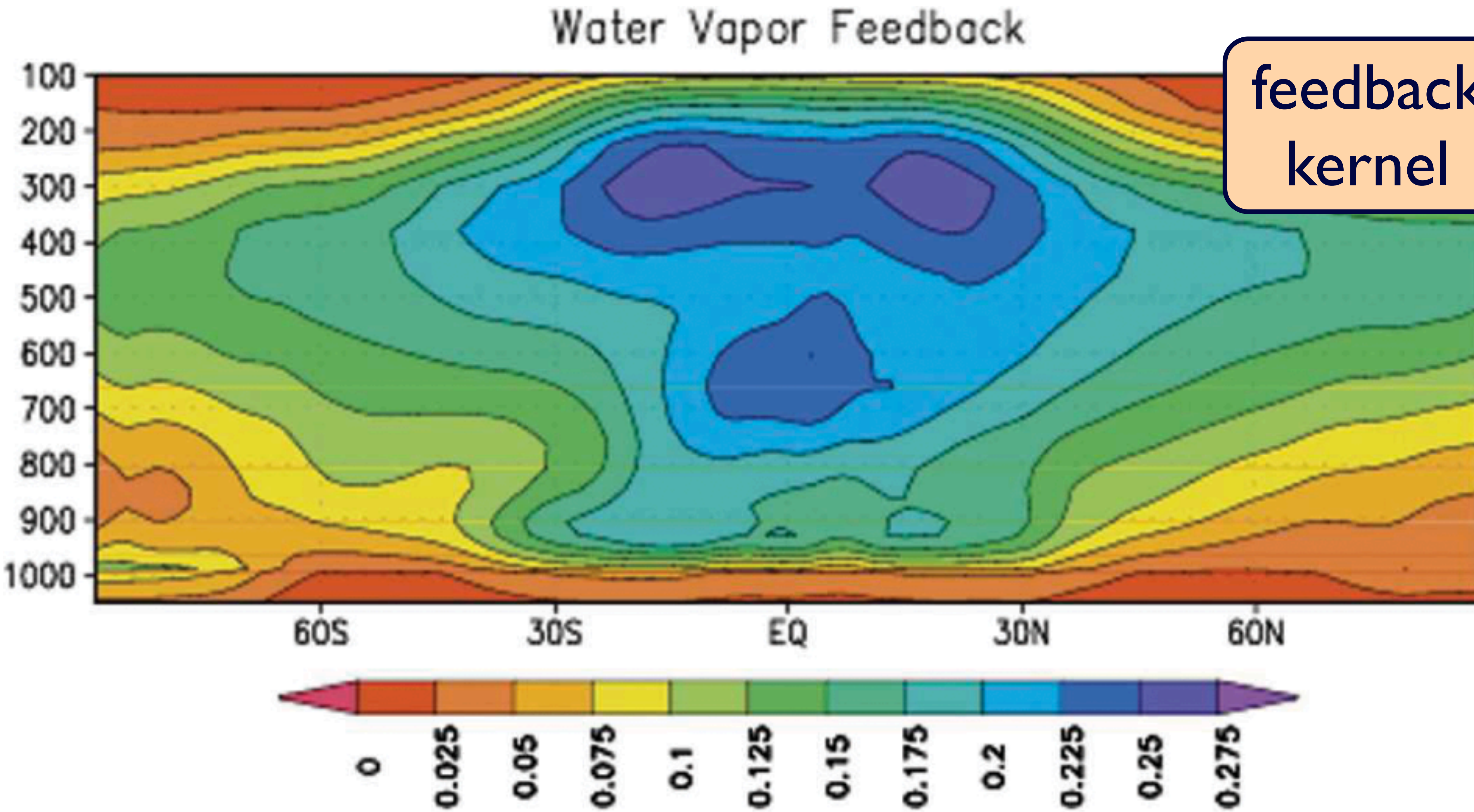
"Feedback from the redistribution of water vapour remains a substantial source of uncertainty in climate models. Much of the current debate has been addressing feedback in the upper troposphere."
-IPCC, 1995

(Summarized in Held and Soden, 2000)

climate model simulations indicate that roughly 35% of the water vapor feedback is in the tropical UT



feedback kernel

Soden & Held 2006

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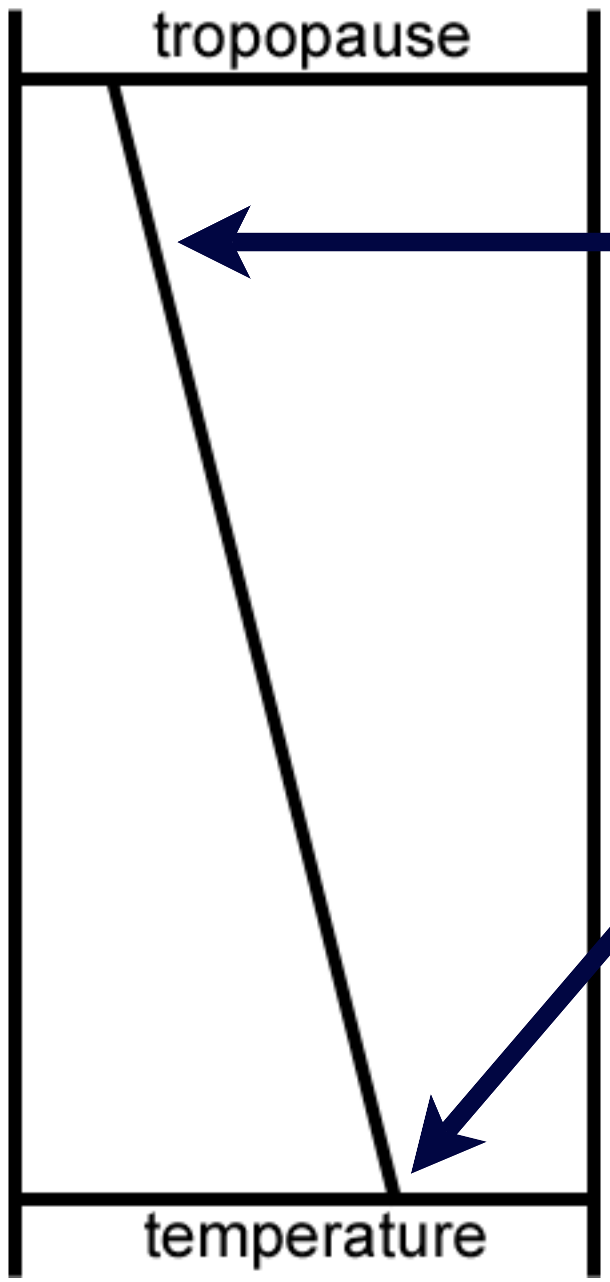
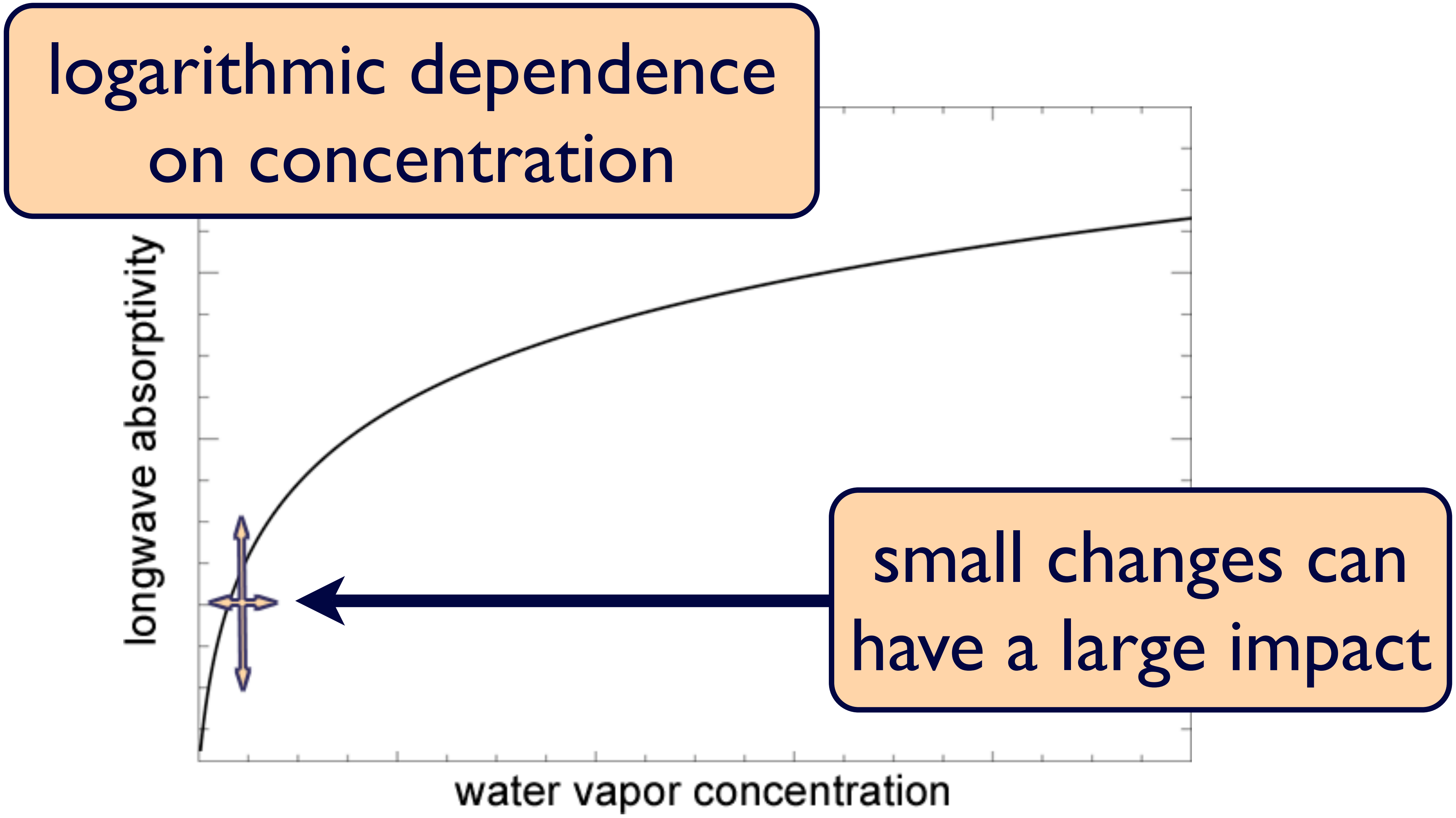


temperatures are much colder than at the surface

climate models indicate that roughly 35% of the water vapor feedback is in the tropical UT



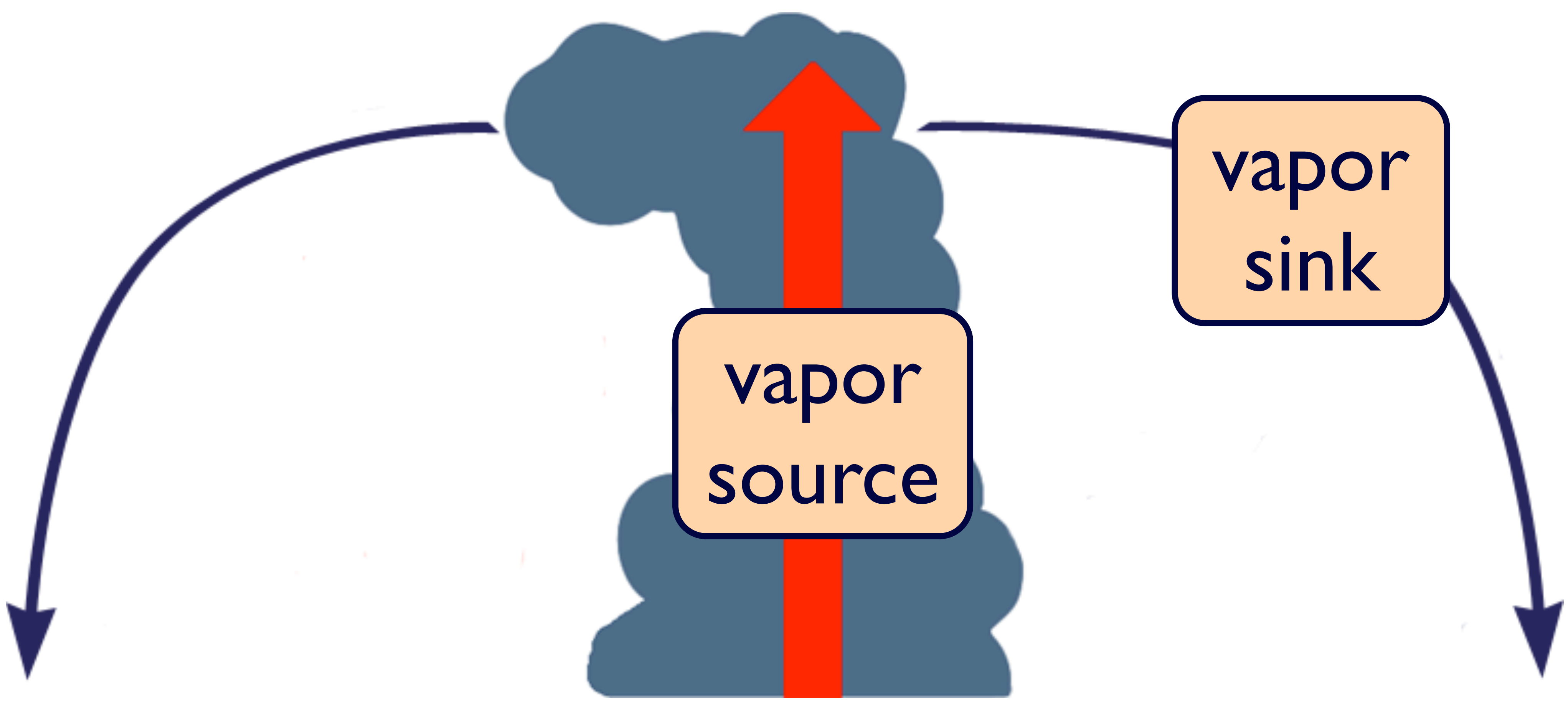
climate models indicate that roughly 35% of the water vapor feedback is in the tropical UT

UT water vapor can trap energy vented by tropical convection

"[A]ppraisal of the confidence in simulated water vapour feedback has shifted from a diffuse concern about upper tropospheric humidity to a more focused concern about the role of microphysical processes in the convection parameterizations, and particularly those affecting tropical deep convection."

-IPCC, 2001

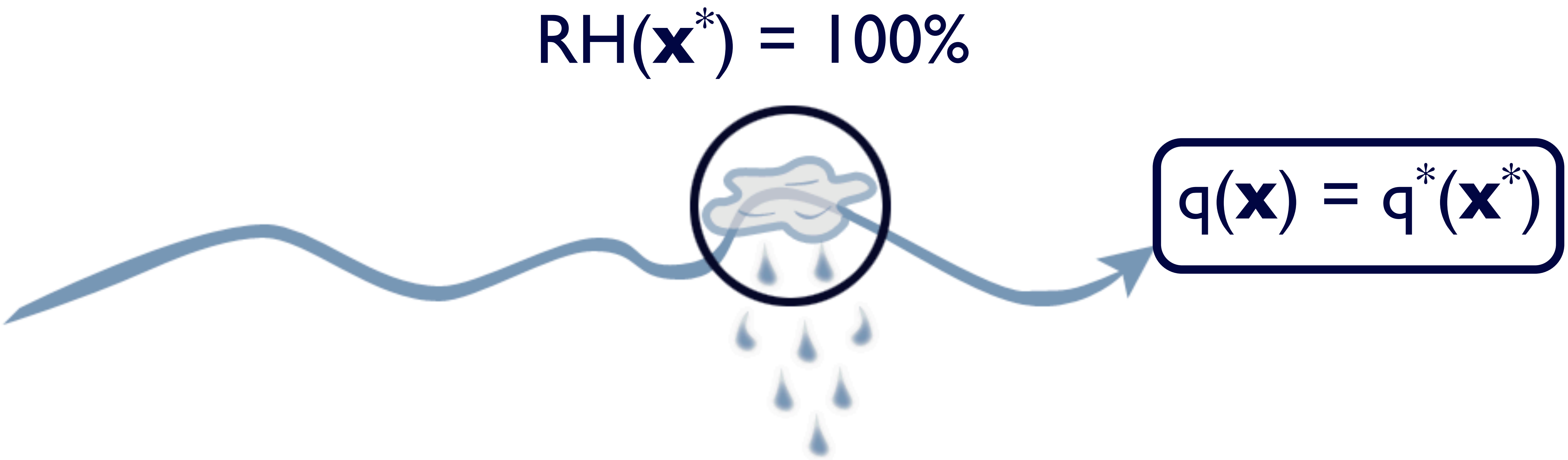
convective detrainment is the primary source of tropical UT water vapor. This is controlled primarily by detrainment temperature, but sublimation of detrained ice also contributes



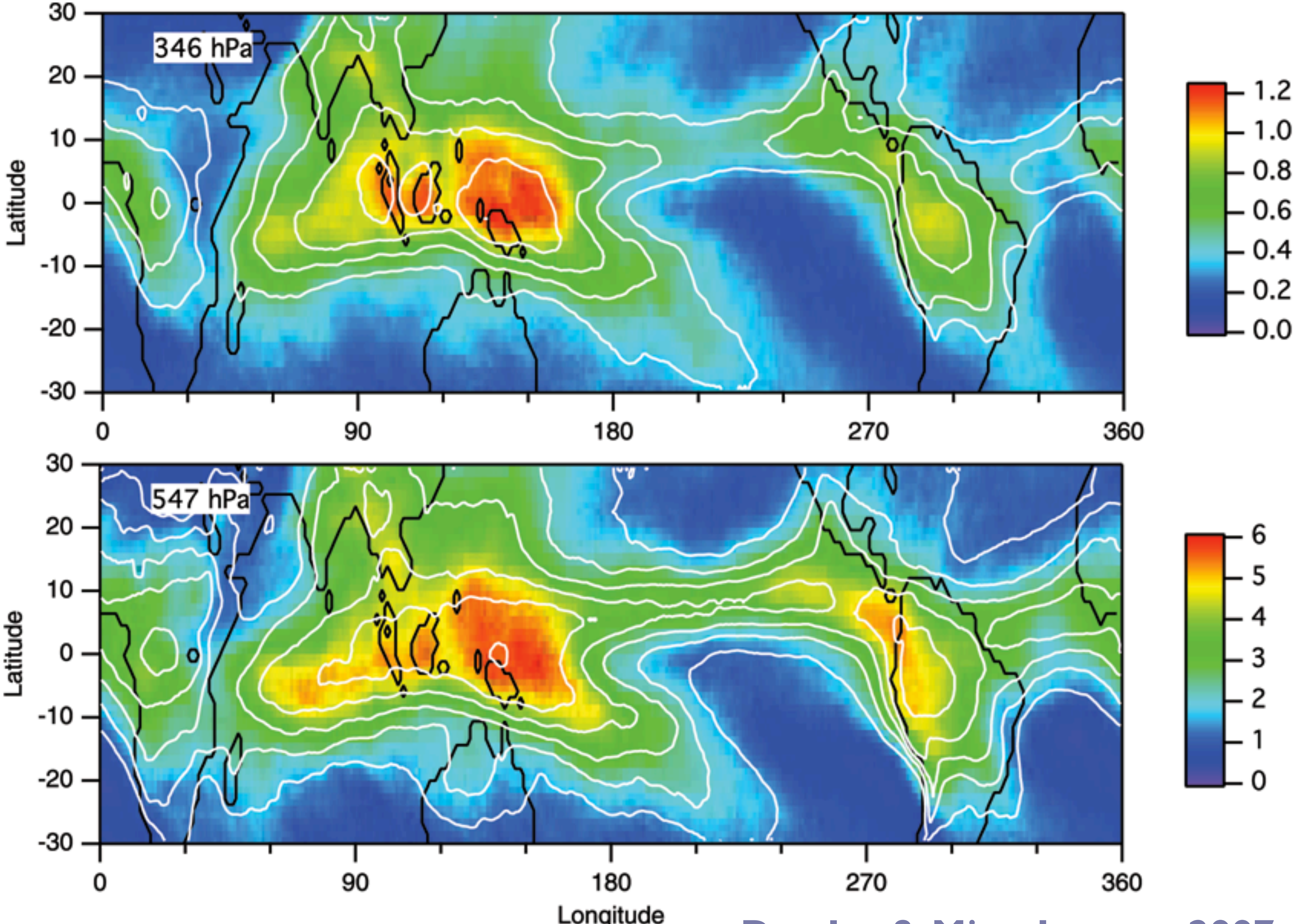
"[E]vidence suggests that the role of microphysics is limited. The observed RH field in much of the tropics can be well simulated without microphysics, but simply by observed winds while imposing an upper limit of 100% RH on parcels."

-IPCC, 2007

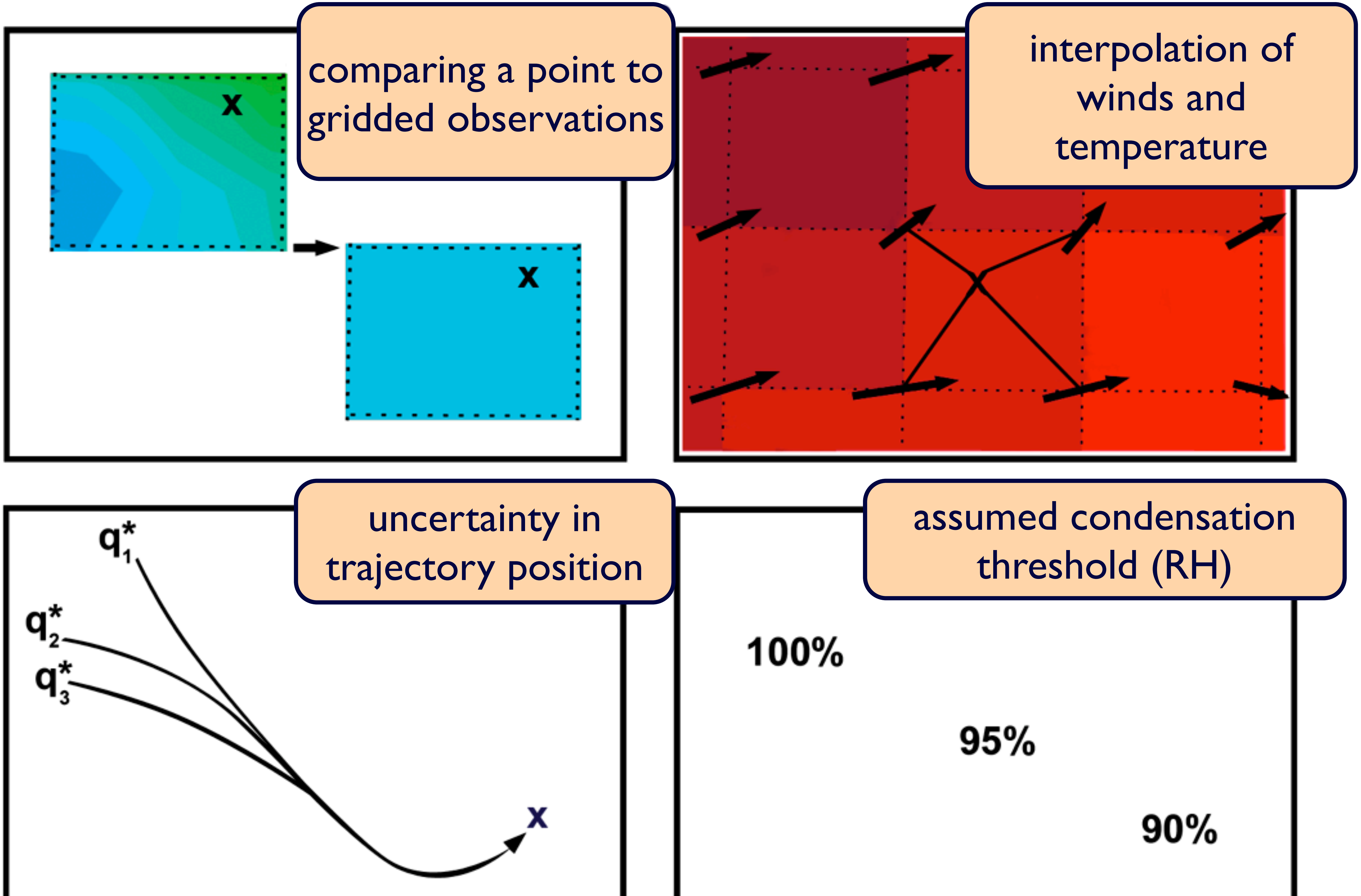
The Advection-Condensation Paradigm:
the humidity at any point is determined to leading order by large-scale temperature and circulation



agreement suggests that the influence of condensate evaporation is small...



