Diagnosis of Relative Humidity Changes in a Warmer Climate Using Tracers of Last Saturation

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with contributions from
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Water vapor is the most influential greenhouse gas, due to its abundance and radiative properties.
greenhouse gas emissions increase longwave absorption and warm the atmosphere
water vapor is temperature dependent and may feed back to warming - but how much?
Both models and observations suggest a WV feedback that is approximated by constant RH.

Climate Model

Cooling by Volcanic Aerosols

ENSO Variability

Dessler et al 2008
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Soden et al 2002

Cess 2005
Both models and observations suggest a WV feedback that is approximated by constant RH.

Cooling by Volcanic Aerosols

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Climate Model

ENSO Variability
But this does not mean that the RH distribution is constant!
RH decreases in the tropics and subtropics...

RH increases near the extratropical tropopause...

...in the lower stratosphere...

...and in the tropical deep convective zone

...with a stronger signal in the Southern Hemisphere
These signals are qualitatively robust among GCMs.
changes in the RH distribution have implications for global and regional climate changes...
... so what controls these changes?
atmospheric water vapor can be simulated using only large-scale circulation and temperature
The Advection-Condensation Philosophy: the humidity at any point is determined to leading order by its location of last saturation.

$$\text{RH}(x^*) = 100\%$$

$$q(x) = q^*(x^*)$$
The Advection-Condensation Philosophy:
the humidity at any point is determined to leading order by its location of last saturation

\[ \text{RH}(x^*) = 100\% \]

...but that’s only for a point - we need more information to reconstruct water vapor for a volume
we can treat water vapor in a volume as the linear combination of all locations of last saturation.
we can treat water vapor in a volume as the linear combination of all locations of last saturation

\[ q(x_0) = \sum_{i=0}^{N} F(x_i) q^*(x_i) \]

where

\[ \sum_{i=0}^{N} F(x_i) = 1 \]
so that RH in a given volume is controlled by...

...the circulation...

...non-local temperatures...

...and the local temperature

\[ RH(x_0) = \frac{\sum_{i=0}^{N} F(x_i)q^*(x_i)}{q^*(x_0)} \]
**Goal:** Investigate the relative influence each of these factors exerts on the RH response to warming in GCMs...
**Approach:** Apply a nested pair of global models

GCM to describe control and doubled CO$_2$ climates

Temperature and Circulation

Tracer transport model driven by GCM output for flexibility

Last saturation tracers to evaluate contributions of T and circulation
GISS ModelE

Modern Simulation (CTL)
* 2°x2.5° Horiz Resolution
* 20 Vertical Levels
* 1979 atmospheric CO₂
* 1975-1984 SSTs & sea ice
* 10 yr run - use last 5 yrs
* Save 6-hrly instantaneous meteorology

2xCO₂ Simulation (WRM)
* 2°x2.5° Horiz Resolution
* 20 Vertical Levels
* 2x 1979 atmospheric CO₂
* Q-flux mixed layer ocean
* Initial implied ocean heat transport from CTL
* Dynamic SSTs & sea ice
* Balanced at 20 yrs; use yrs 28-32
* Save 6-hrly instantaneous meteorology
The ModelE meteorology then gets fed into a global tracer transport model:

Model of Atmospheric Transport and Chemistry

* T42 horizontal resolution; 20 vertical levels
* Internal hydrologic cycle
* Prognostic clouds and parameterized deep and shallow convection (as in NCAR CCM3)
* Semi-Lagrangian tracer advection w/ mass fixer
* 112 zonally symmetric last saturation tracers
* Four runs: one each using CTL and WRM output; two mix & match T and circulation
* Analyze 5 years after 2 month spinup
Divide the atmosphere into $N$ zonally axisymmetric tracer domains.
Suppose a grid cell $\mathbf{x}$ within tracer domain $T_2$ is saturated...

...then we set $T_2(\mathbf{x})$ equal to 1, and all other tracers $T_i(\mathbf{x})|_{i \neq 2}$ equal to 0.
The tracers advect and mix... so that every grid cell ends up with a distribution of tracers... each of which represents a location where some local air was last saturated.
Tracer Formulation