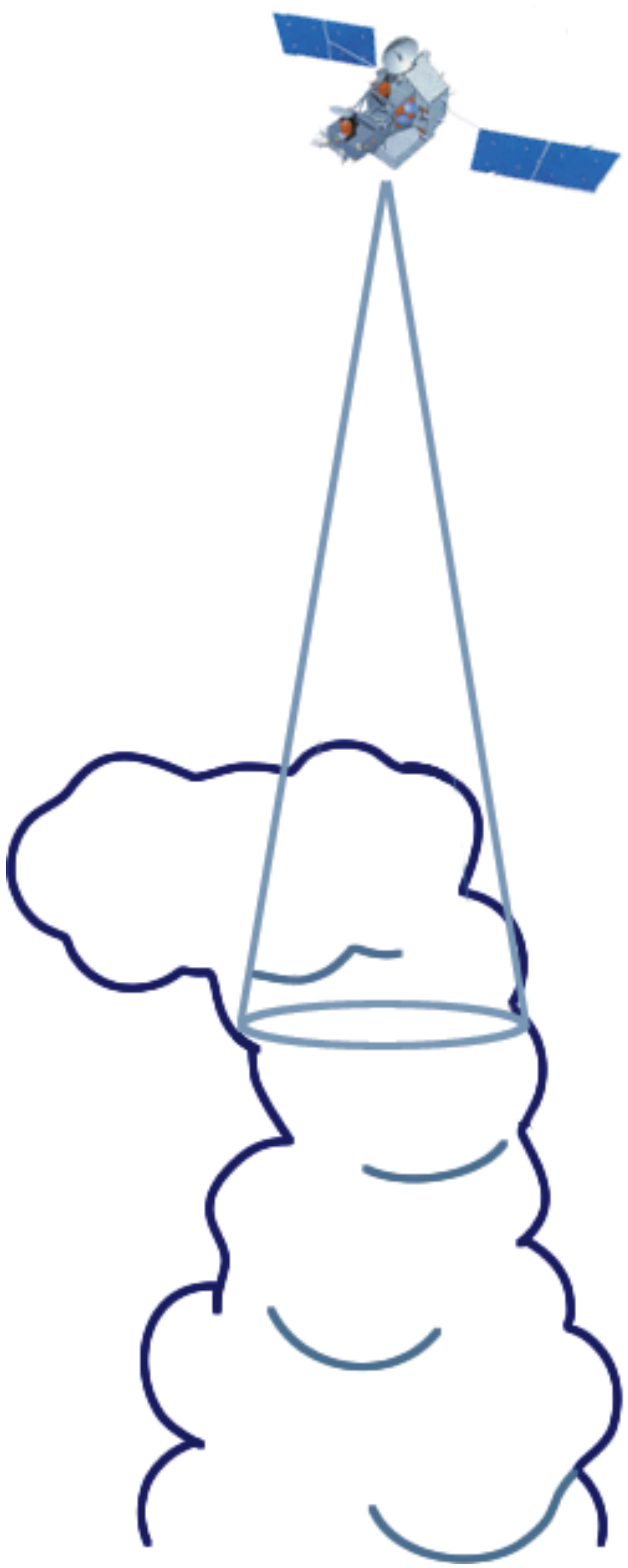
Dessler & Minschwaner 2007



...but there are uncertainties that are difficult to quantify...

...so is it actually small enough to ignore?

1. Convective Detrainment



TRMM precipitation radar observes convective clouds

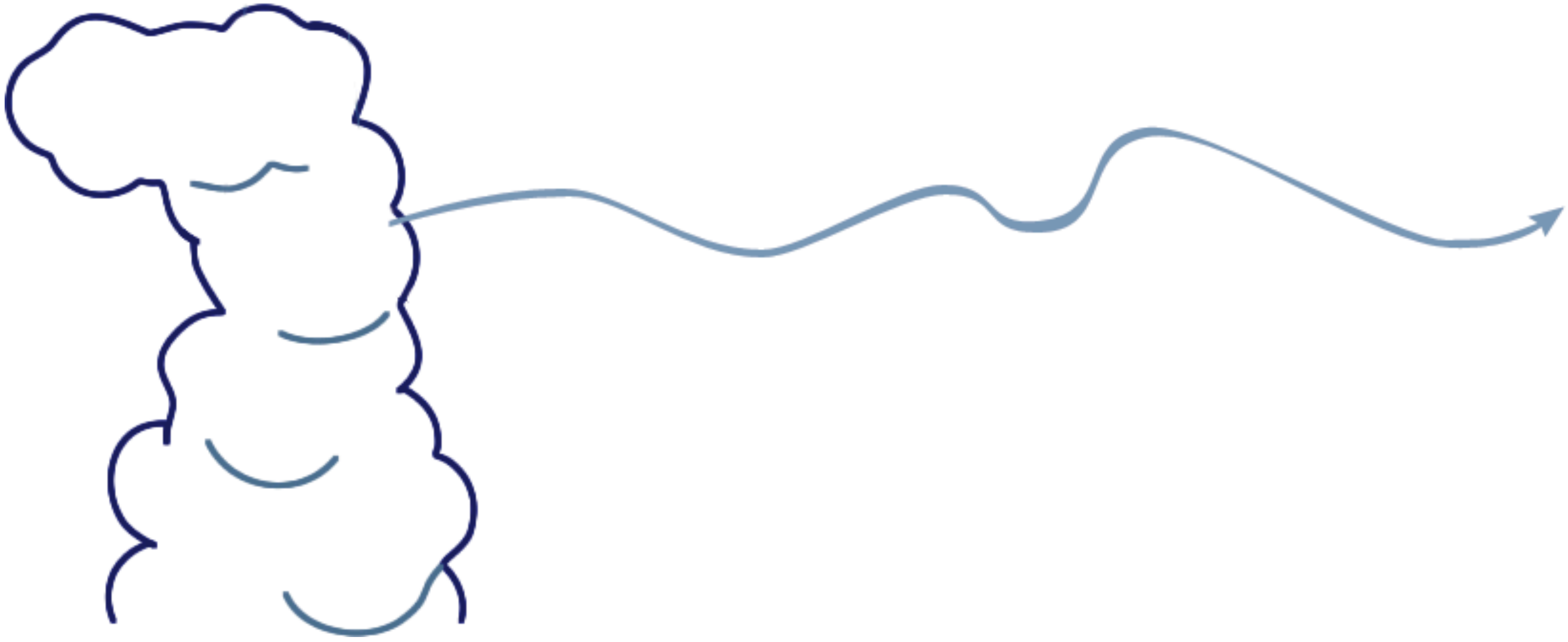
search for **intense** (>20dBZ) **deep** (>10km) tropical convection

convert from **radar reflectivity** to **ice water content** using an empirical relationship

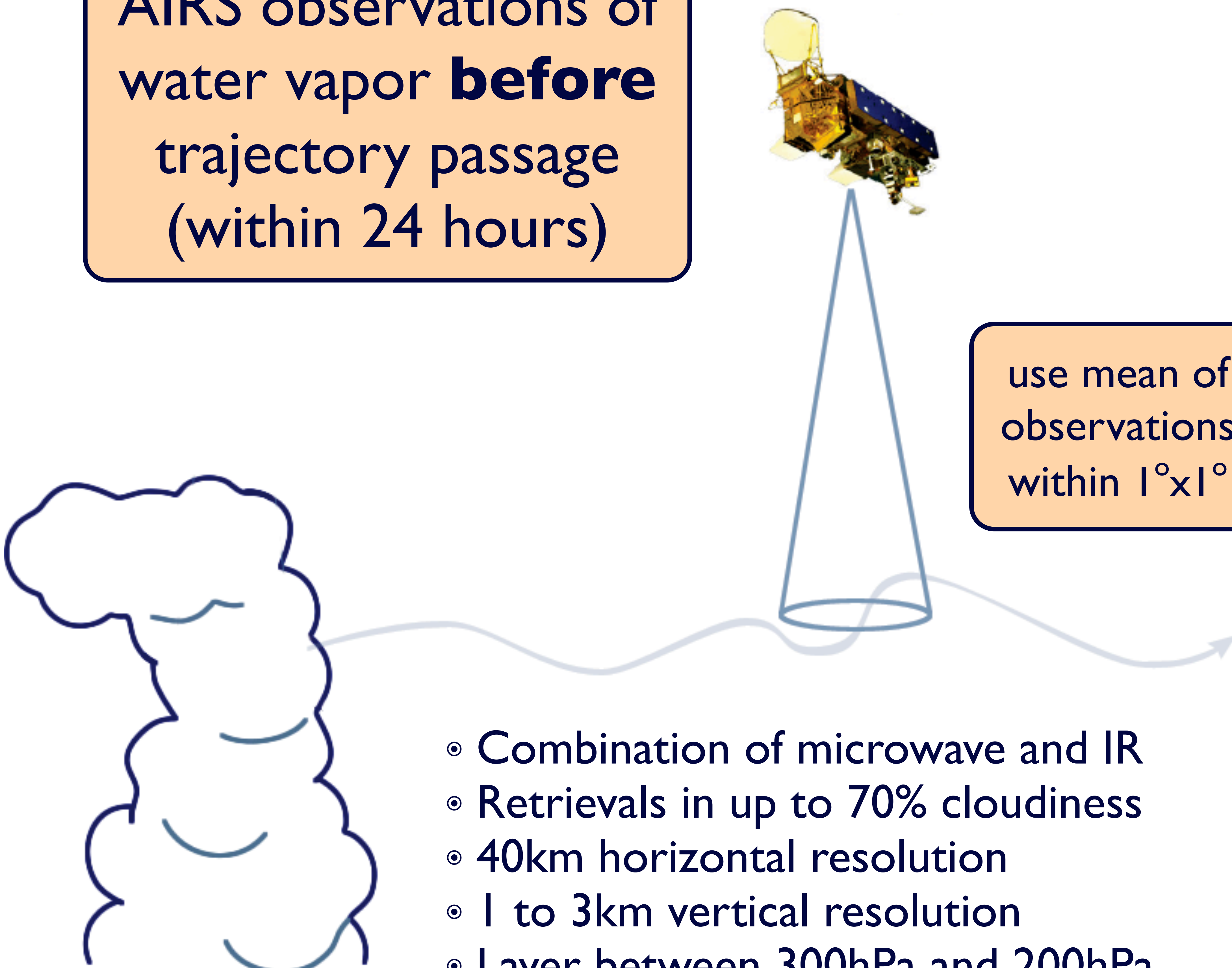
- amount of water and ice in a volume
- 4.2km x 4.2km horizontal resolution
- 250m to 1km vertical resolution

Integrate forward trajectory model

- UKMO reanalysis (daily, 2.5°x3.75°)
- Diabatic vertical motion
- 30 minute timestep
- 48 hour integration period

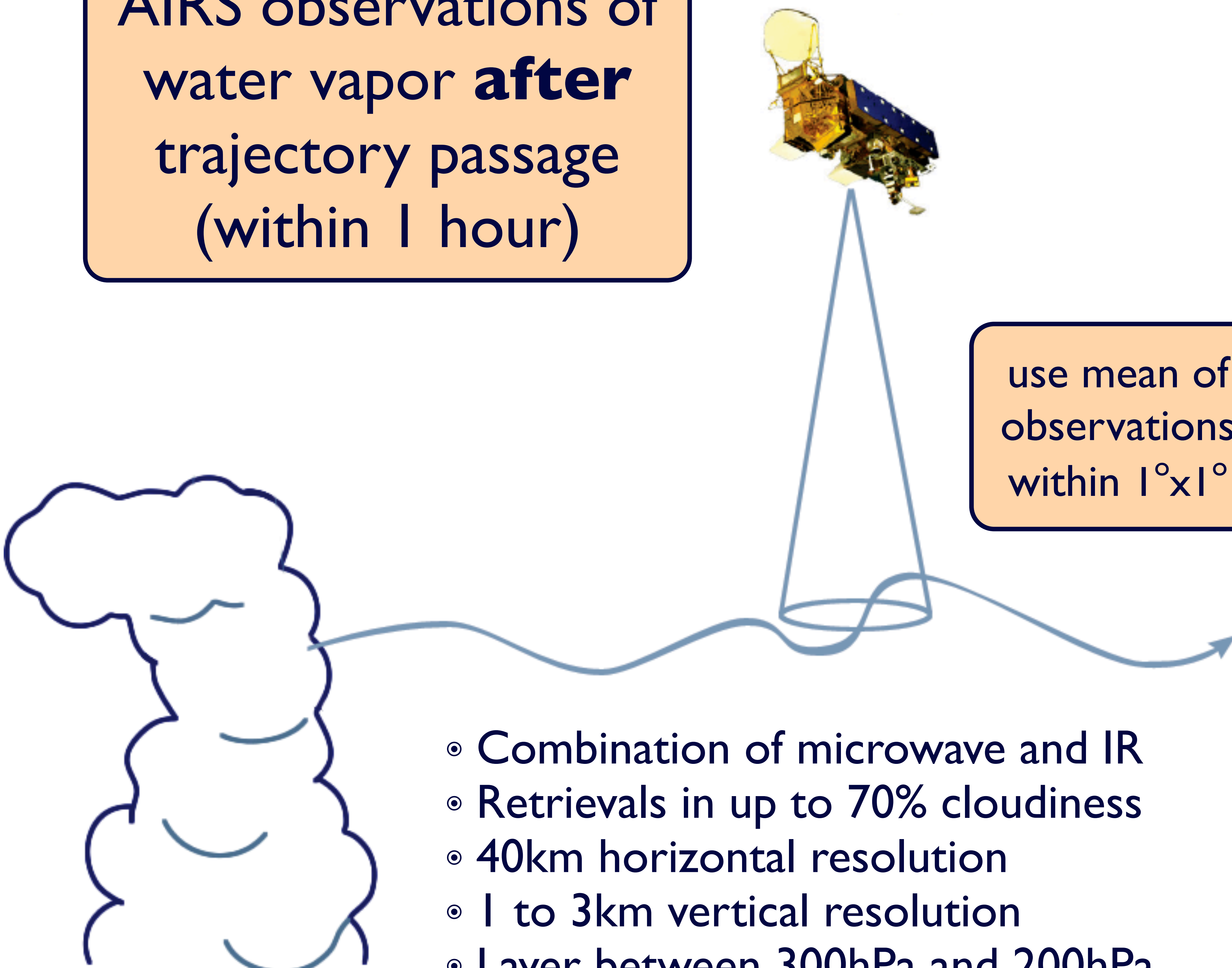


AIRS observations of water vapor **before** trajectory passage (within 24 hours)



- Combination of microwave and IR
- Retrievals in up to 70% cloudiness
- 40km horizontal resolution
- 1 to 3km vertical resolution
- Layer between 300hPa and 200hPa

AIRS observations of water vapor **after** trajectory passage (within 1 hour)



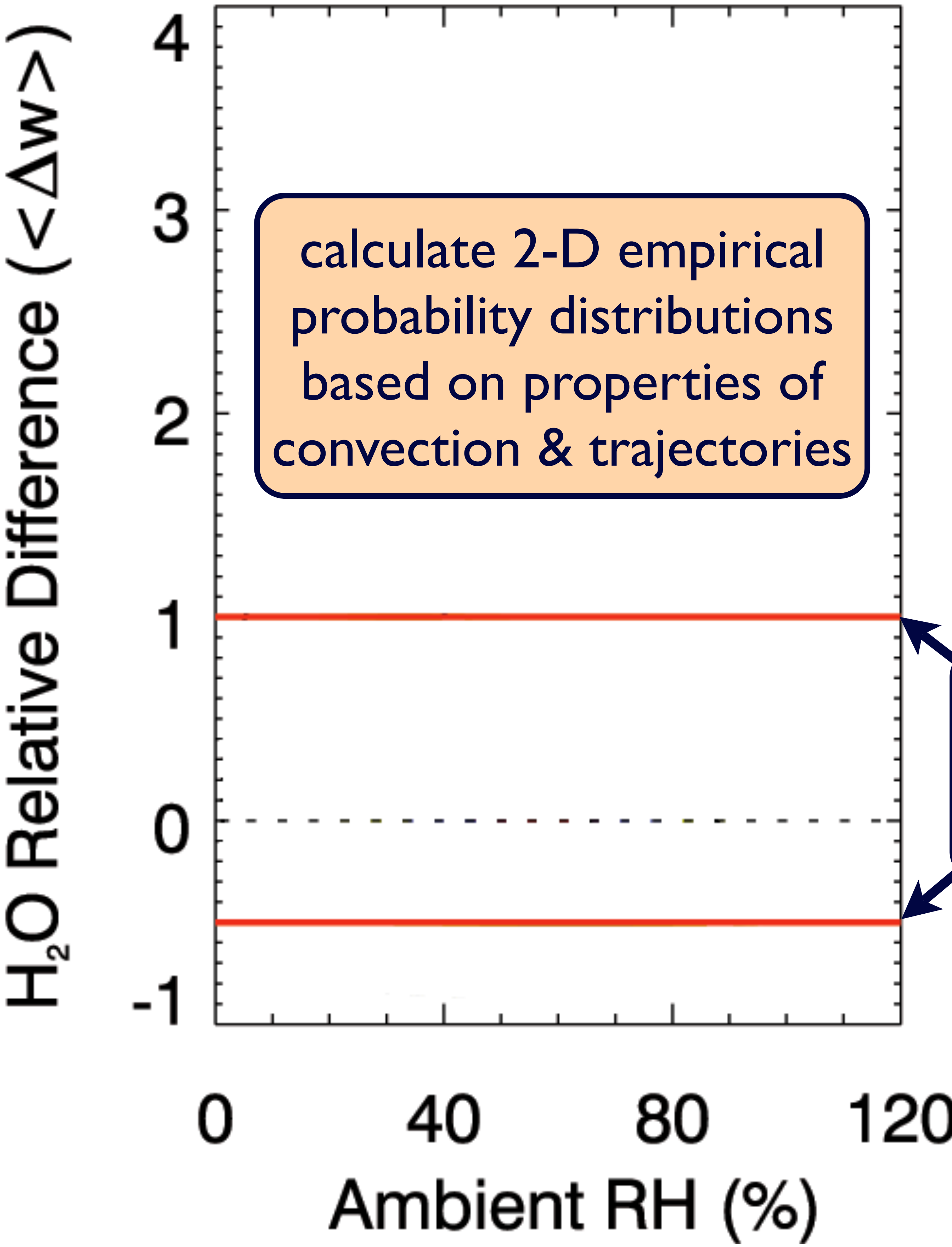
use mean of observations within 1°x1°

- Combination of microwave and IR
- Retrievals in up to 70% cloudiness
- 40km horizontal resolution
- 1 to 3km vertical resolution
- Layer between 300hPa and 200hPa

present the statistical distribution of results

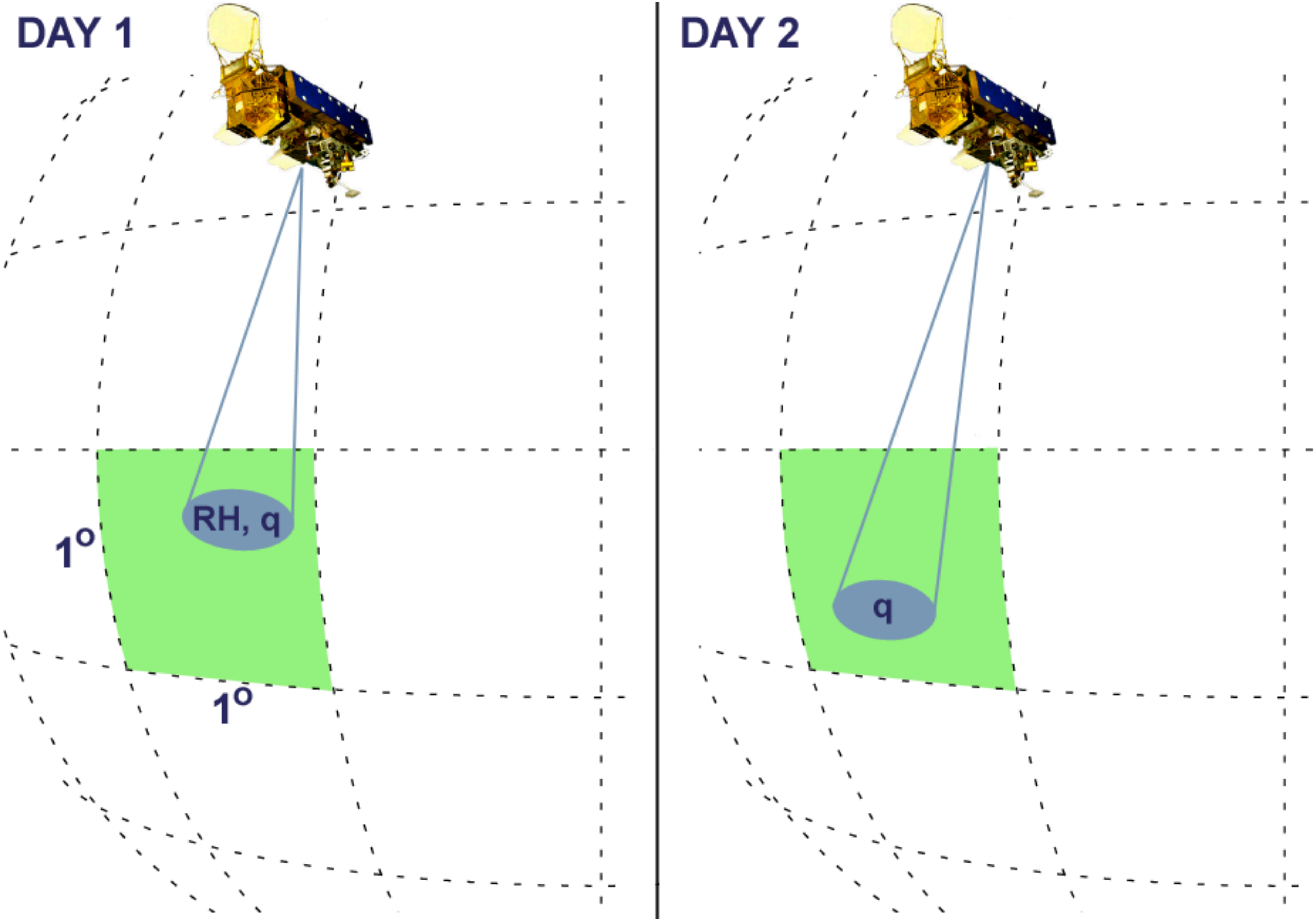
normalize the water vapor change to reduce the T dependence and better represent the radiative impact:

$$\frac{(q_{aft}-q_{bef})}{q_{bef}}$$



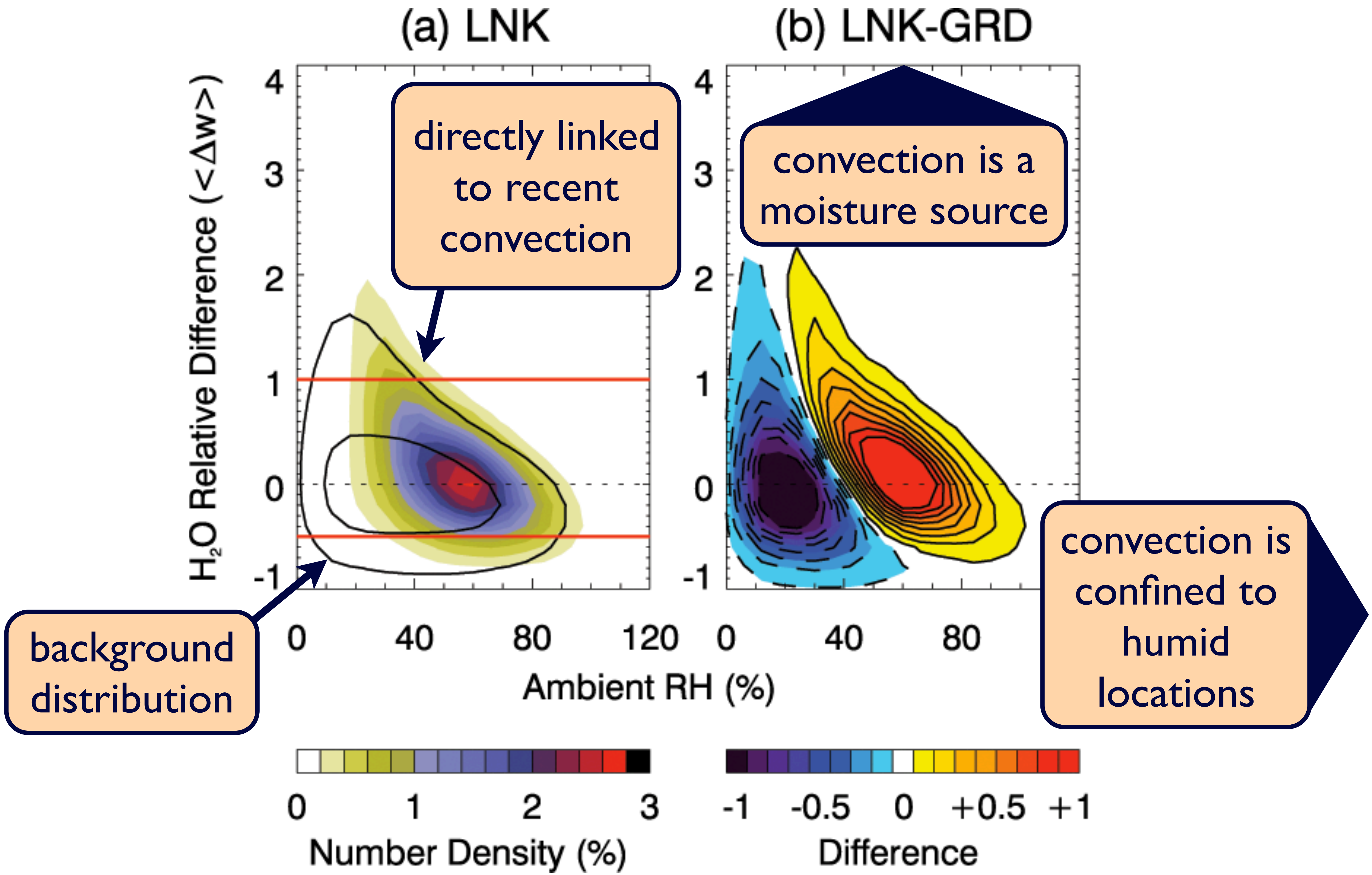
calculate 2-D empirical probability distributions based on properties of convection & trajectories

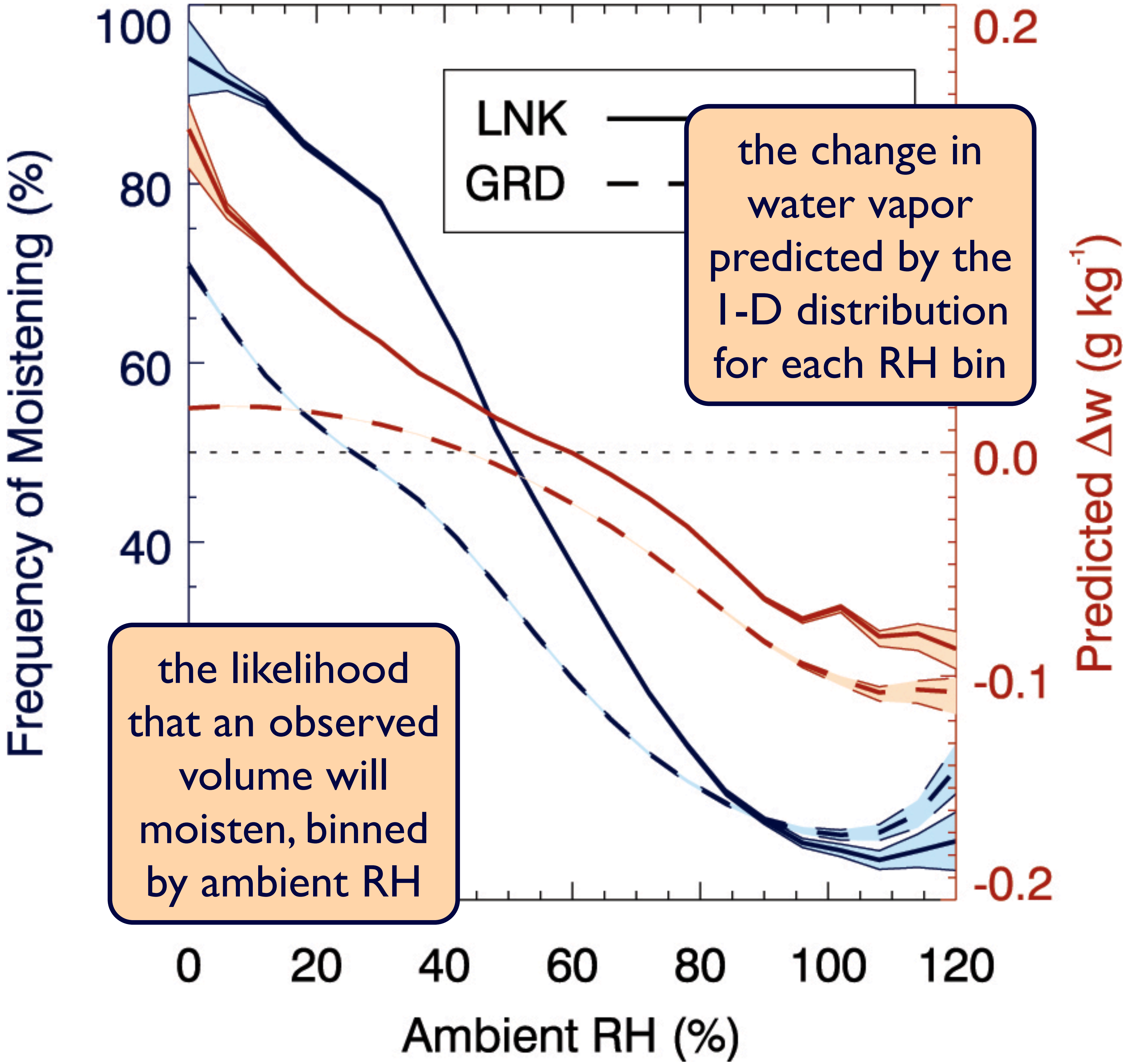
threshold values to track likelihood of large changes



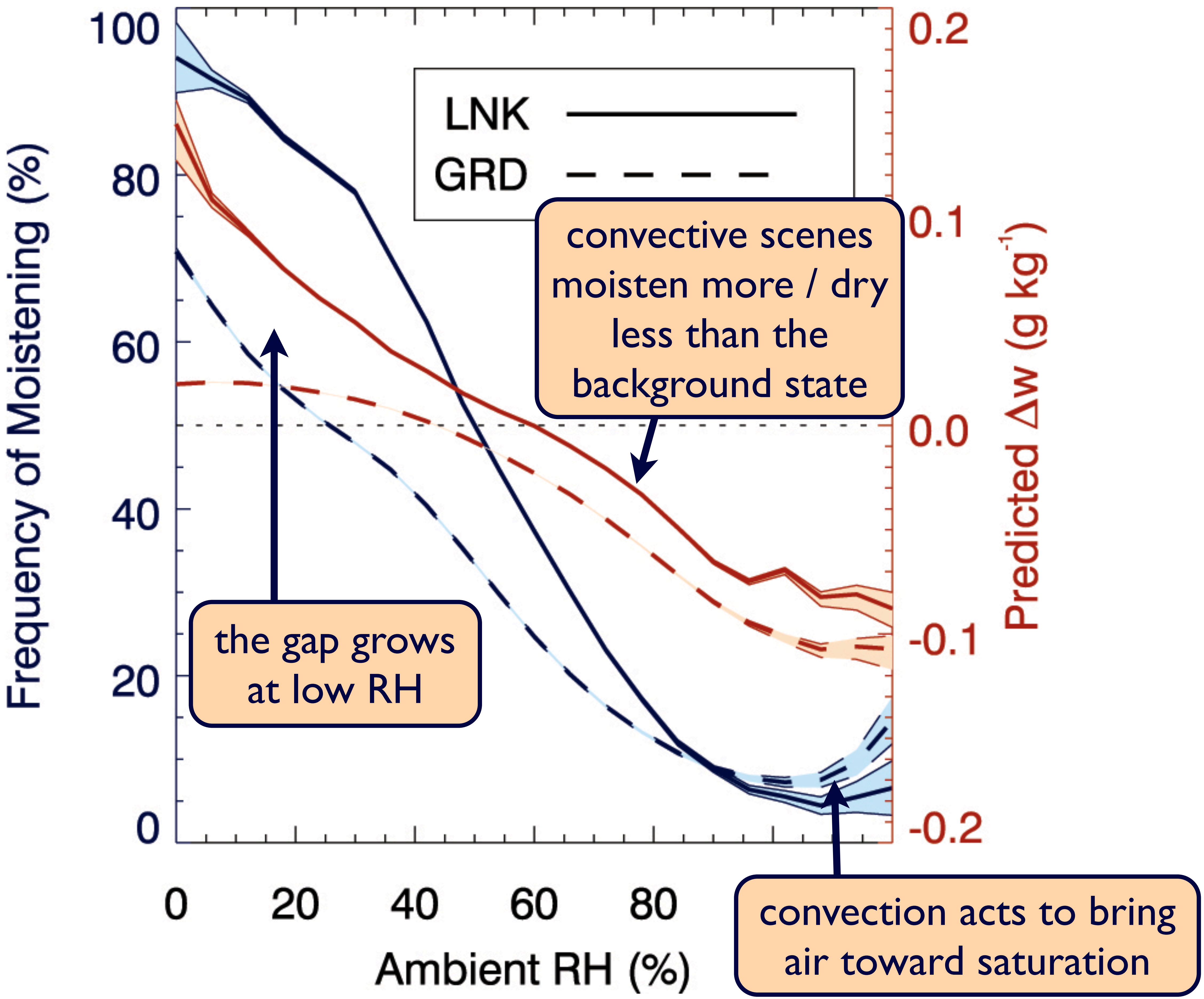
develop a background distribution (GRD) for context

distribution of water vapor changes





LNK
GRD
the change in water vapor predicted by the 1-D distribution for each RH bin
the likelihood that an observed volume will moisten, binned by ambient RH
Frequency of Moistening (%)
Predicted Δw (g kg-1)
Ambient RH (%)
100
80
60
40
0.2
0.0
-0.1
-0.2
0
20
40
60
80
100
120



100
80
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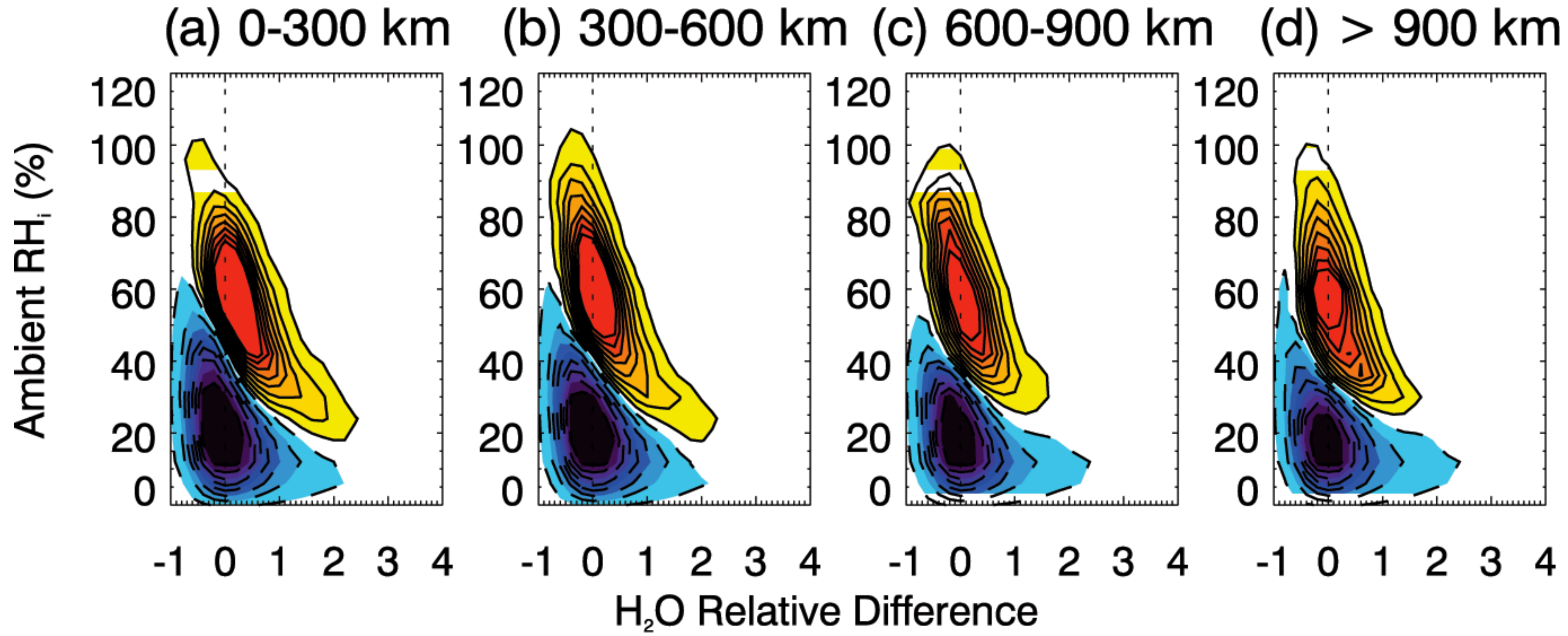
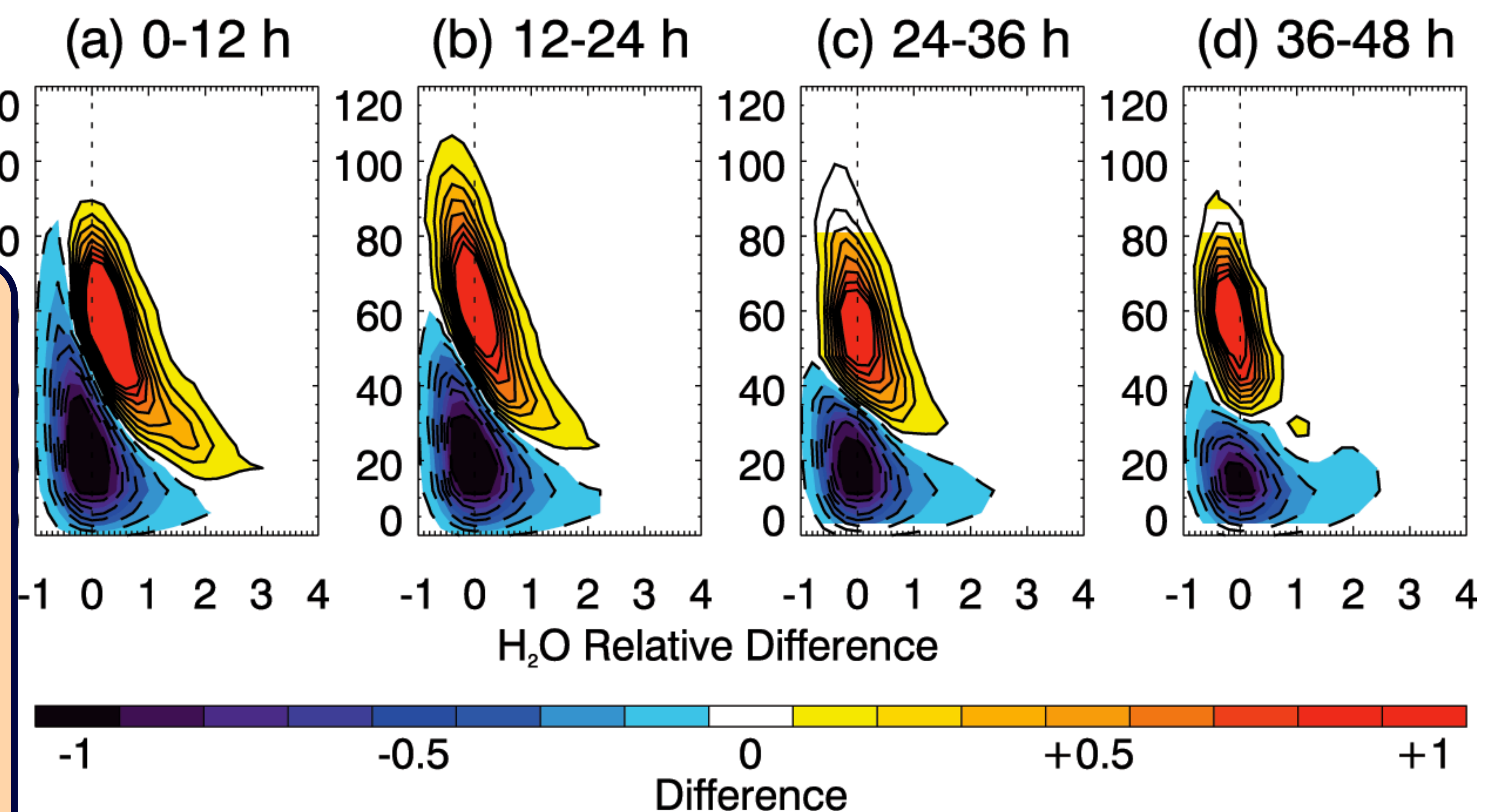
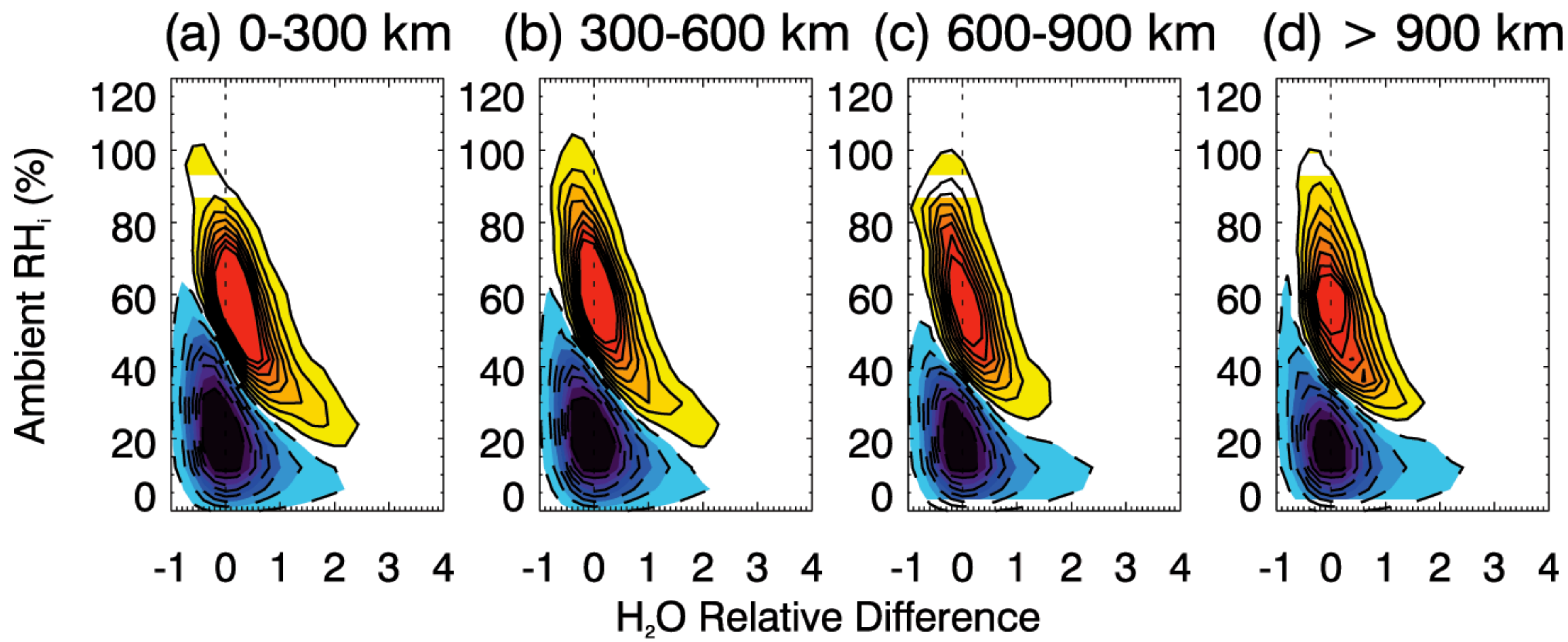
0
Frequency of Moistening (%)
0
20
40
60
80
Ambient RH (%)
0.2
0.1
0.0
-0.1
-0.2
Predicted Δw (g kg^{-1})
LNK
GRD
convective scenes moisten more / dry less than the background state
the gap grows at low RH
convection acts to bring air toward saturation



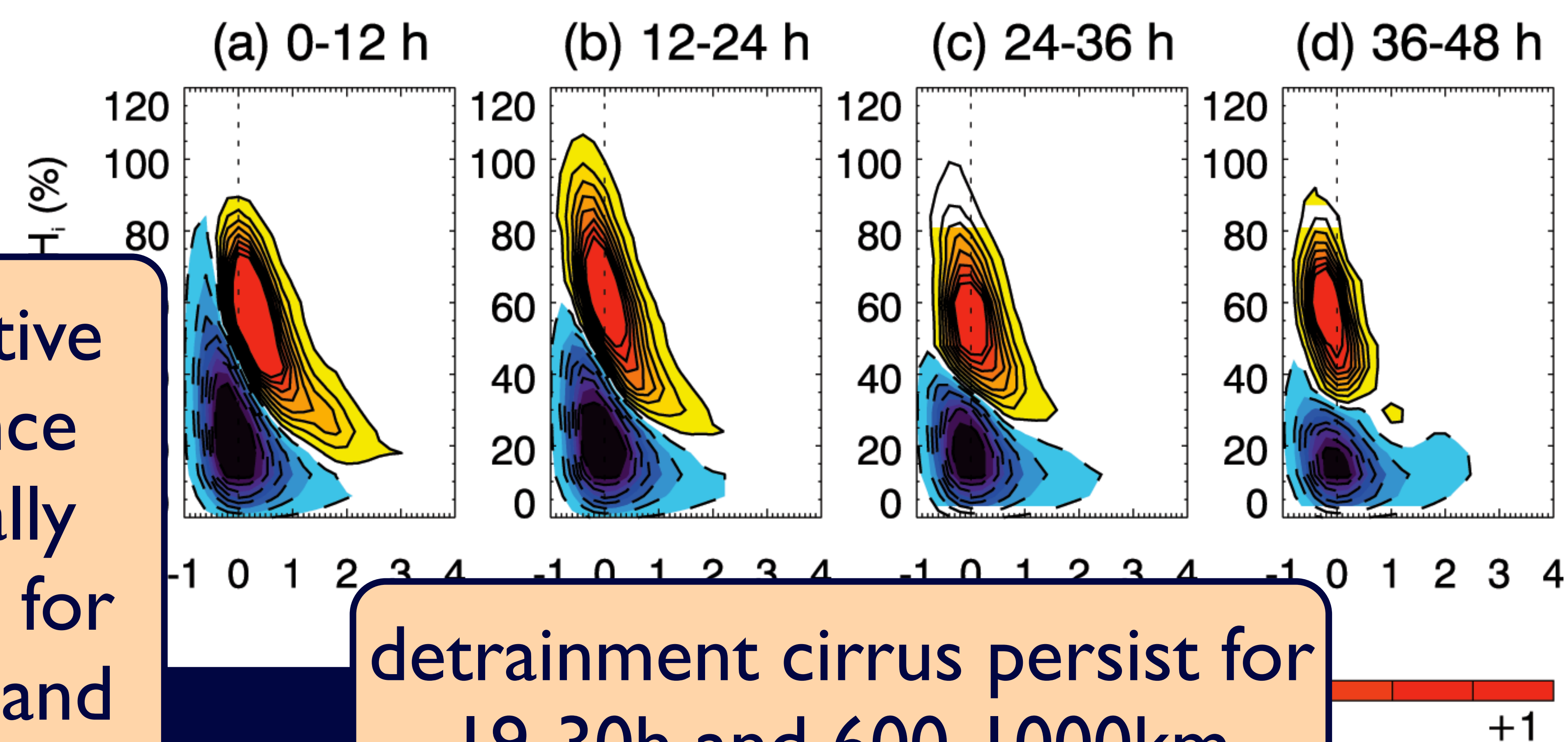
distributions by distance traveled and time elapsed