We can then reconstruct the relative humidity:

$$RH(x) = \frac{\sum_{i=1}^{N} T_i(x) \langle q^*(T_i) \rangle}{q^*(x)}$$

where $T_i(x)$ is the local concentration of tracer $i$ and $\langle q^*(T_i) \rangle$ is the density weighted mean $q^*$ associated with tracer domain $i$.
tracer reconstruction agrees well with model RH

qualitative & quantitative agreement in zonal mean

point-to-point comparisons with $R^2 > 0.95$
The distribution of RH changes in the ModelE is consistent with the multimodel mean...
...as is the simulated change in MATCH
Distribution of changes is similar in ModelE and MATCH simulations, despite different representations of the hydrologic cycle...
The change in RH distribution is controlled by temperature and circulation, and is largely insensitive to hydrologic cycle parameterizations.
The tracer reconstruction also matches up well...
...the tracers capture the relevant physical processes in the troposphere
$T_2$ is the **local tracer** at point $x$.
All other tracers $\mathcal{T}_i$ are **nonlocal tracers** at point $\mathbf{x}$.
RH changes follow the local tracers
Enhanced local control of humidity near the extratropical tropopause
Reduced local control of humidity in the tropical UT and subtropics.
Two sets of upper tropospheric tracers
Zones of last saturation shift upward in the tropics
Zones of last saturation for the NH subtropics shift upward and poleward.
The shift is even stronger in the SH subtropics.
**Approach**: Apply a nested pair of global models

- **GCM** to describe control and doubled \( \text{CO}_2 \) climates
- **Temperature and Circulation**
- **Tracer transport model driven by GCM output for flexibility**
- Last saturation tracers to evaluate contributions of \( T \) and circulation
**Approach**: Perturbation MATCH simulations

- **GCM** to describe control climate
- **GCM** to describe $2\times\text{CO}_2$ climate

**Tracer transport model** driven by GCM output for flexibility

- Last saturation tracers to evaluate contributions of $T$ and circulation
- Circulation
- Temperature
Swapping T and circulation in input meteorology
Swapping T and circulation in input meteorology
Tropics and subtropics dominated by circulation changes

Extratropical tropopause layer dominated by temperature changes
Tracer Formulation

Reconstruction of relative humidity

\[ RH(x) = \sum_{i=1}^{N} \frac{T_i(x) \langle q^*(T_i) \rangle}{q^*(x)} \]

where \( T_i(x) \) is the local concentration of tracer \( i \) and \( \langle q^*(T_i) \rangle \) is the density weighted mean \( q^* \) associated with tracer domain \( i \)
Tracer Formulation

Reconstruction of relative humidity

\[
RH(x) = \sum_{i=1}^{N} T_i(x) \langle q^*(T_i) \rangle
\]

where \( T_i(x) \) is the local concentration of tracer \( i \) and \( \langle q^*(T_i) \rangle \) is the density weighted mean \( q^* \) associated with tracer domain \( i \)

Control

2xCO₂
Swapping $q^*$ and $T_i$ in the tracer reconstructions

Another way to separate temperature and circulation effects
Swapping $q^*$ and $T_i$ in the tracer reconstructions.
Reconstructed RH Difference (WRM Temperatures; CTL Tracers)

Circulation again appears to be more influential in the tropics & subtropics.

Reconstructed RH Difference (CTL Temperatures; WRM Tracers)

The distinction is not clean - temperature still contributes to the tracer distributions.
Extratropical tropopause layer warms, but not as much as the tropical zone of last saturation.
tropopause shifts upward

tropical tropopause cools

temperature gradient toward the poles

tropopause shifts upward
jets shift poleward

more in SH

Hadley cell expands and deepens
The jets shift poleward and the Hadley cell expands.

These shifts are more pronounced in the SH.
The tropopause shifts upward, and the Hadley cell deepens.
The extratropical tropopause layer warms, but less than its last saturation zones: increased local control.
Summary

• Relative humidity changes with a robust zonal mean pattern in simulations of a warmer climate

• This pattern is governed by both temperature changes and circulation shifts:
  • A poleward shift of the jets and a poleward expansion of the Hadley cell lead to a shift in 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 upper tropospheric RH
  • Local and remote temperature changes lead to RH increases near the extratropical tropopause

• Zones of last saturation shift upward and poleward throughout the tropics and subtropics

• Last saturation tracers provide a powerful tool for diagnosing the mechanisms behind RH shifts
The change in RH distribution is controlled by temperature and circulation, and is largely insensitive to hydrologic cycle parameterizations.
RH changes in MATCH are generally more pronounced than in the ModelE.
The GISS GCM has a lot of cloud ice.
more condensate evaporation at low RH, less at high RH: condensate evaporation may suppress RH sensitivity
RH changes follow the local tracers
The current tracer scheme is computationally intensive and unwieldy...

...can it be replaced by a binary tracer formulation without excessive information loss?