convective influence generally persists for 36-48h and 900-1200km



distributions by distance traveled and time elapsed

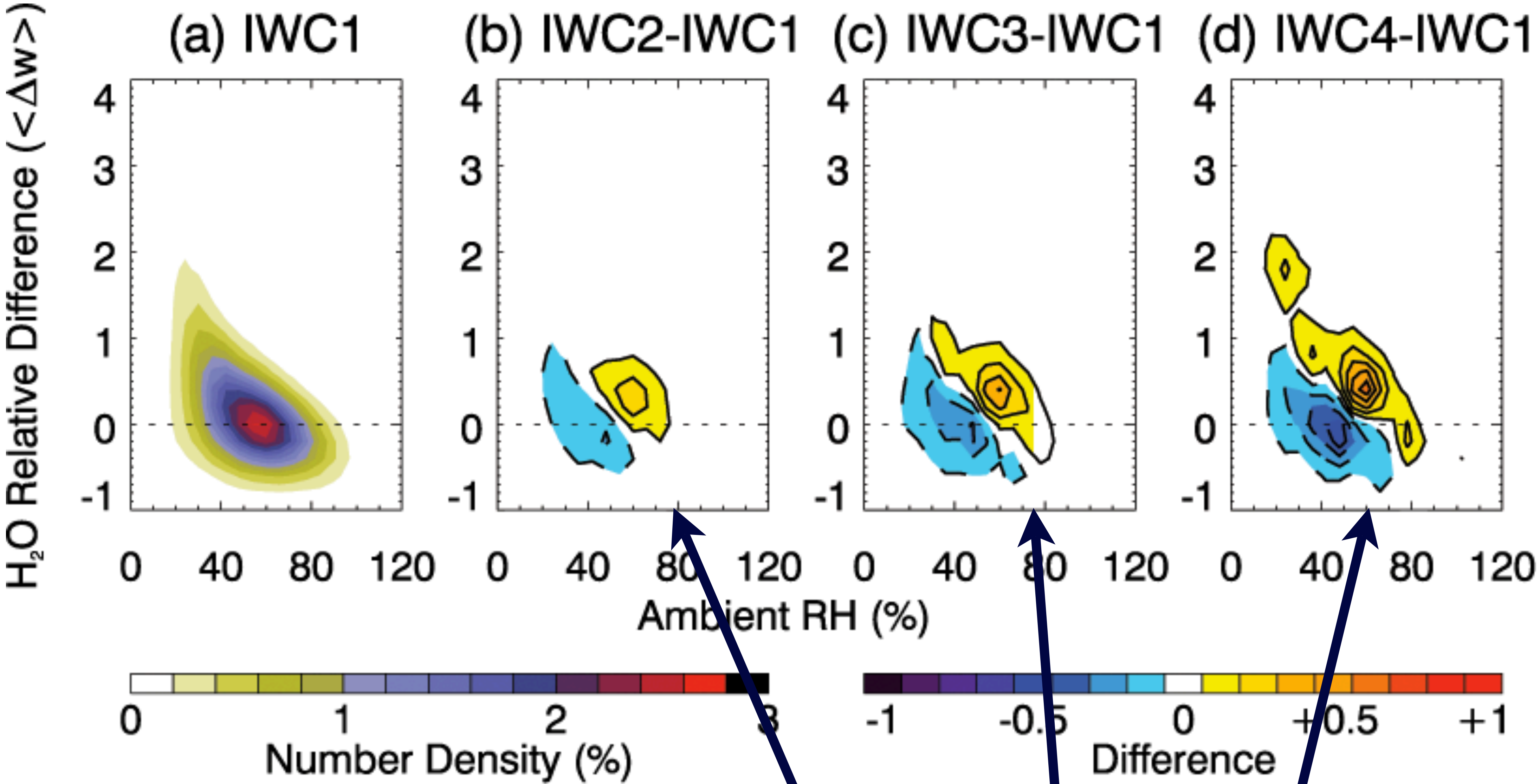


convective influence generally persists for 36-48h and 900-1200km

detrainment cirrus persist for 19-30h and 600-1000km

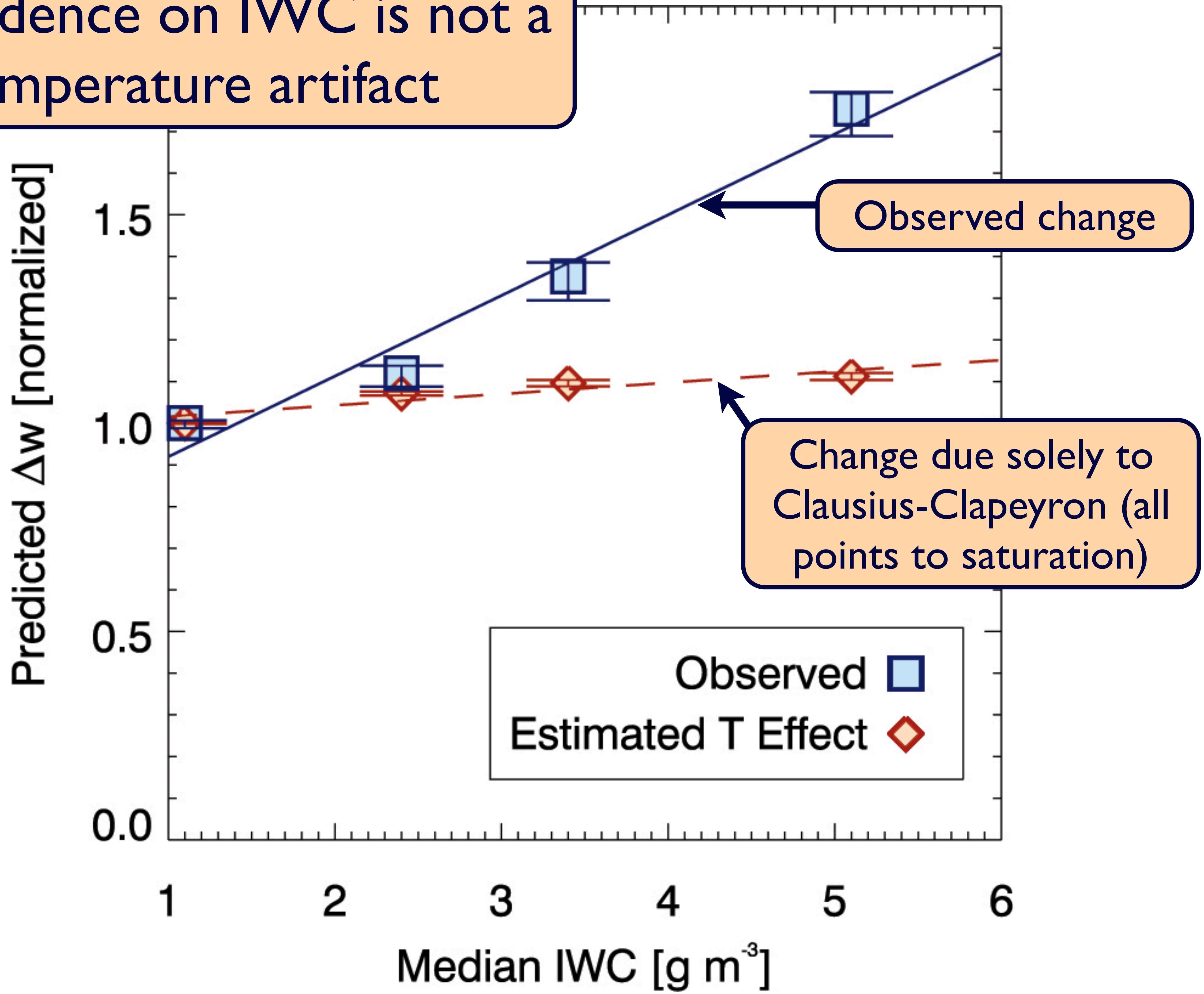
(Luo & Rossow 2004)

by ice water content at the source

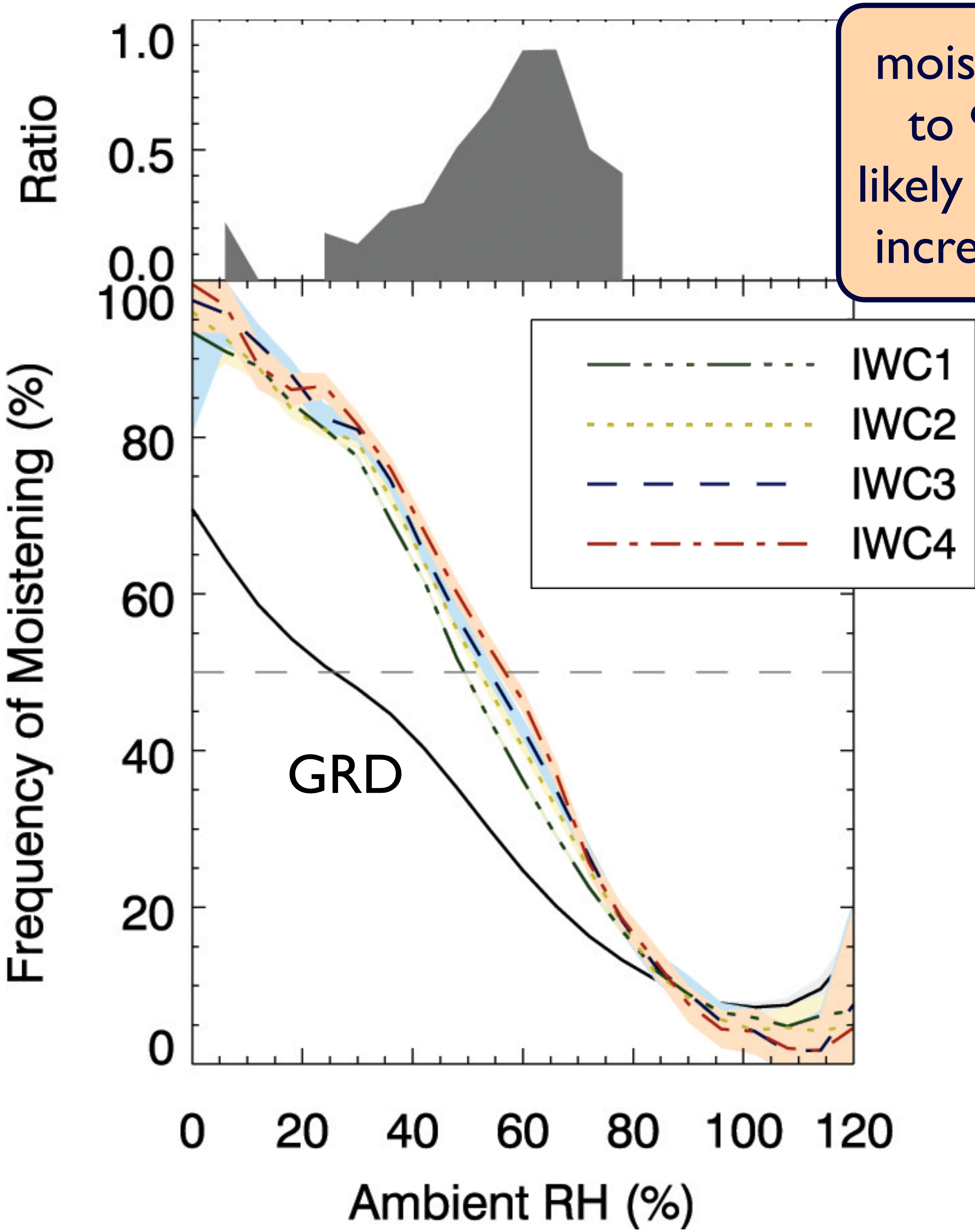


additional IWC leads to additional moistening downstream

Dependence on IWC is not a temperature artifact

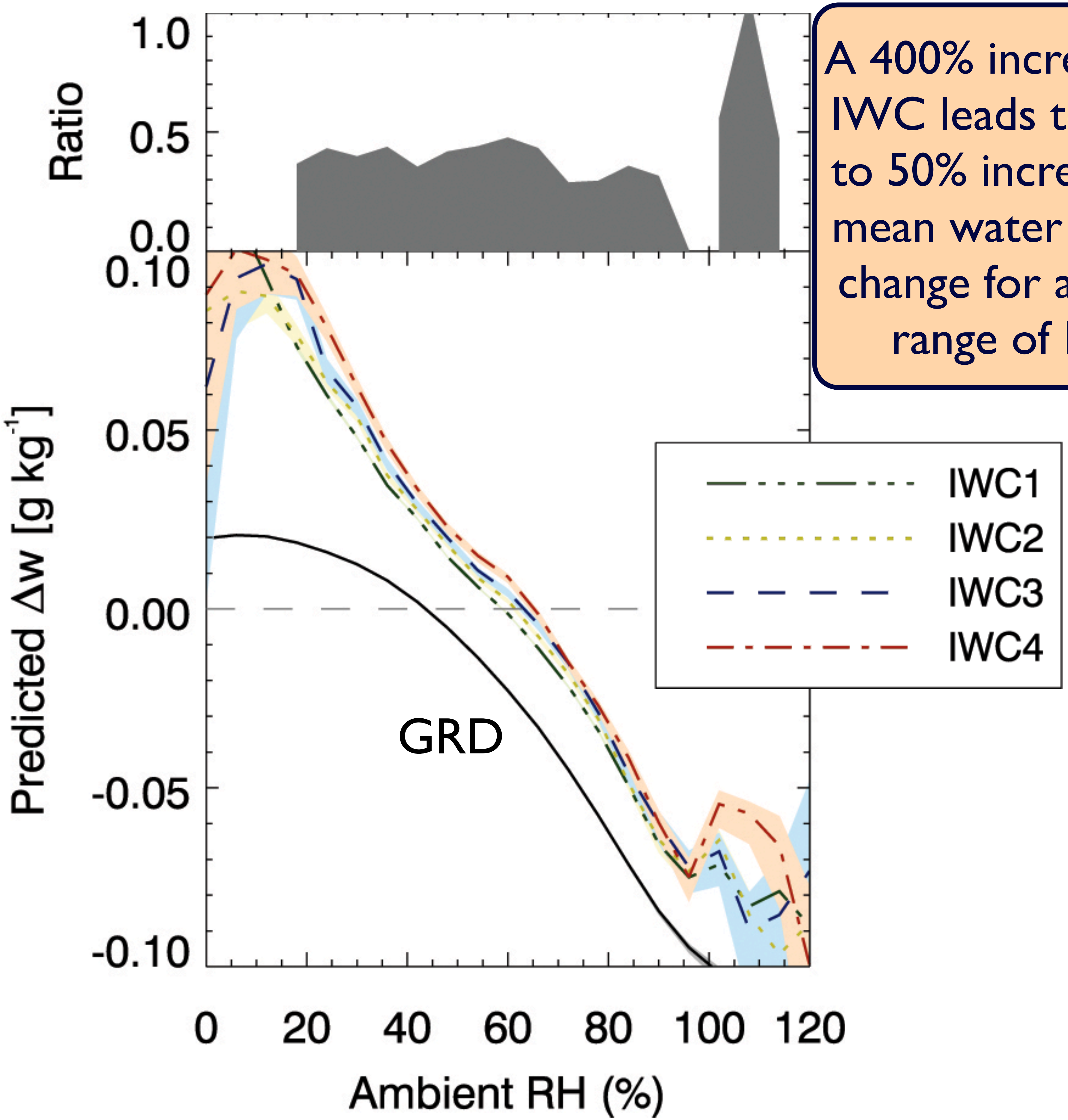


Between 20% RH and 80% RH, greater IWC is associated with a greater frequency of moistening at 95% confidence



moistening is 10 to 90% more likely with a 400% increase in IWC

The predicted magnitude of moistening is also consistent with initial IWC



A 400% increase in IWC leads to a 30 to 50% increase in mean water vapor change for a wide range of RH

Summary

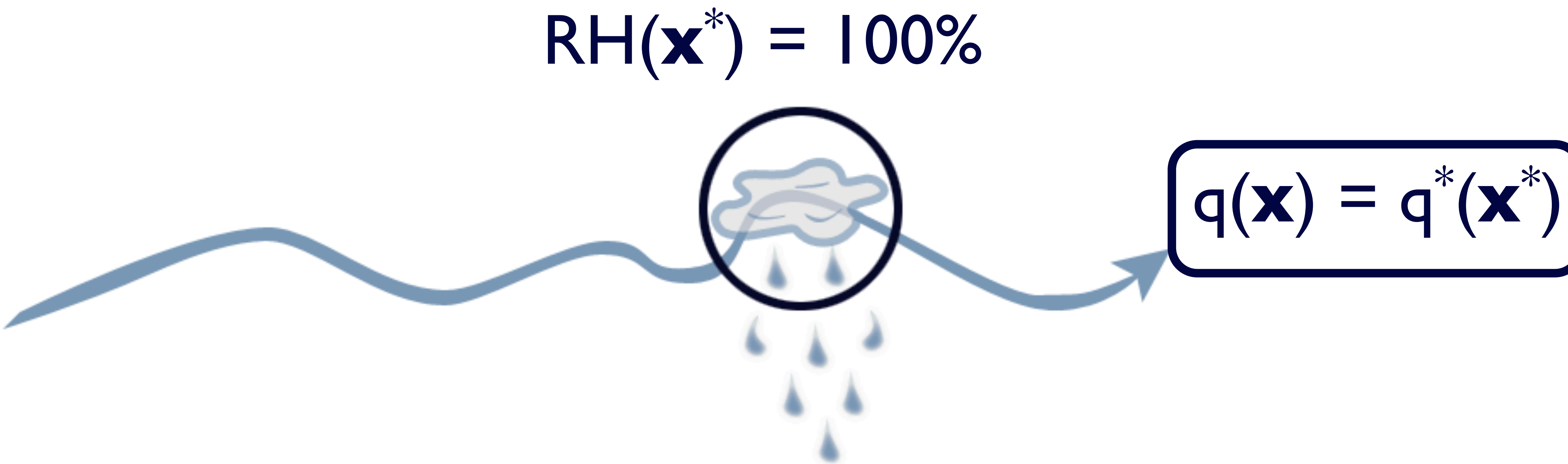
- Convection constitutes a net moisture source to the upper troposphere, although this source is largely confined to regions that are already humid.
- The extent of the moistening influence of convective detrainment in space and time corresponds well with the lifetimes of anvil cirrus.
- Additional ice water content at the location of detrainment corresponds to additional moistening downstream. This is true in terms of relative moistening, absolute moistening, and frequency of moistening.
- The effectiveness of convective moistening by both vapor detrainment and ice sublimation depends strongly on the ambient relative humidity.

Wright et al., Atm. Chem. Phys., 2009

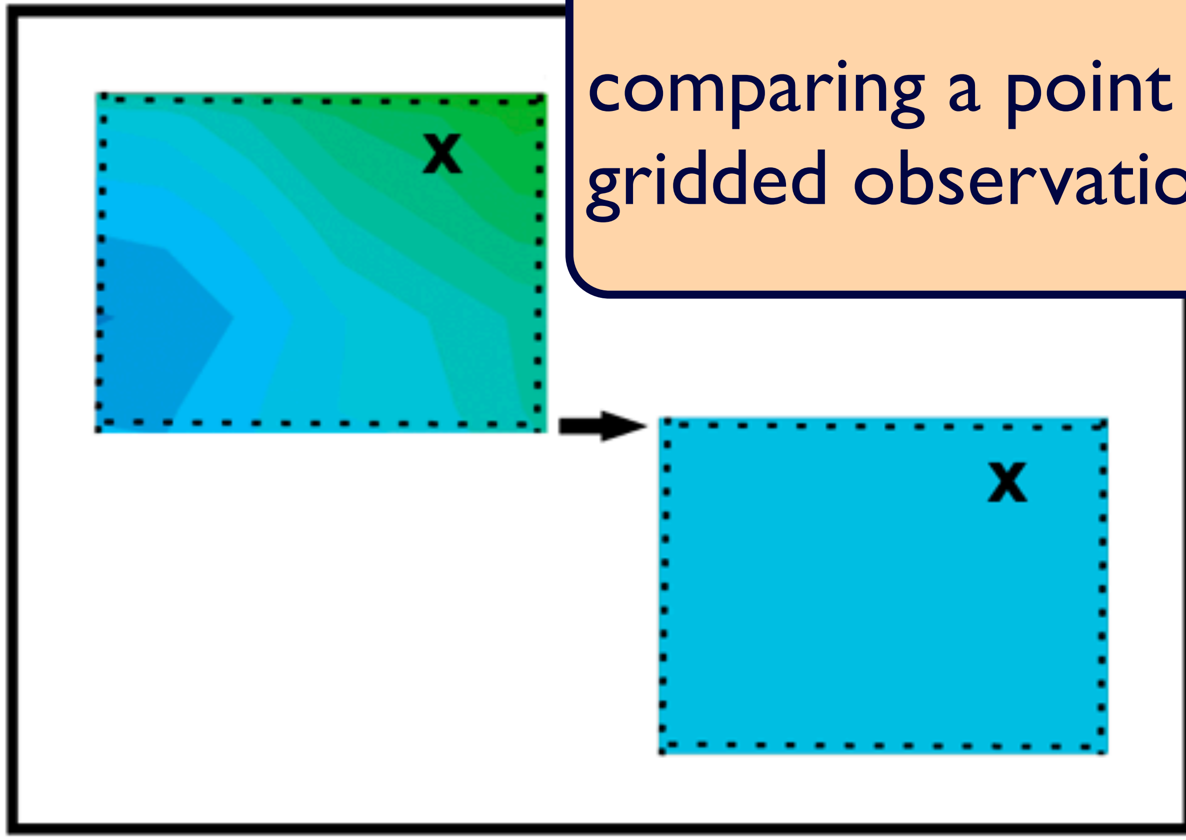
2. Condensate Evaporation in a GCM

The Advection-Condensation Paradigm:

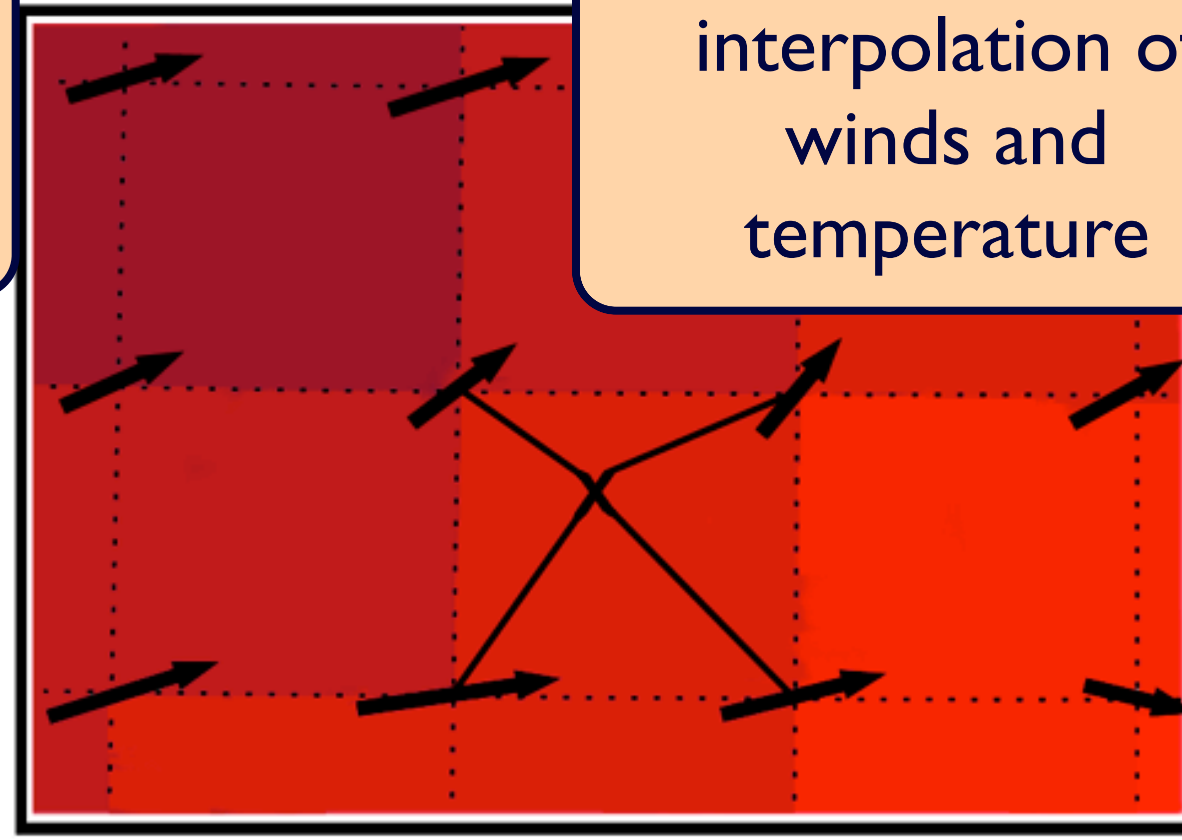
the humidity at any point is determined to leading order by large-scale temperature and circulation



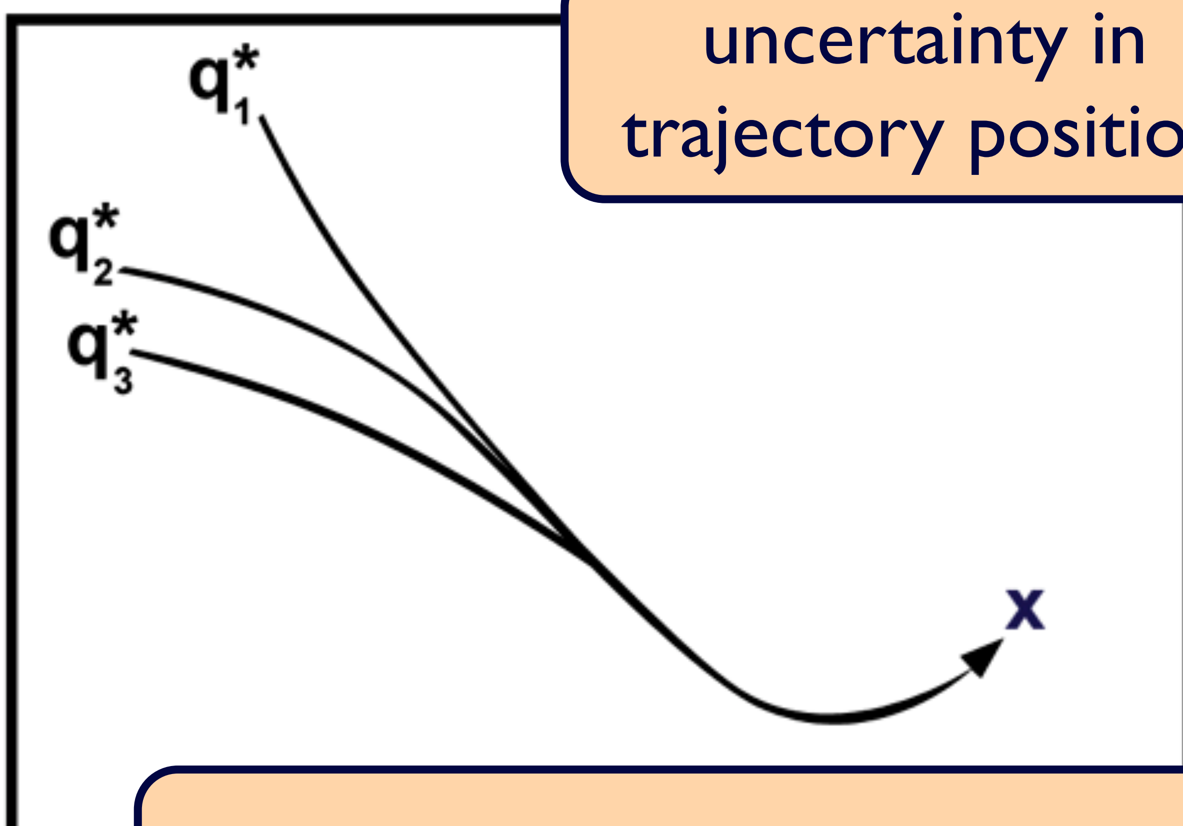
comparing a point to gridded observations



interpolation of winds and temperature



uncertainty in trajectory position



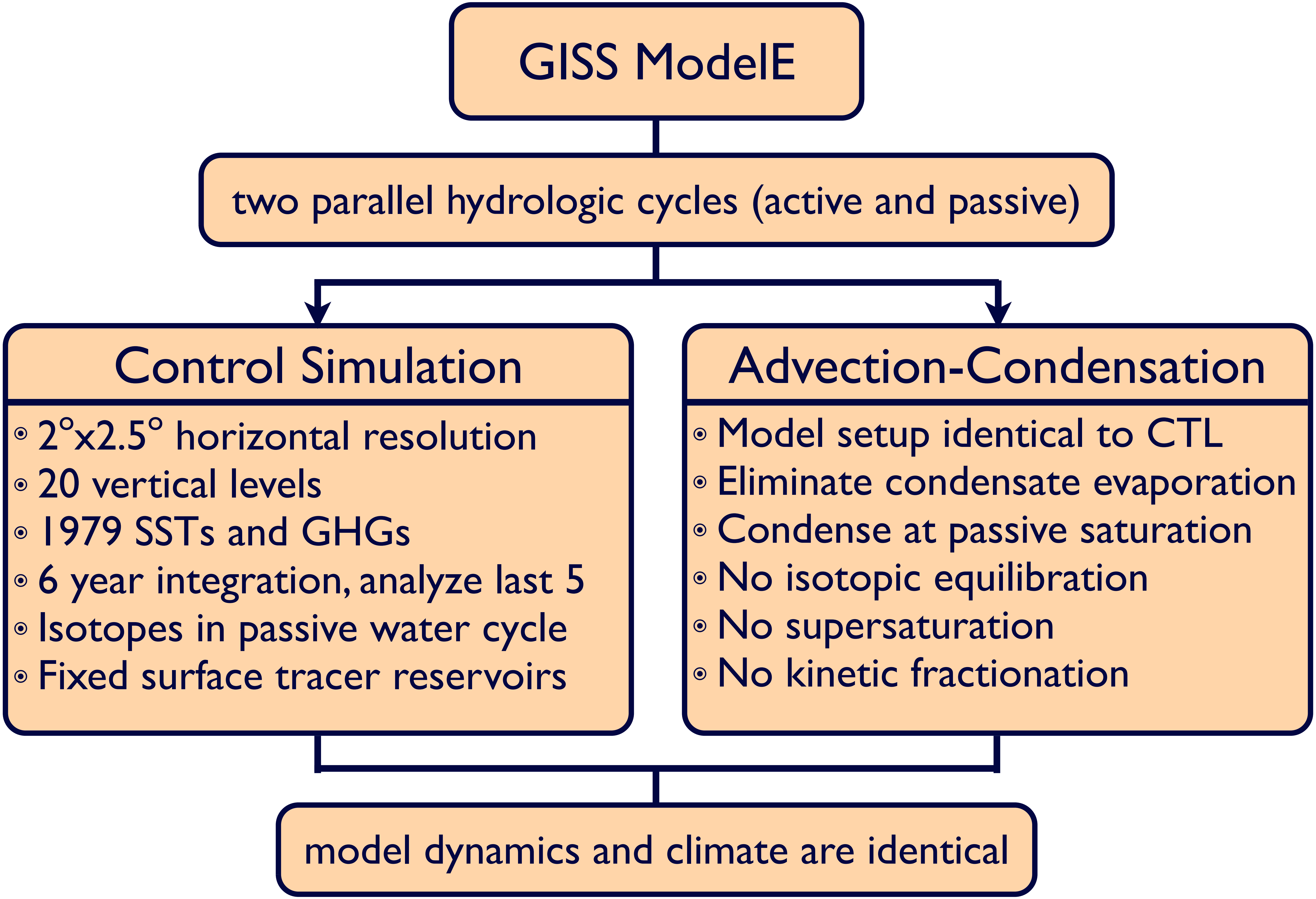
assumed condensation threshold (RH)

100%

95%

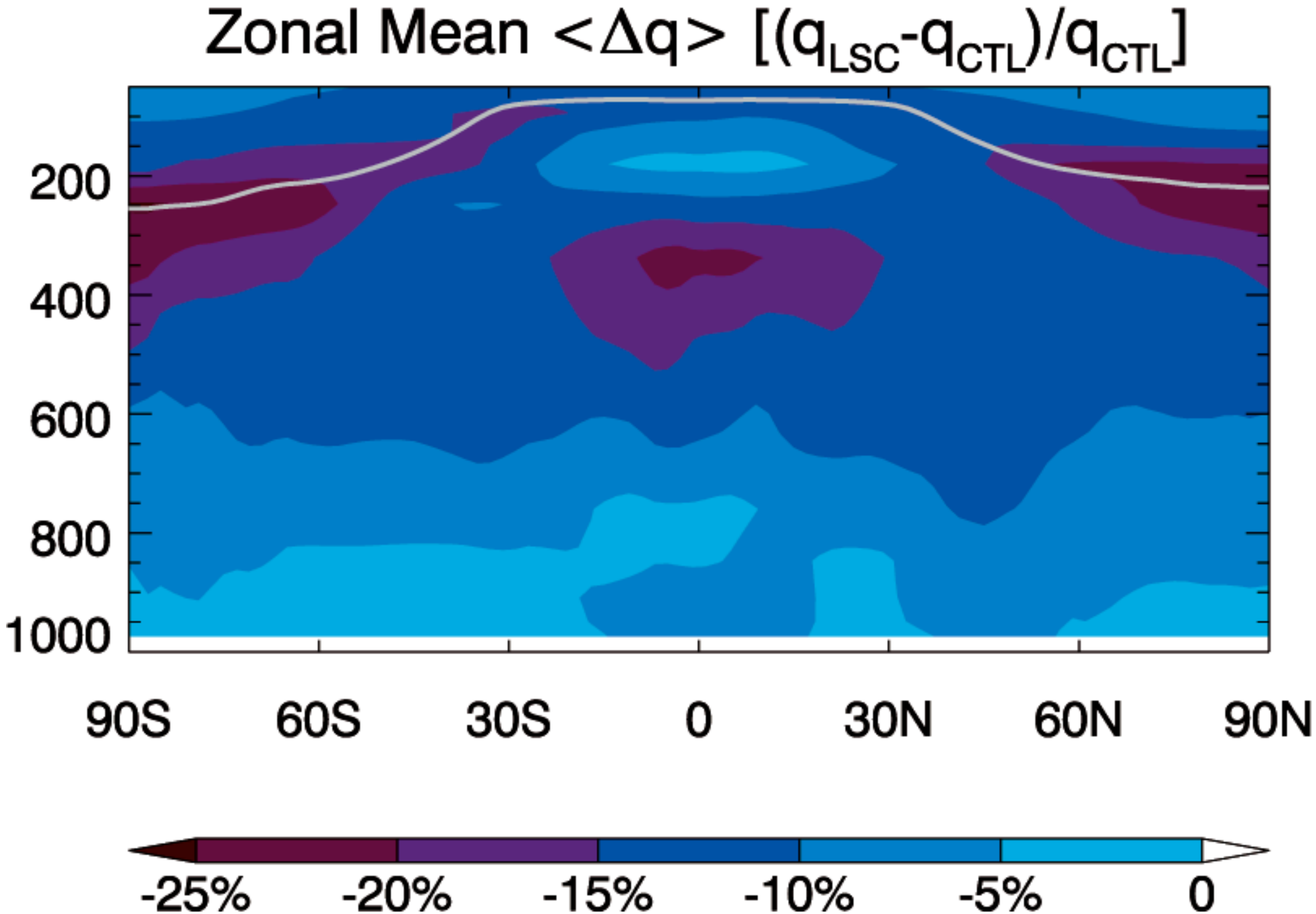
90%

we can sidestep these difficulties in a GCM



GISS ModelE
two parallel hydrologic cycles (active and passive)
Control Simulation
2°x2.5° horizontal resolution
20 vertical levels
1979 SSTs and GHGs
6 year integration, analyze last 5
Isotopes in passive water cycle
Fixed surface tracer reservoirs
Advection-Condensation
Model setup identical to CTL
Eliminate condensate evaporation
Condense at passive saturation
No isotopic equilibration
No supersaturation
No kinetic fractionation
model dynamics and climate are identical

Disabling condensate evaporation dries the model atmosphere by 5-25%



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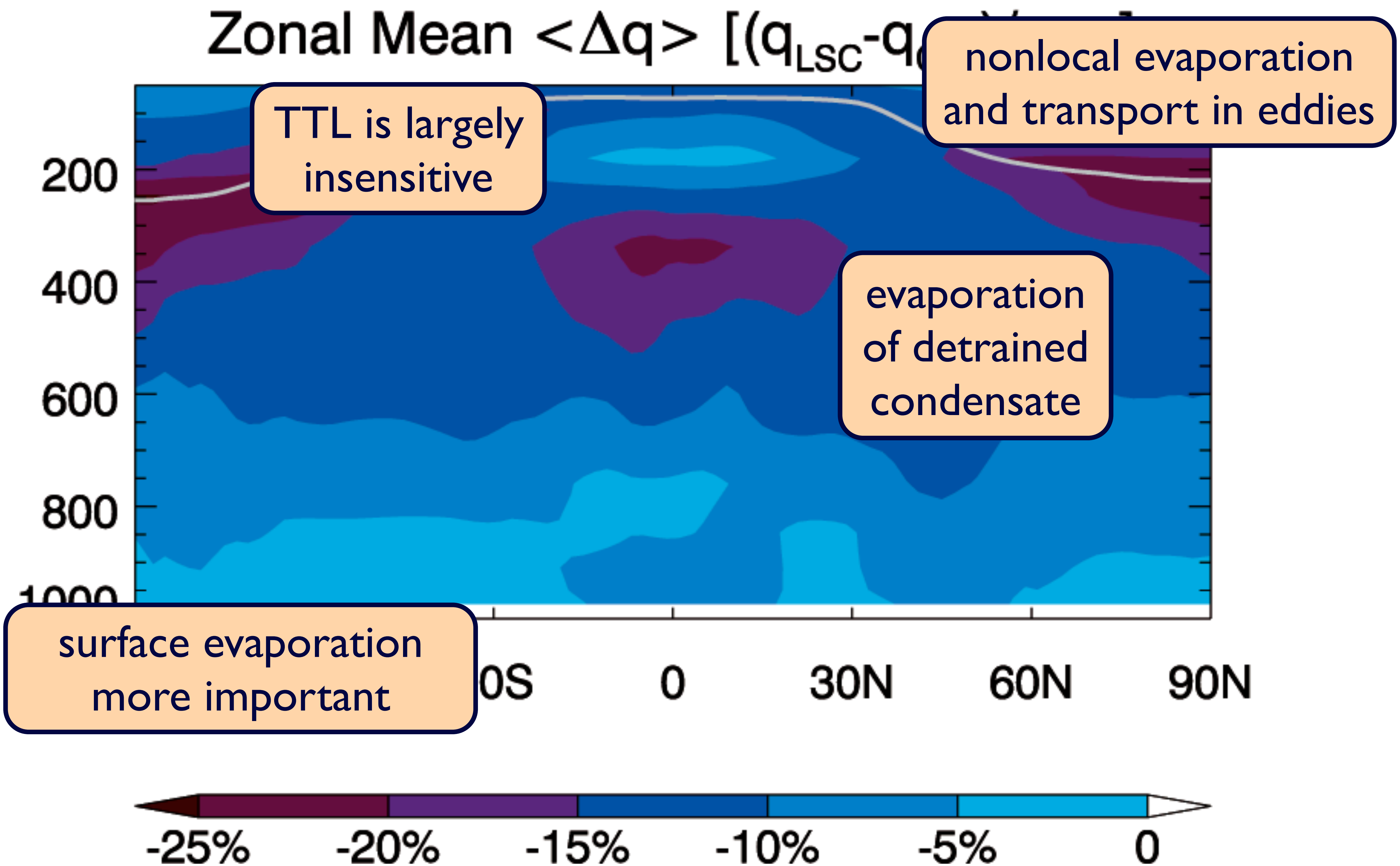

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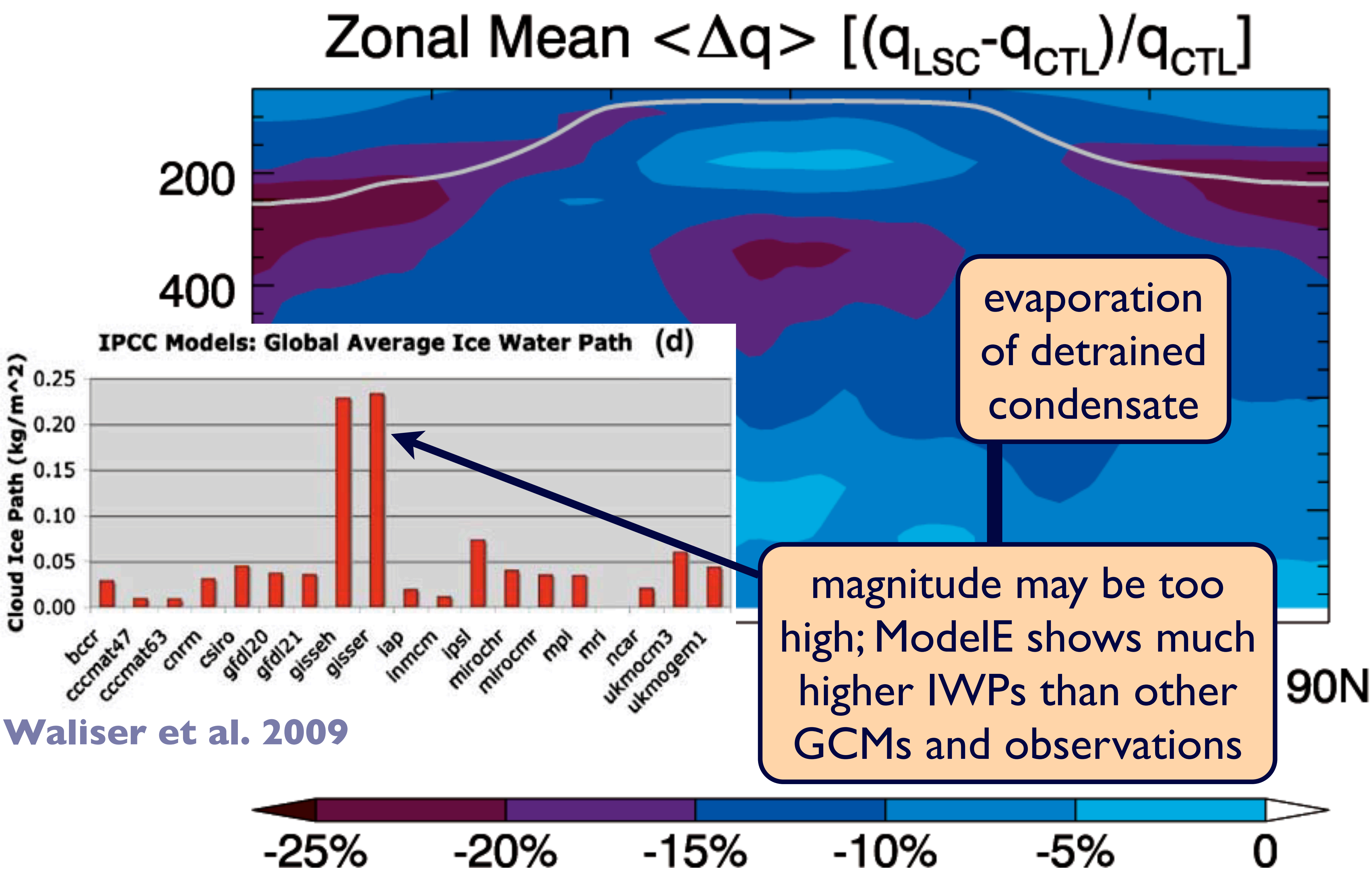
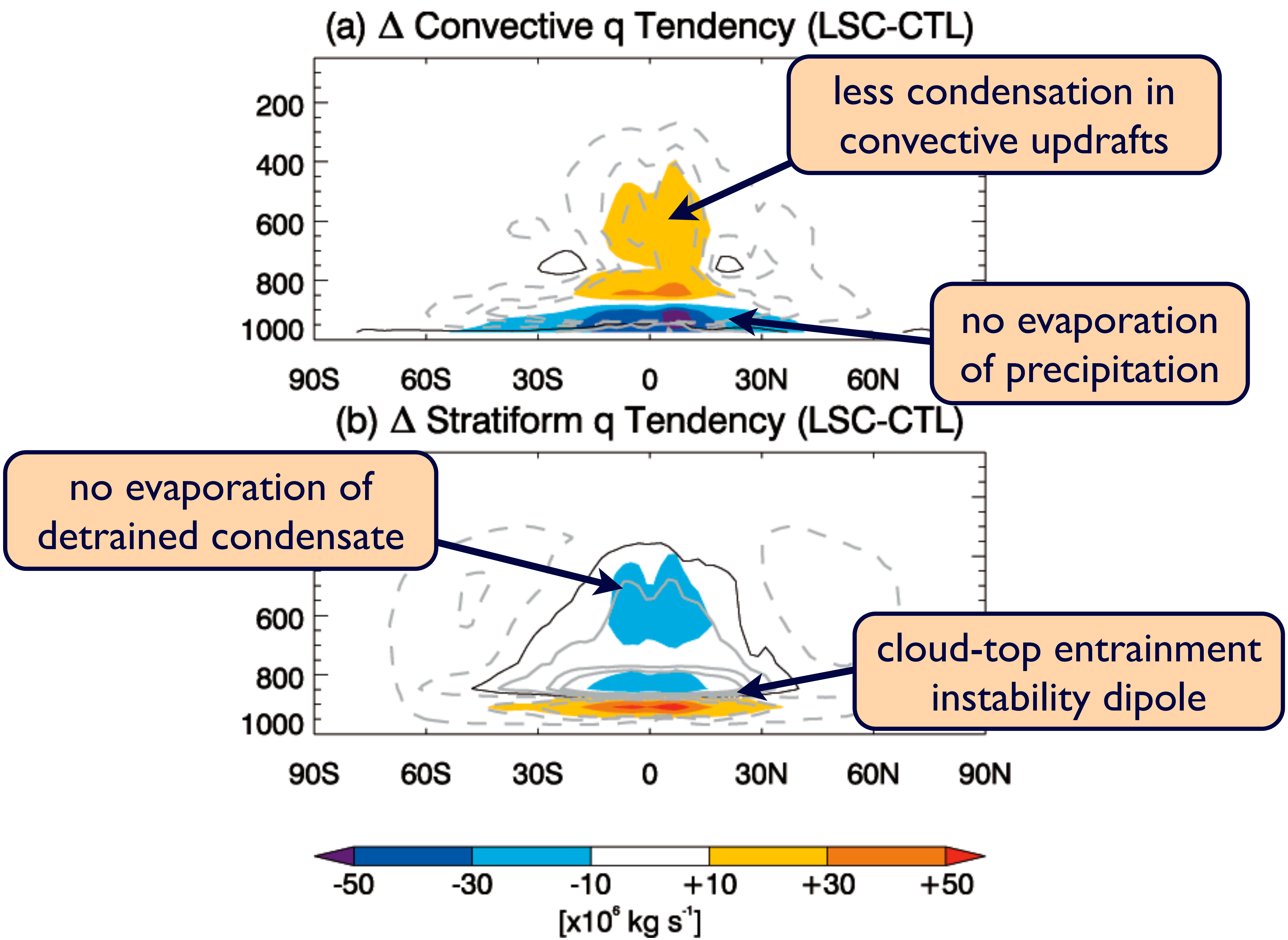
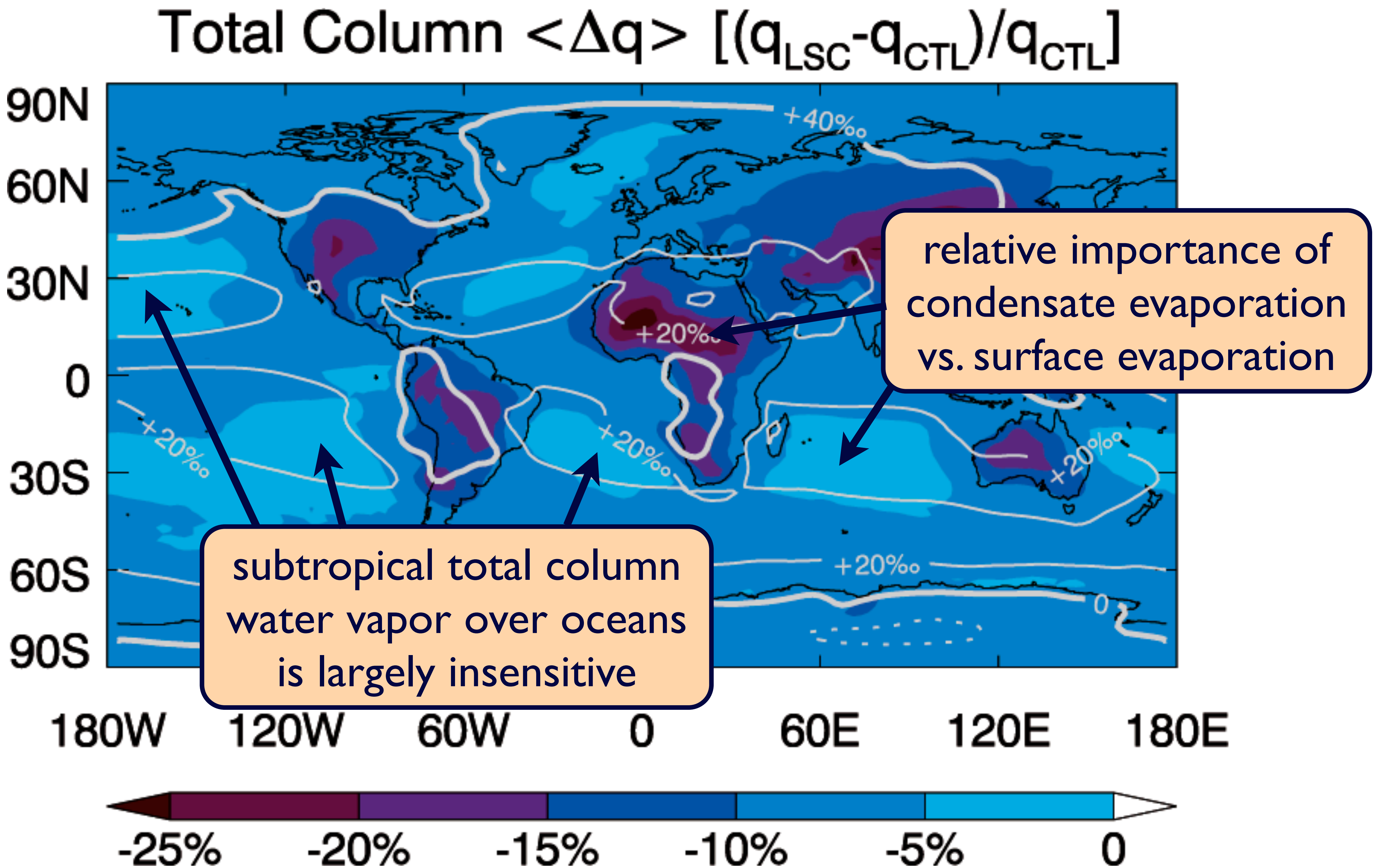


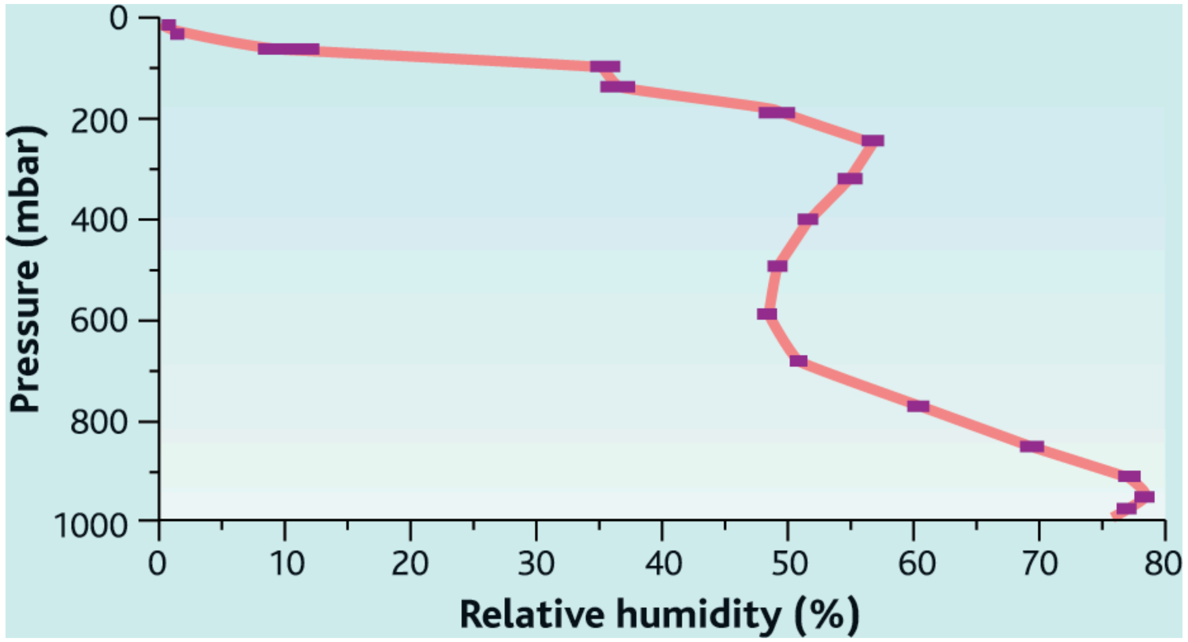
Water vapor tendencies



Total column water vapor



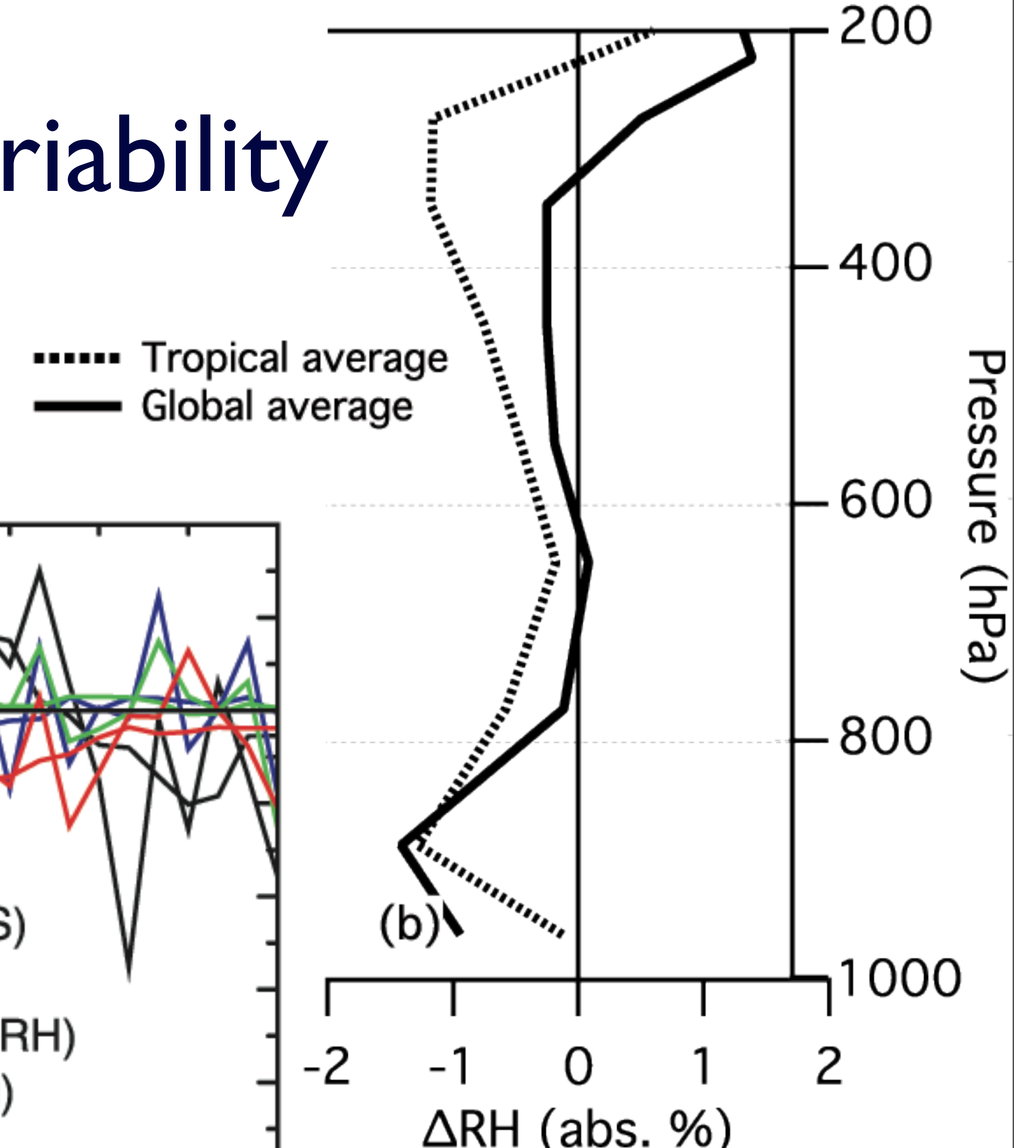
Climate Model



Cess 2005

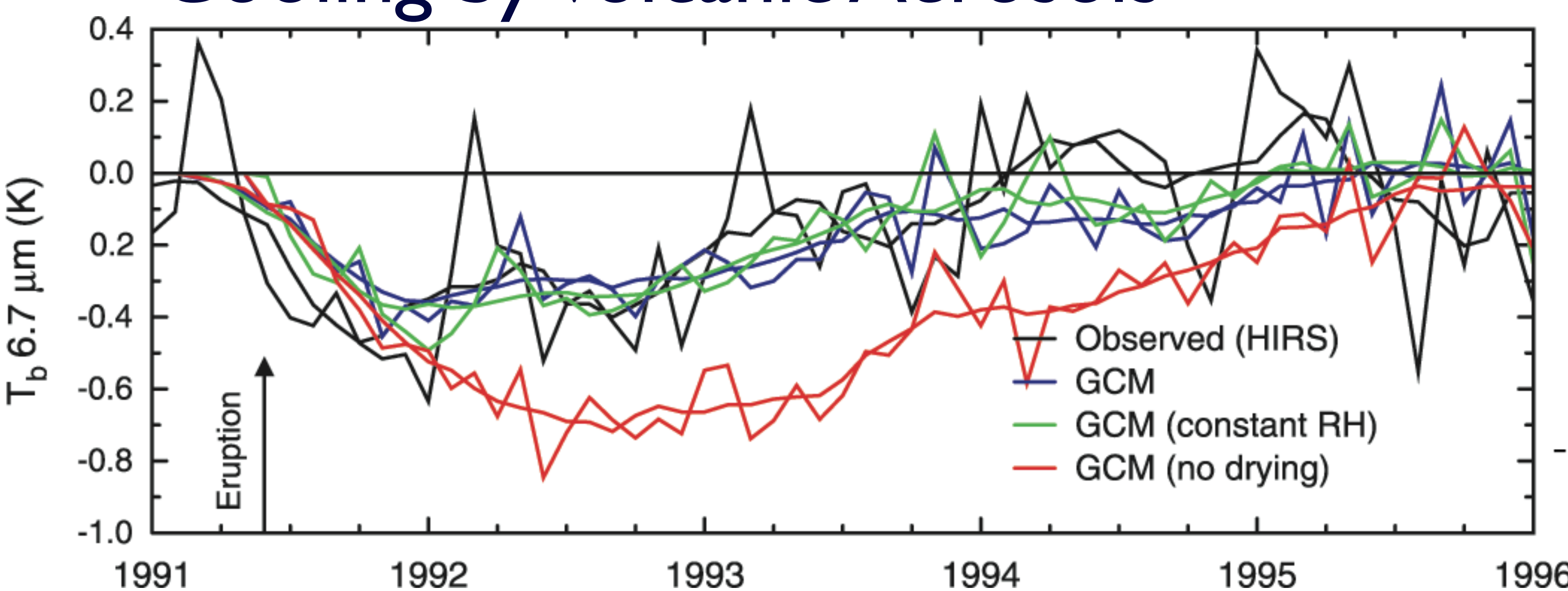
Models and observations both suggest that WV feedback is approximated by constant global mean RH

ENSO Variability

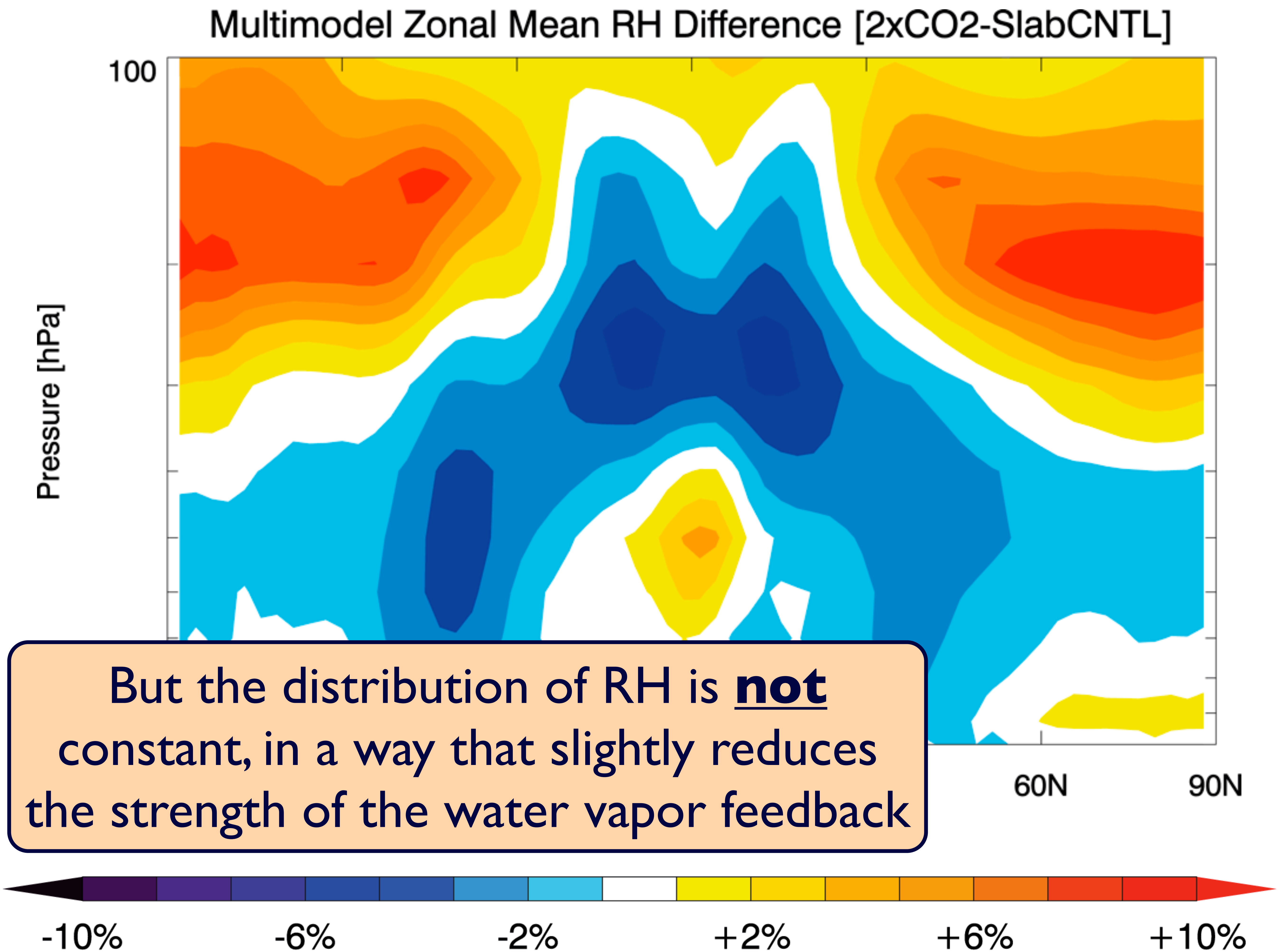


Dessler et al 2008

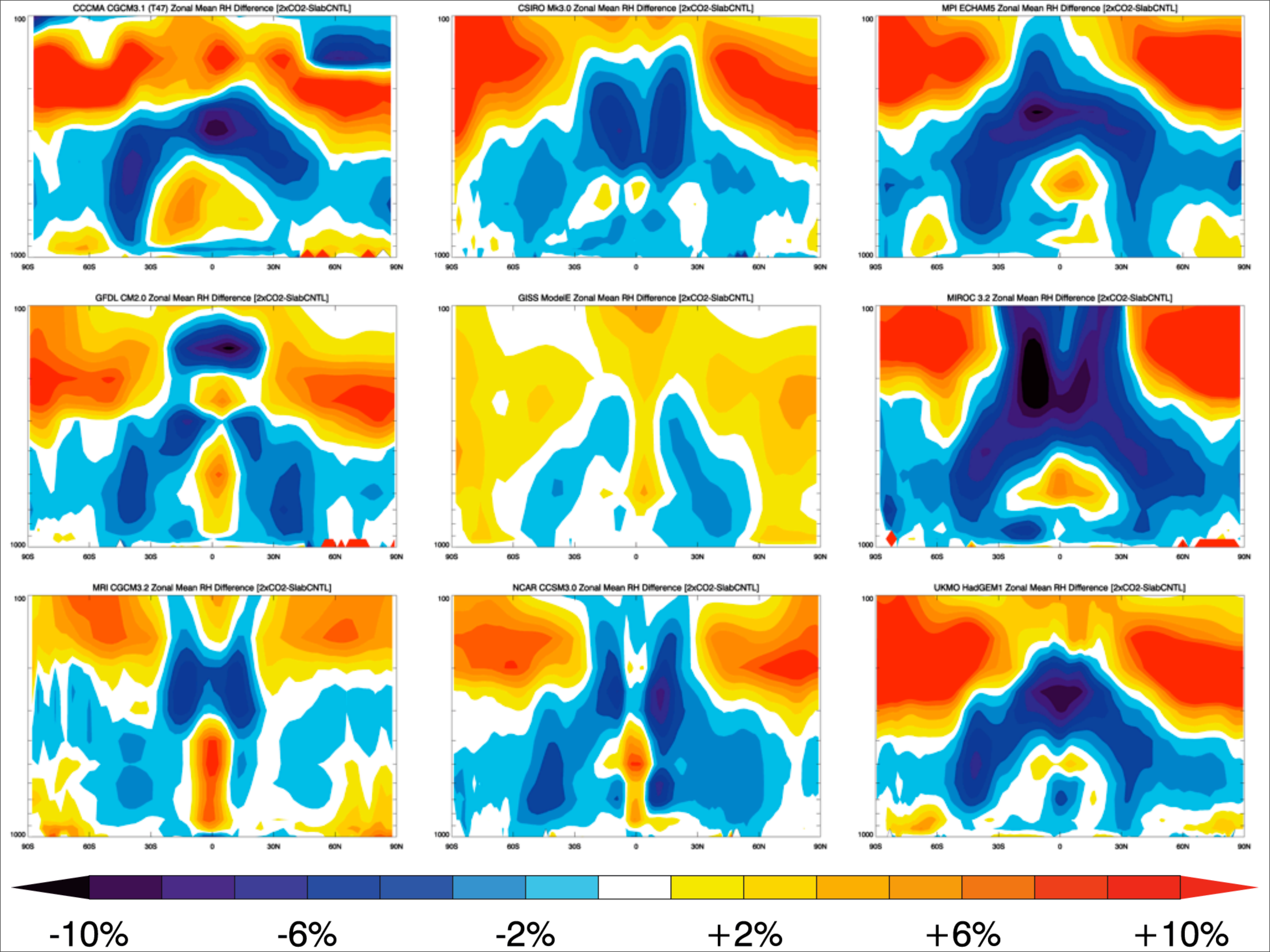
Cooling by Volcanic Aerosols



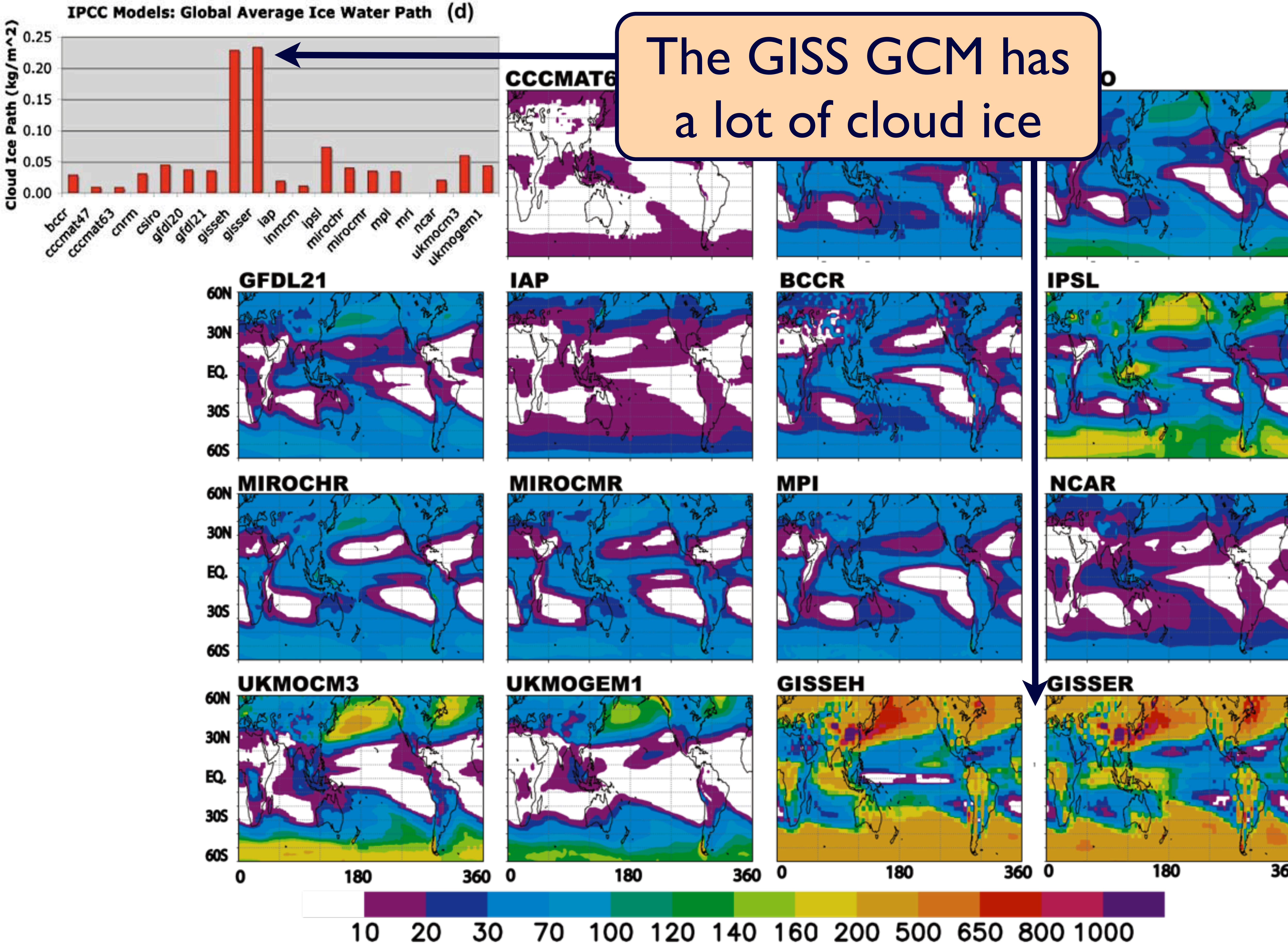
Soden et al 2002



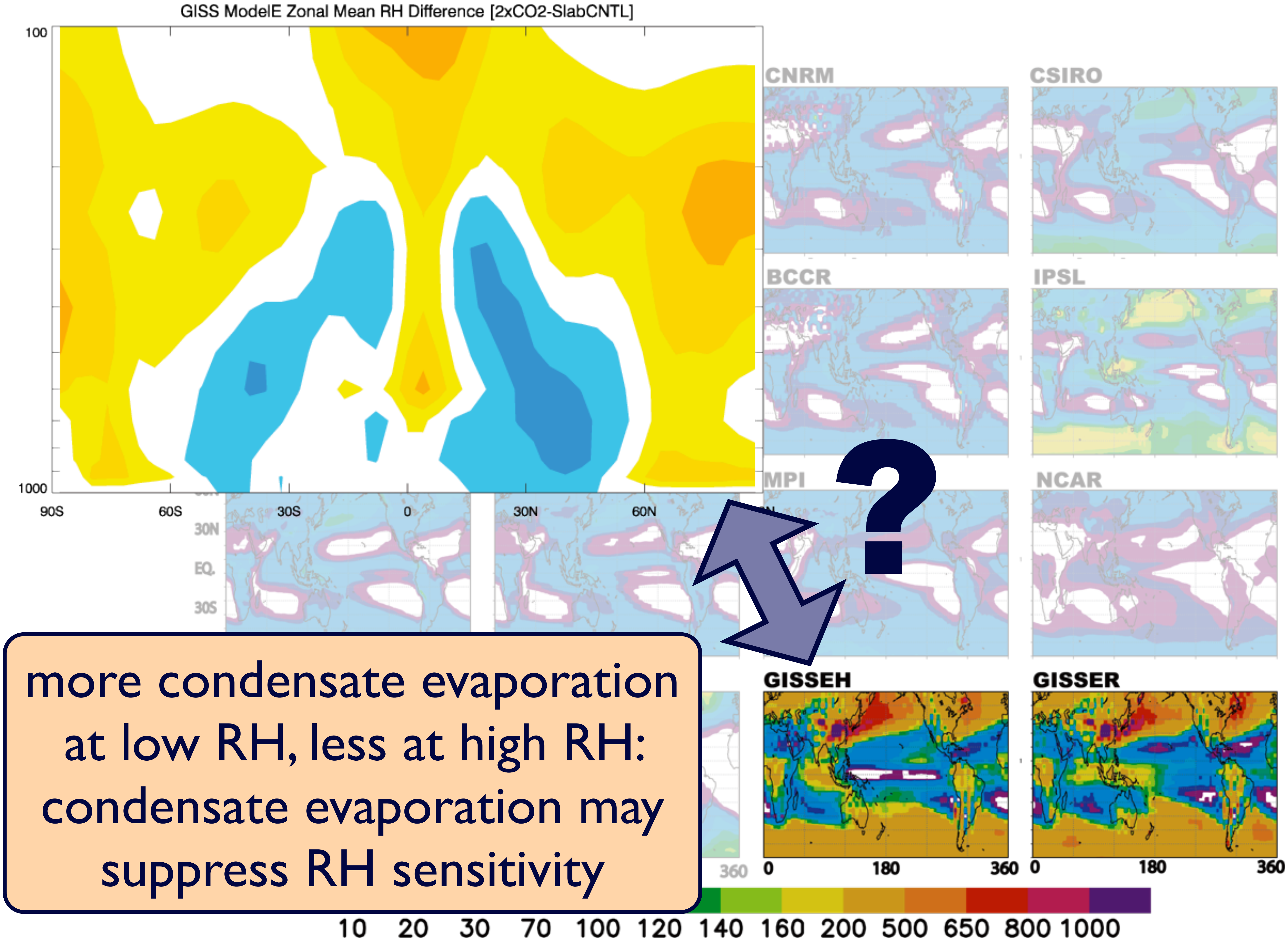
But the distribution of RH is **not** constant, in a way that slightly reduces the strength of the water vapor feedback


CCCMA CGCM3.1 (T47) Zonal Mean RH Difference [2xCO2-SlabCNTL]
CSIRO Mk3.0 Zonal Mean RH Difference [2xCO2-SlabCNTL]
MPI ECHAM5 Zonal Mean RH Difference [2xCO2-SlabCNTL]
GFDL CM2.0 Zonal Mean RH Difference [2xCO2-SlabCNTL]
GISS ModelE Zonal Mean RH Difference [2xCO2-SlabCNTL]
MIROC 3.2 Zonal Mean RH Difference [2xCO2-SlabCNTL]
MRI CGCM3.2 Zonal Mean RH Difference [2xCO2-SlabCNTL]
NCAR CCSM3.0 Zonal Mean RH Difference [2xCO2-SlabCNTL]
UKMO HadGEM1 Zonal Mean RH Difference [2xCO2-SlabCNTL]
100
1000
90S
60S
30S
0
30N
60N
90N
-10%
-6%
-2%
+2%
+6%
+10%

The GISS GCM has a lot of cloud ice



Waliser et al. 2009



more condensate evaporation at low RH, less at high RH: condensate evaporation may suppress RH sensitivity

Waliser et al. 2009

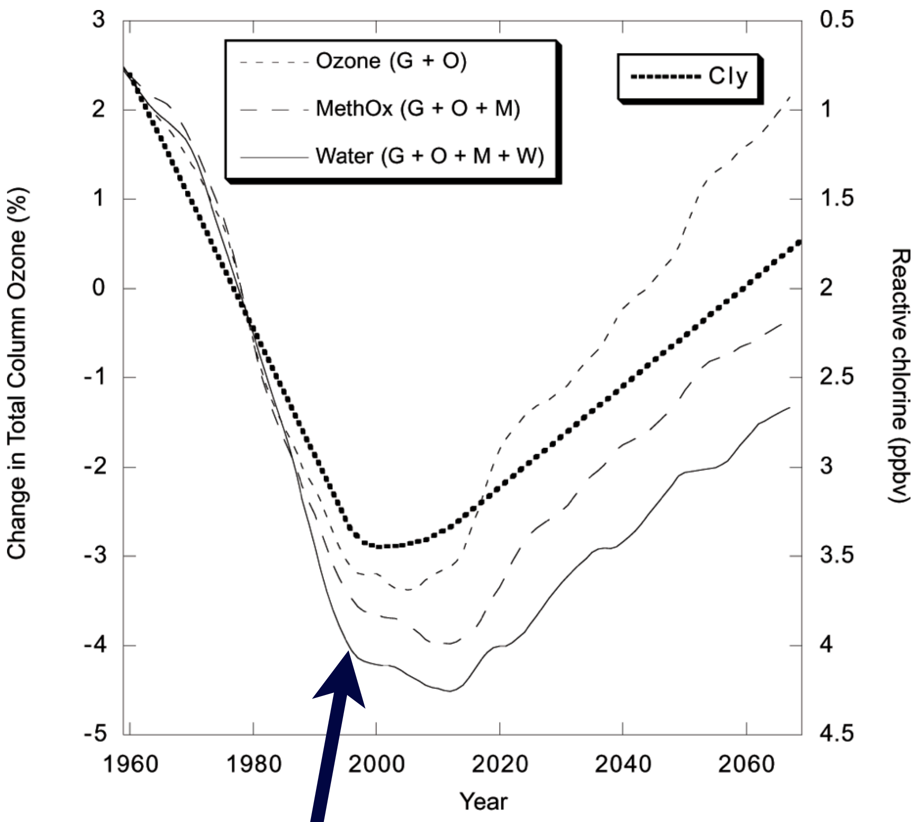
Summary

- Disabling condensate evaporation dries the model atmosphere by 5% to 25%. This is the direct importance of microphysics to atmospheric humidity in this model.
- Drying is most pronounced in the tropical upper troposphere (detrained condensate) and near the extratropical tropopause (non-local condensate evaporation and transport).
- Total column water vapor over the subtropical oceans and zonal mean water vapor in the TTL are largely insensitive to condensate evaporation.
- Enhanced condensate evaporation is likely to reduce the RH sensitivity to warming and slightly strengthen the WV feedback.

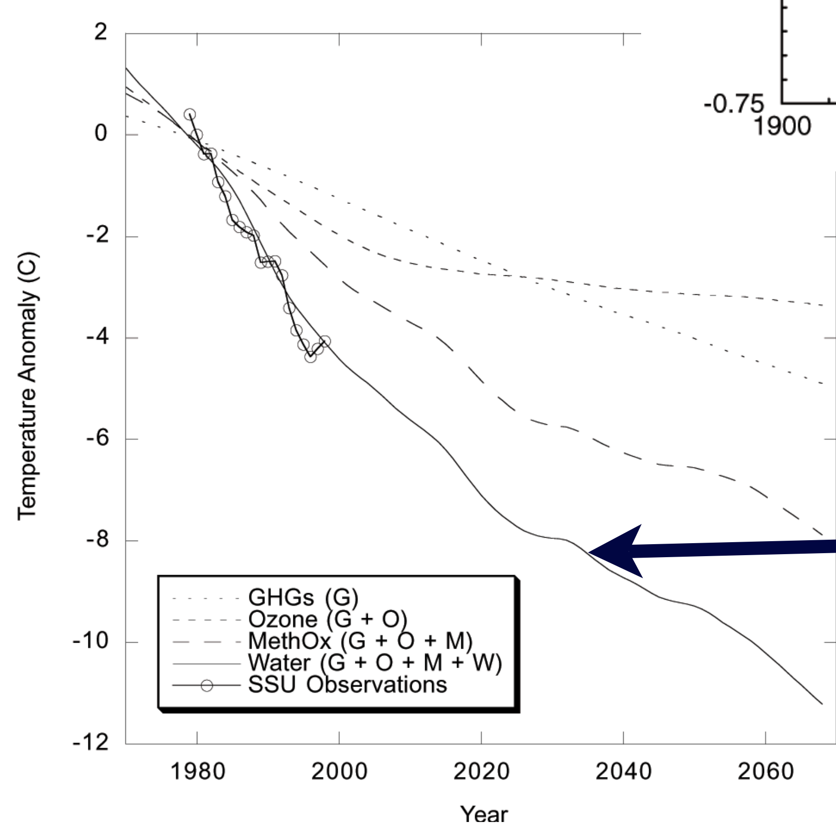
Wright et al., Geophys. Res. Lett., 2009

3. Troposphere-Stratosphere Transport

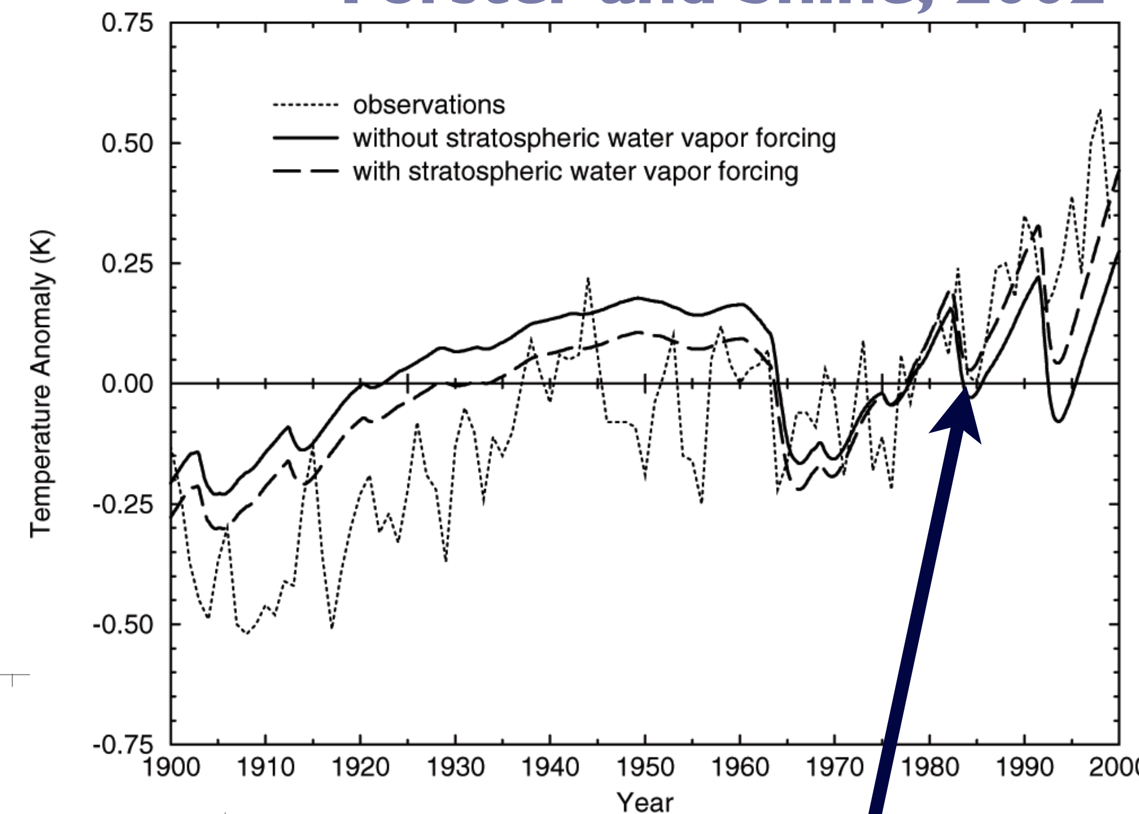
Water vapor is of central importance to both chemical and radiative processes in the stratosphere



Shindell 2001



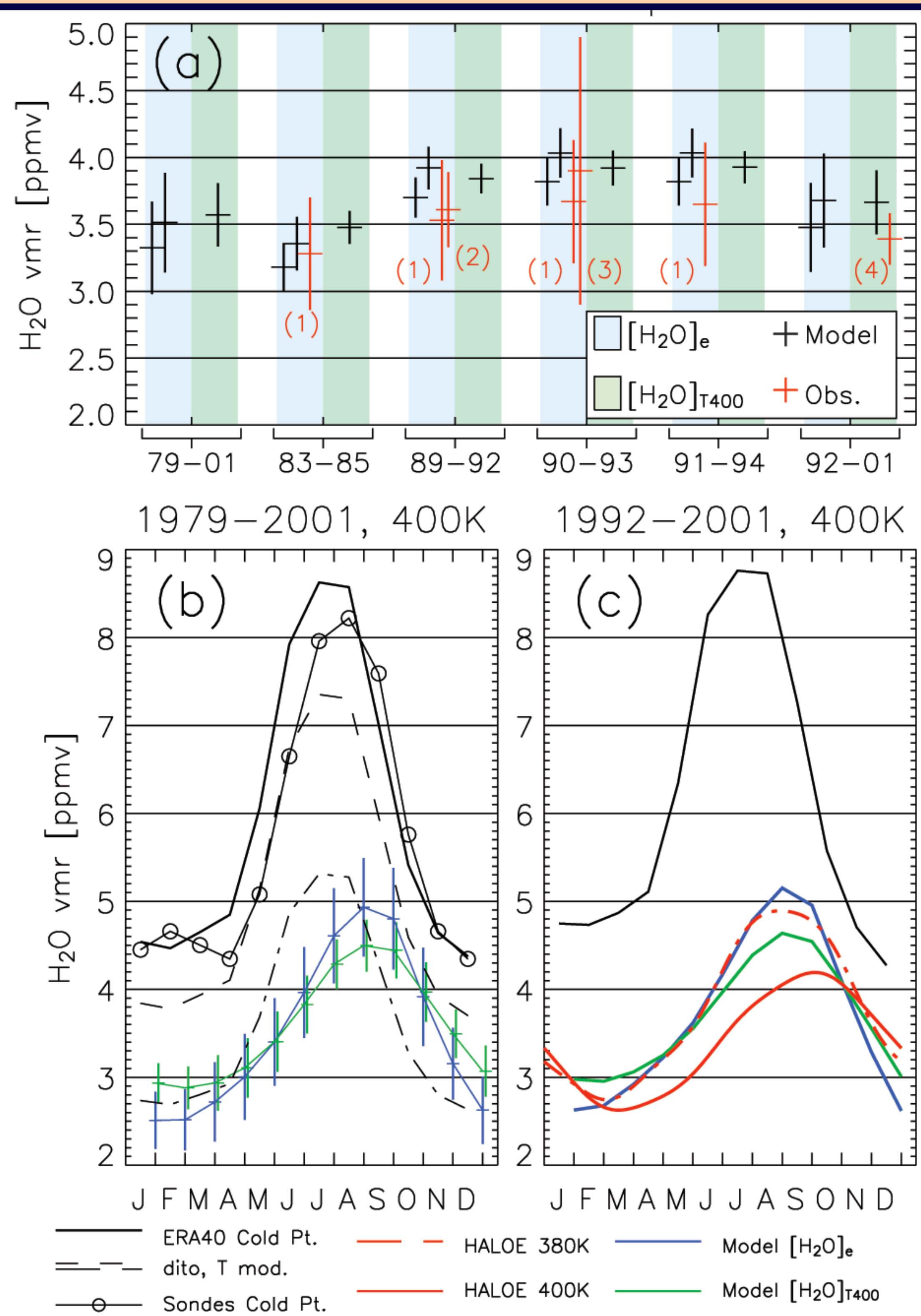
Forster and Shine, 2002



loss rate of ozone via OH: **more WV** means **less ozone**

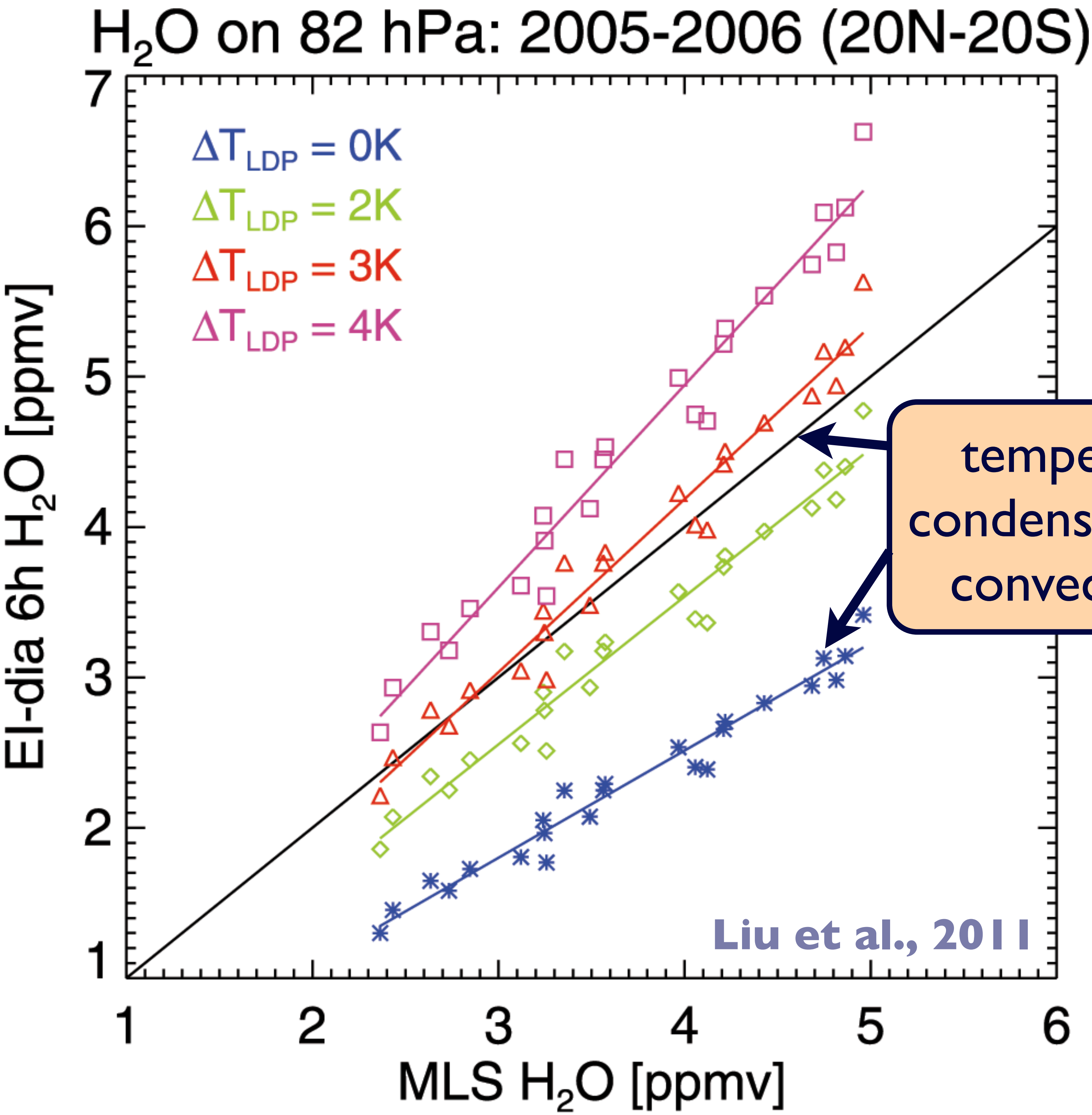
More WV **warms surface** and **cools stratosphere**

Initial results suggested that advection-condensation can simulate observed stratospheric water vapour



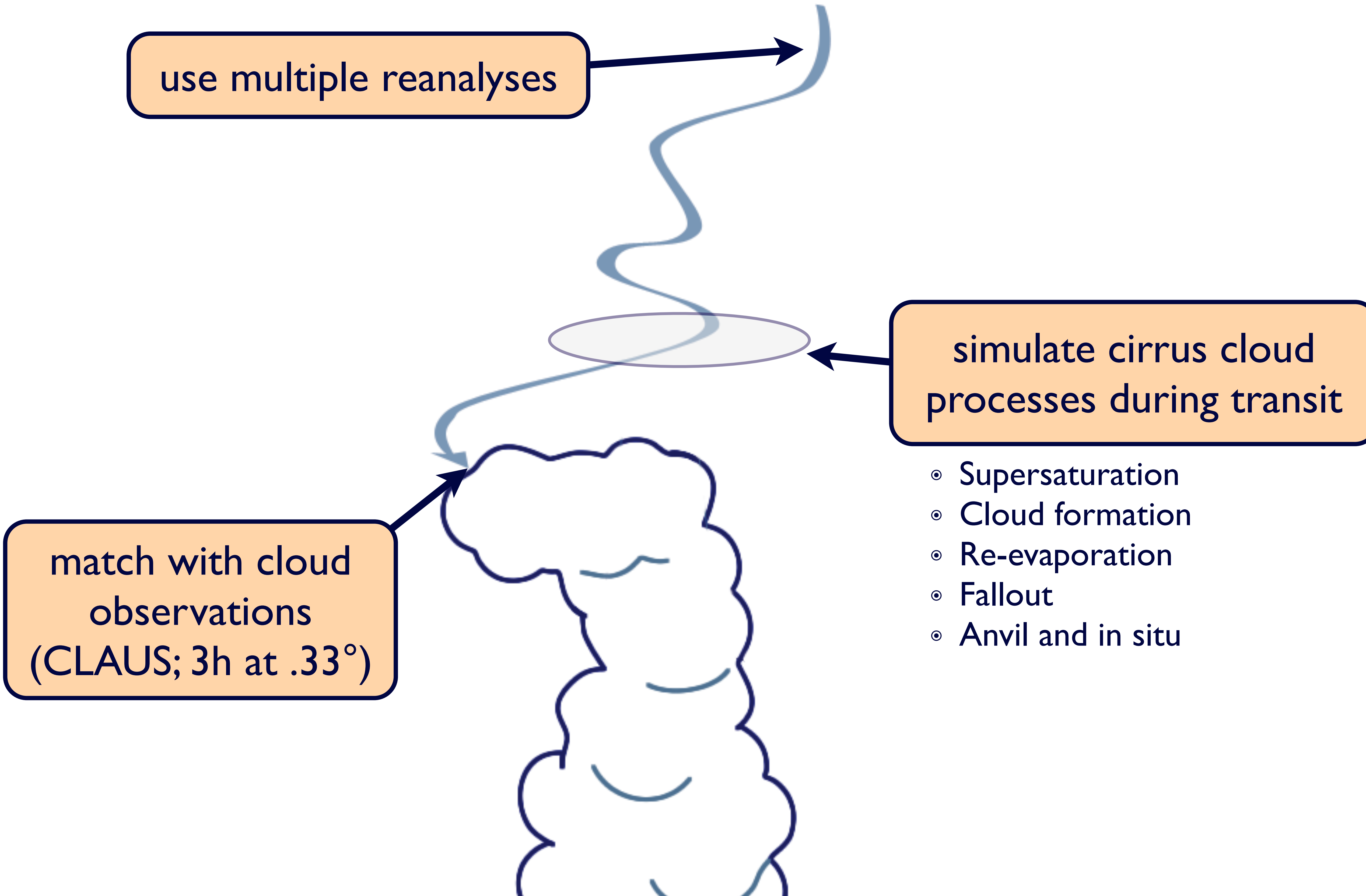
Fueglistaler et al., 2005

But more recent results indicate that there are substantial unexplained discrepancies...



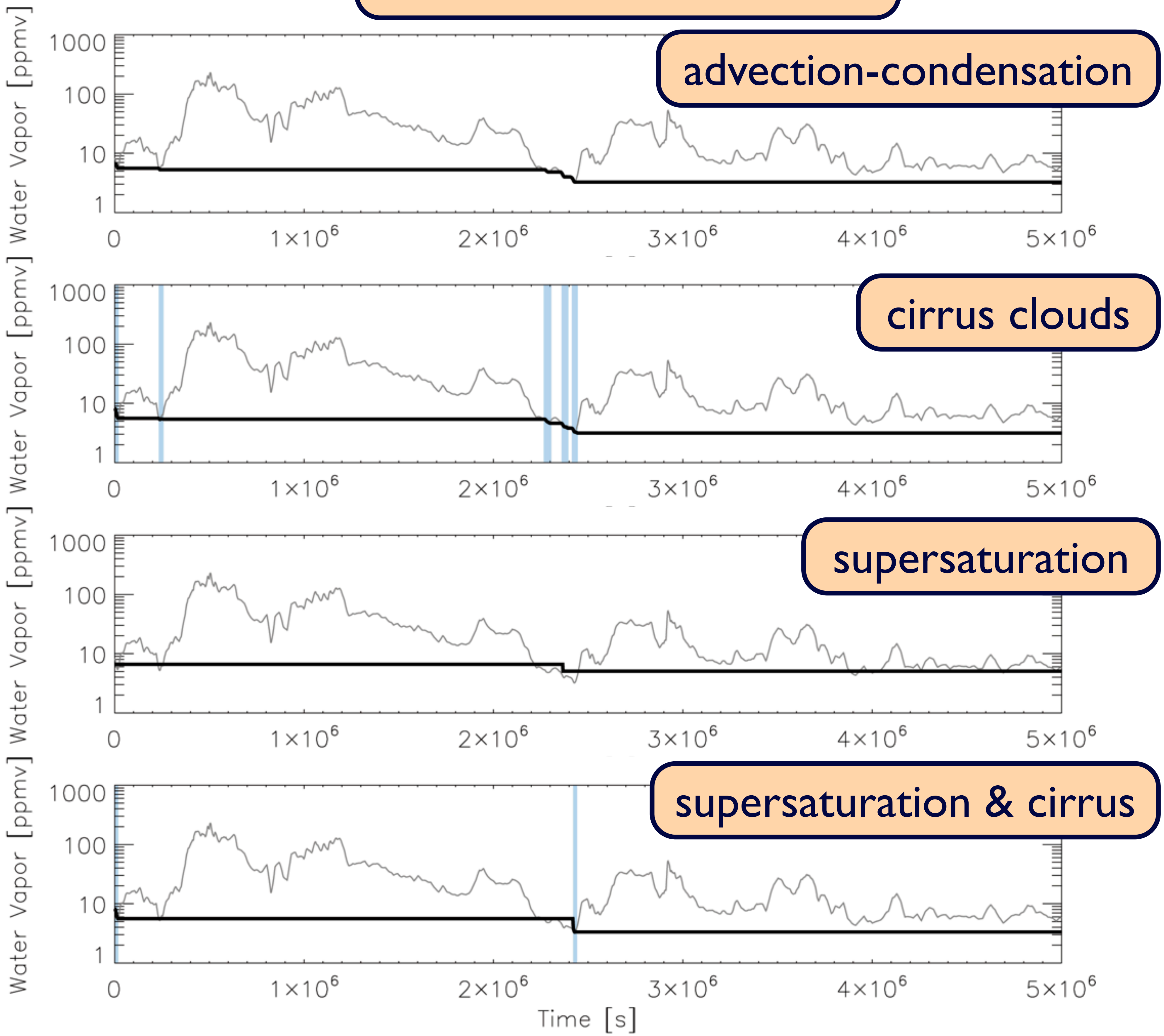
temperature biases?
condensate evaporation?
convective influence?

Current work aims to address these questions...

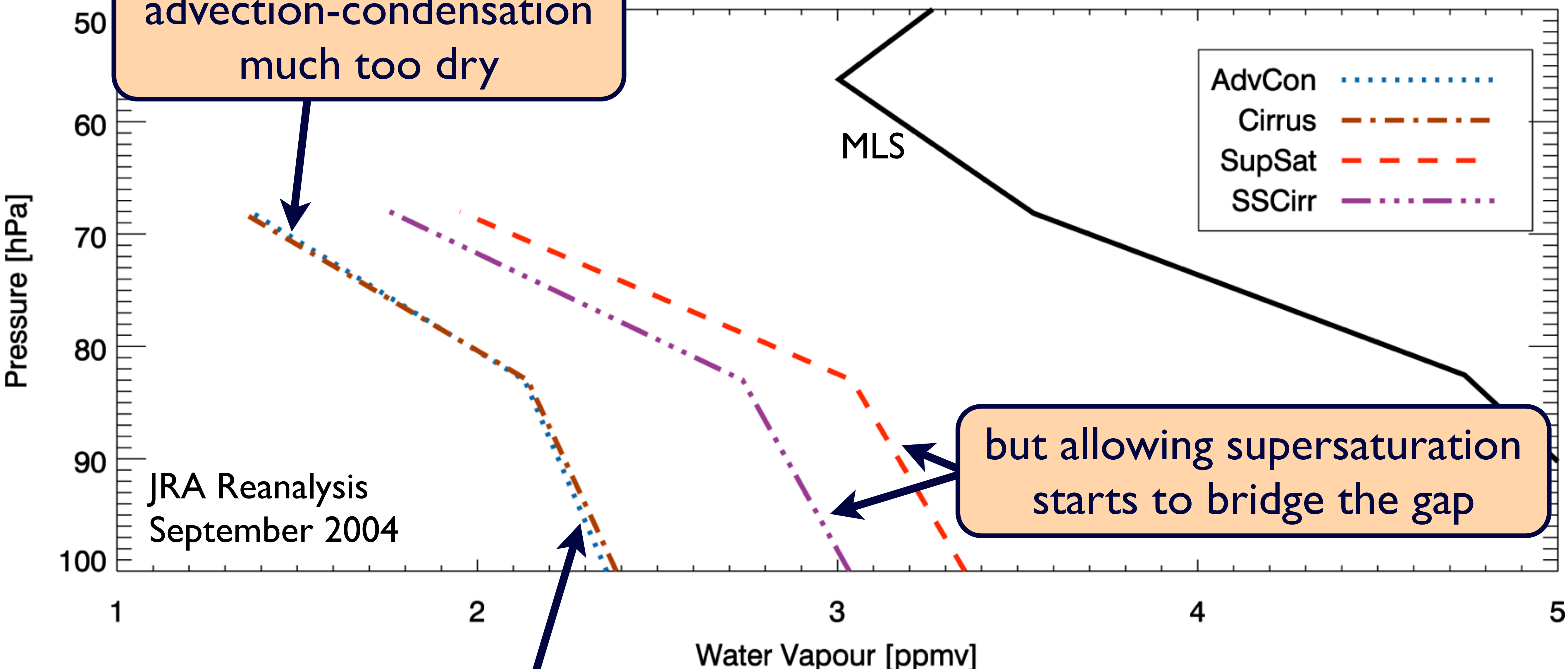


- Supersaturation
- Cloud formation
- Re-evaporation
- Fallout
- Anvil and in situ

Four simulations:



Early Results



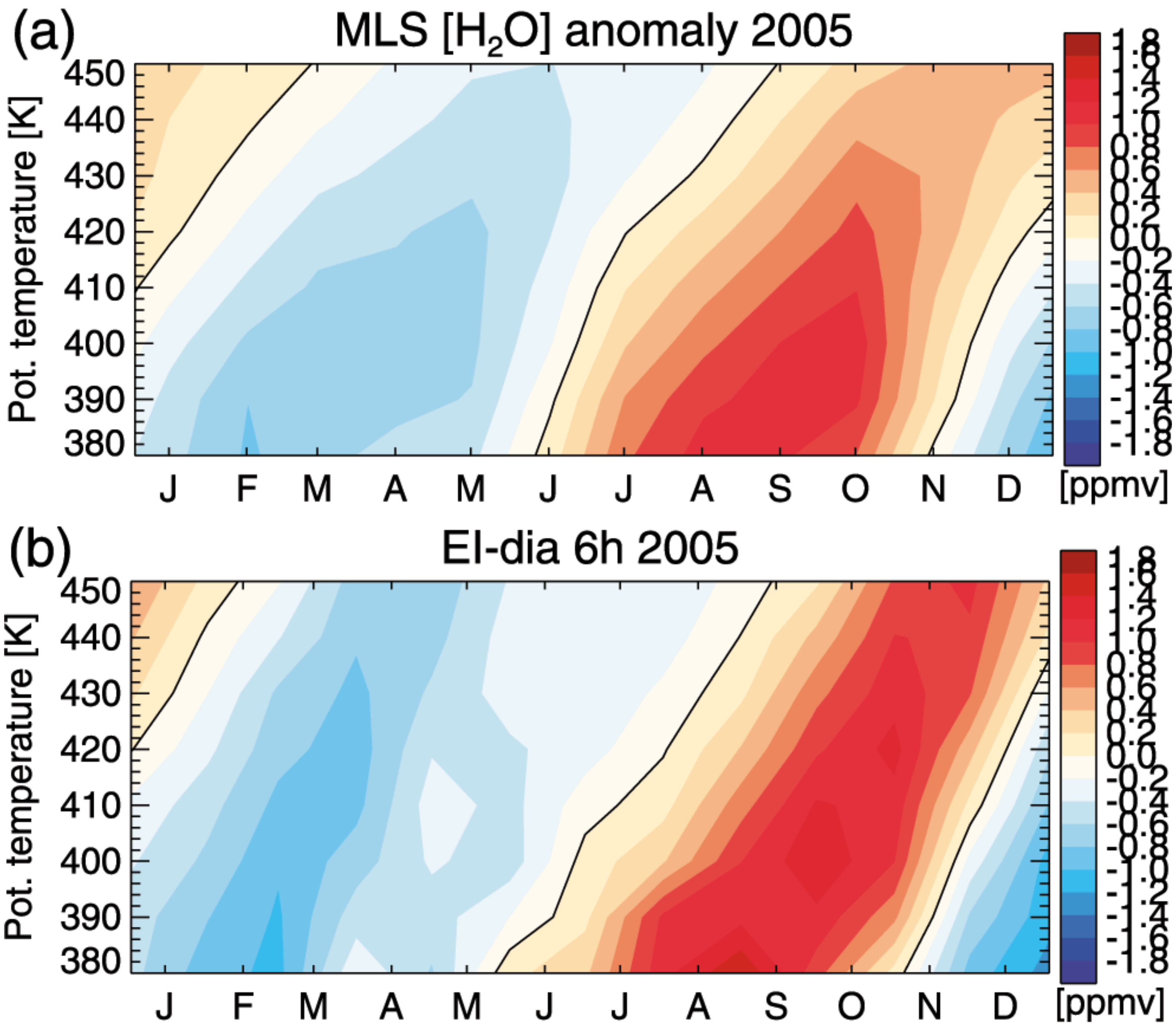
advection-condensation much too dry

but allowing supersaturation starts to bridge the gap

condensate re-evaporation appears to be unimportant

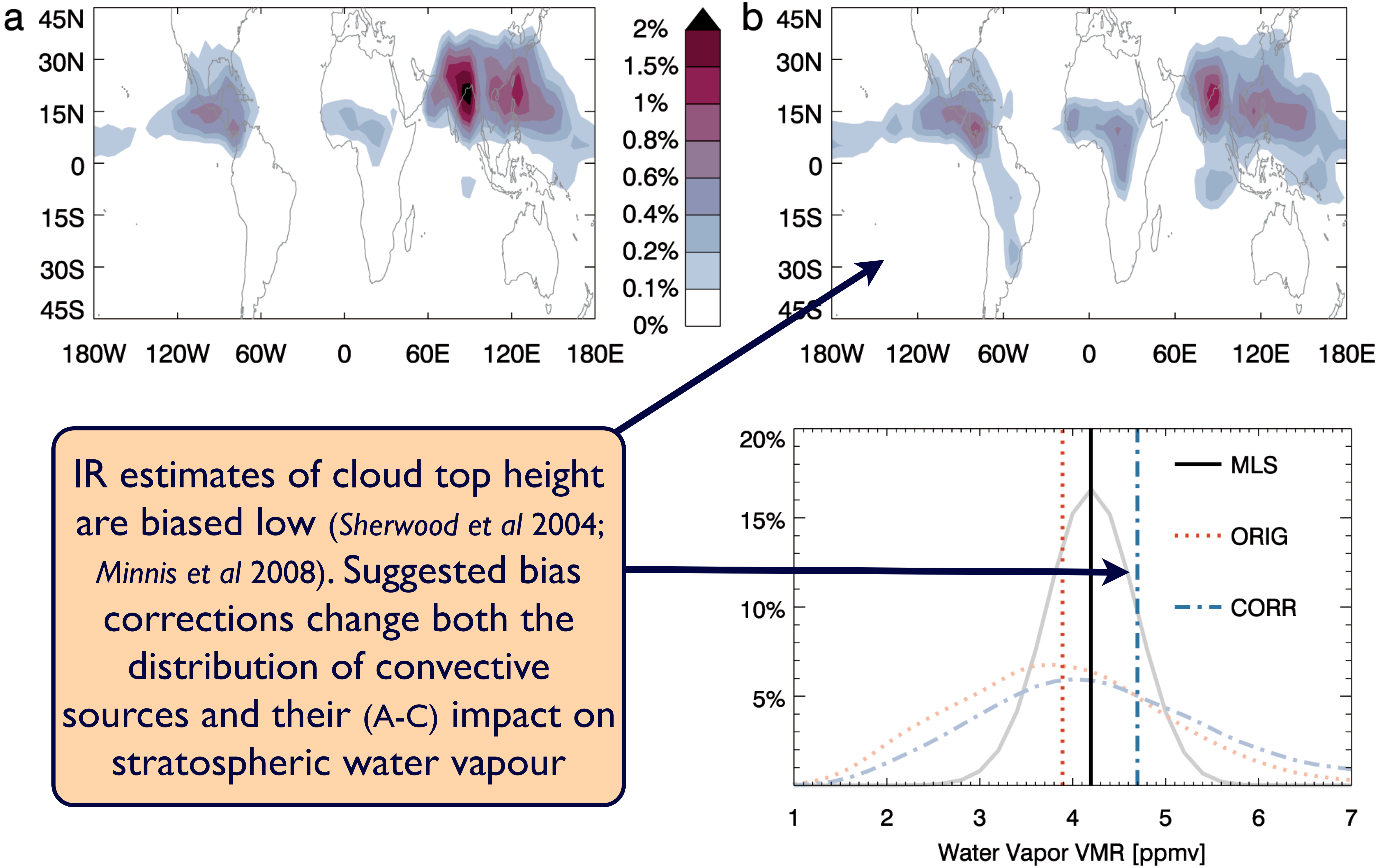
Goal: Tape Recorder

aim to simulate phase and amplitude



Liu et al., 2011

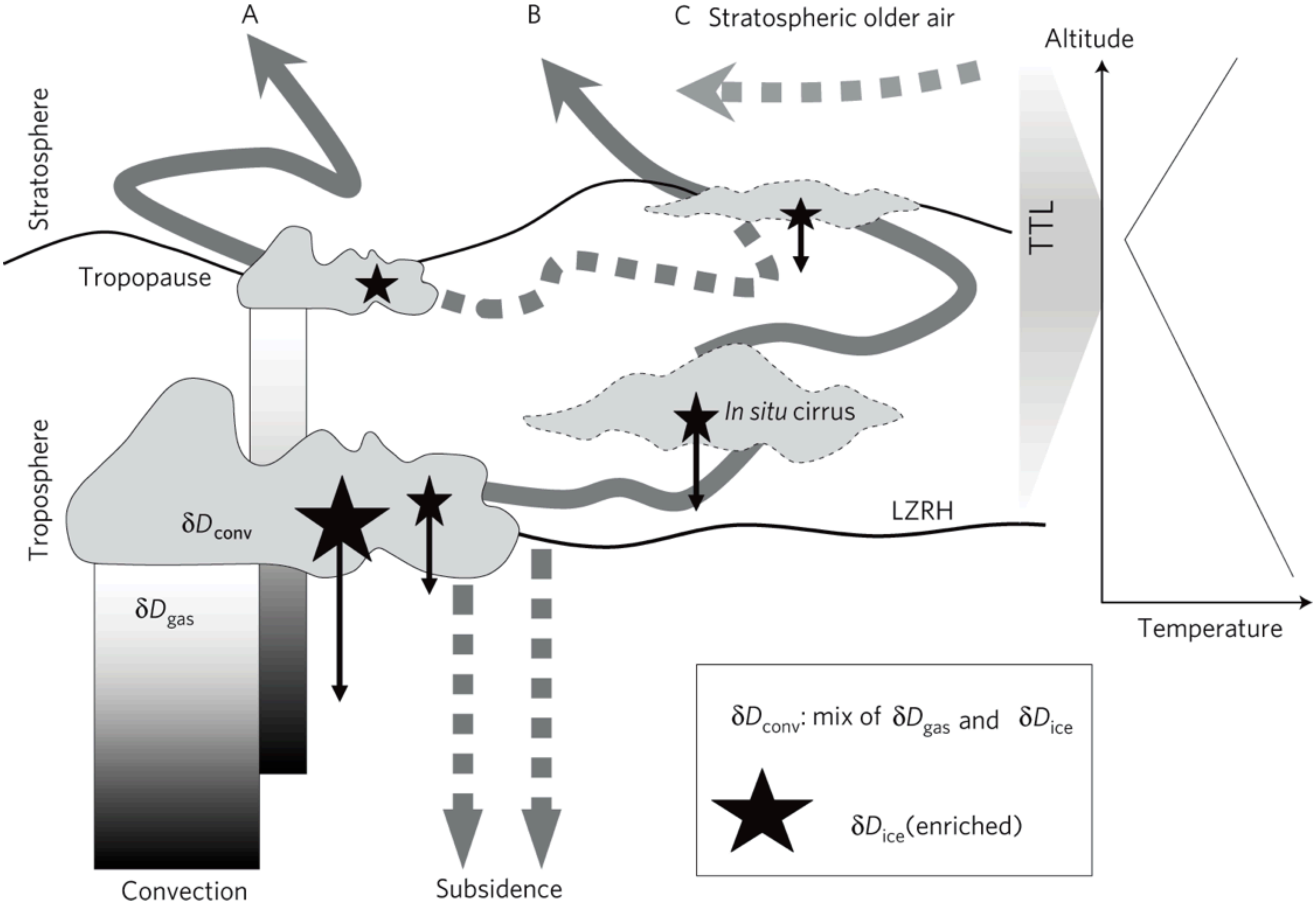
Importance of Direct Convective Injection



IR estimates of cloud top height are biased low (*Sherwood et al* 2004; *Minnis et al* 2008). Suggested bias corrections change both the distribution of convective sources and their (A-C) impact on stratospheric water vapour

Stable Water Isotopes

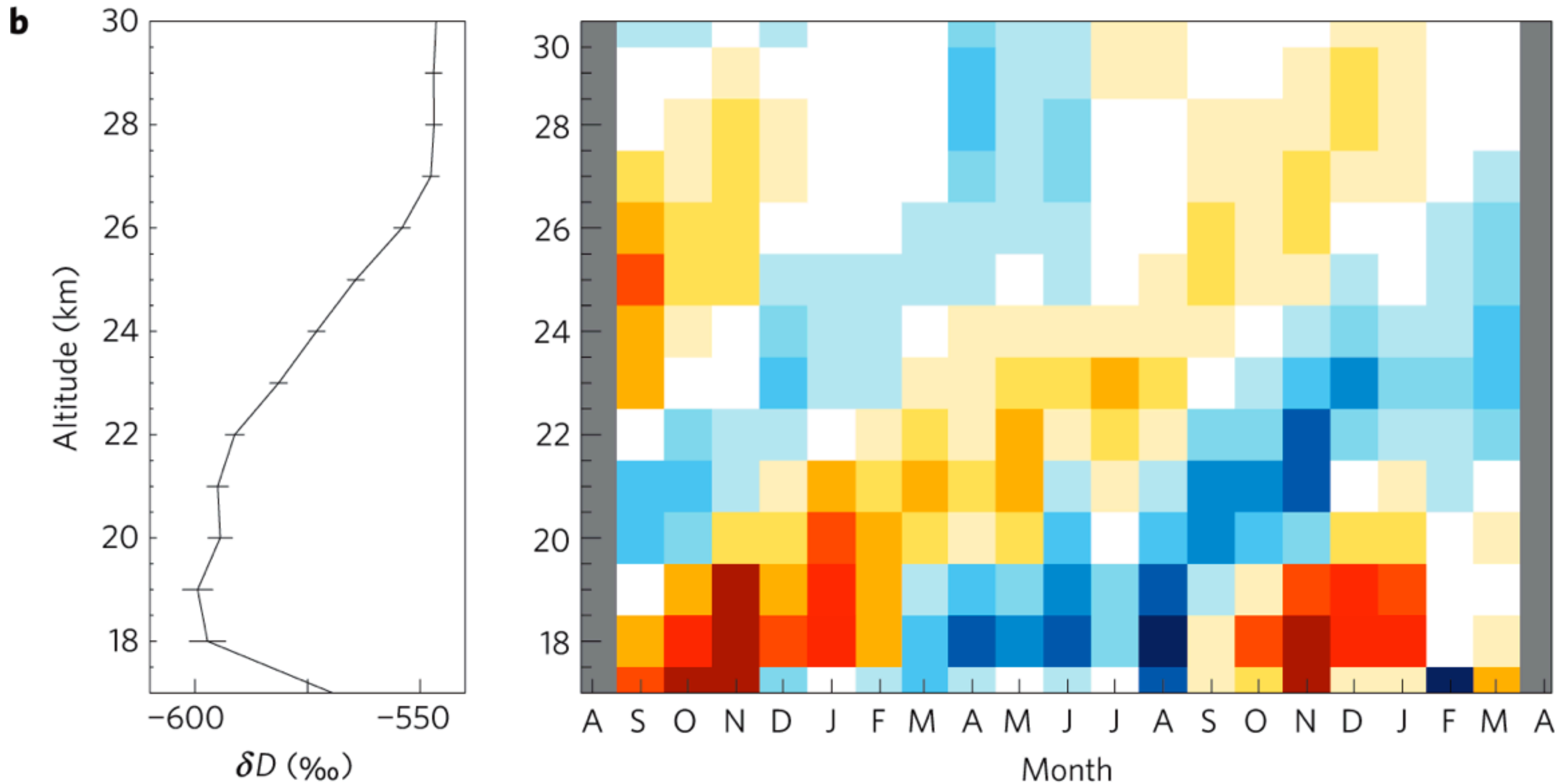
help to distinguish partitioning of pathways

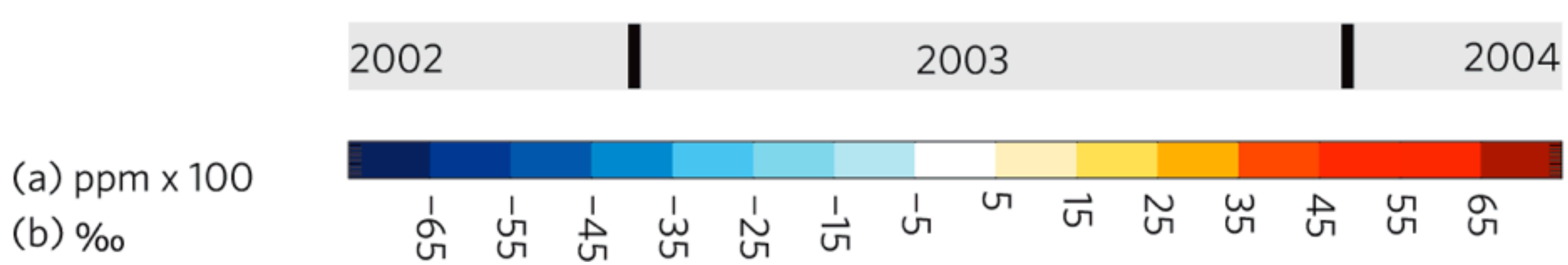


Steinwagner et al, 2010

Stable Water Isotopes

...and provide an additional constraint





Isotopologues included in cloud model

Steinwagner et al, 2010

Summary

- Considerable uncertainty remains regarding water vapour entry into the tropical lower stratosphere, and particularly the role of microphysical processes.

- Early results indicate that condensate evaporation plays a very minor role, and that accounting for supersaturation with respect to ice may be more important.

- The importance of these cirrus cloud processes relative to that of direct convective injection remains to be investigated.

- Stable water isotopologues provide a powerful additional constraint.

- This work has implications for the transport of other trace species that are sensitive to cloud microphysics, such as very short-lived halogenated compounds.