Horizontal variability of water and its relationship to cloud fraction near the tropical tropopause

Using aircraft observations of water vapor to improve the representation of grid-scale cloud formation in GEOS-5

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Talk topics

- The chronic water vapor problem in the GEOS-5
- Two possible source and a potential remedy for one
- Motivating science questions
- Overview of cloud processes in GEOS-5
- Methodology: estimating $\text{RH}_{\text{crit}}$ from aircraft data
- Initial results from TC4: DC-8 and WB-57
- Summary, long-term goals and future work
The chronic water vapor problem in the GEOS-5

GEOS-5 tropics are too wet at 300 hPa but too dry at 100 hPa

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GEOS-5 vs. MLS

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Two possible causes of the problem:

- **Convective scheme not lofting condensate high enough**
  - Evidence from ice water
  - Evidence from CO
  - Suggestions from TOA radiative balance (OLR, SW)
  - At high-res (7 km) with RAS turned way down, problem goes away!

- **Vertical distribution of condensation processes not properly captured**
  - Currently extrapolating AIRS results into UT where AIRS provides little information
  - Need more observations in upper troposphere
Motivating Science Questions

- What physical processes control the water budget in the upper troposphere and lower stratosphere?
- What is the relationship between thin, cold clouds and supersaturation?
- Given depletion of vapor by numerous small ice particles, are there really extended regions of supersaturation?
- What are the causes of the fine structure of water vapor and what are the implications for cloud formation?
- How will each of these respond to a warming atmosphere?
Large-scale cloud processes and sub-grid scales in GEOS-5

- Like many AGCMs, in GEOS-5 a simple, two-parameter “Top-hat” PDF distribution relates grid-scale $q$ and cloud fraction to subgrid-scale variations of $q$
- Vertical variation of top hat PDF width obtained with information from AIRS
- But AIRS provides no real information above 300 hPa, so current PDF falls back to a simple extrapolation
The PDF formalism

- $q_T$ - total specific humidity
- $q^*(T)$ - grid-box mean saturation specific humidity
- $P(q_T)$ - the distribution of $q_T$ within the grid box
- Cloud fraction ($C_f$)
  - the portion of a model grid box where $q_T > q^*(T)$
  - formally expressed as integral of $P(q)$ from $q^*$ to infinity
- PDFs such as the “Top Hat” are simplification of $P(q_T)$
  - Width of PDF is standard deviation of $q_T$ or $\sigma_T$
  - Define $RH_{crit} = 1 - \sigma_T / q^*(T)$

$RH_{crit}$ is the threshold for condensation in a grid box expressed in terms of the grid-scale quantities, i.e. condensation if $RH > RH_{crit}$
"Top-hat" PDF parameterization

PDF of Grid Box Total Water

\[ \text{RH}_{\text{crit}} = \frac{1 - \sigma_T}{q^*(T)} \]

Other distributions in the literature, but derived parameters from CRM:
- Triangular – need 3 parameters (asymmetry)
- Beta – need 4 parameters
Estimating $RH_{\text{crit}}$ with aircraft observations

1. Break aircraft flights into level-leg segments equal to model resolution (e.g. 100 km for $1^\circ \times 1^\circ$).
2. Estimate sub-grid scale variability in segment with sigma, the standard deviation of specific humidity $q$.
3. Estimate large-scale saturation specific humidity $q^*$ in segment.
4. Derive $RH_{\text{crit}} = 1 - \text{sigma}/q^*$. 

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Example of DC-8 transit, Dryden to Costa Rica

DLH WV mixing ratio and standard deviation (ST DEV) of water vapor and temperature for 200-km on the DC-8 transit, NASA Dryden to Costa Rica, 13 July, 2007. Also plotted are flight-leg pressure and the zonal wind.

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Top-hat PDF parameterization

Other distributions in the literature, but derived parameters from CRM:

- Triangular – need 3 parameters (asymmetry)
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Mean TC4 Specific Humidity and $q^*$

12 DC-8 flights and 6 WB-57 flights
Top-hat PDF parameterization

Other distributions in the literature, but derived parameters from CRM:

- Triangular – need 3 parameters (asymmetry)
- Beta – need 4 parameters

TC4 sub-grid scale variability of $q$

12 DC-8 flights and 6 WB-57 flights
**RH_{\text{crit}}** estimates from TC4

Spread of **RH_{\text{crit}}** at lower levels may suggest dependence on other factors, e.g. temperature.

Higher **RH_{\text{crit}}** near tropopause from aircraft data would inhibit formation of condensate and thus lead to moistening.

**RH_{\text{crit}}** estimates from TC4 Pacific Missions Meeting – 21 October 2014
Summary

- GEOS-5 has a chronic problem of excess moisture at 300 hPa and above in tropics but too little at trop.
- Improvement may come by informing PDF parameterization of condensation through estimates of RH$_{crit}$ profile with aircraft water vapor measurements.
- Have done this for a single tropical airborne mission (TC4).
- Encouraging results:
  - Higher RH$_{crit}$ than AIRS-based estimate near the tropopause (above 200 hPa) should lead to moistening.
  - Below 200 hPa seeing spread of estimates, suggesting different large-scale condensation regimes.
Long-term goals

- Reduction of tropical UT wet bias of GEOS-5
- Improved TOA radiative balance
- Improve moisture at tropical tropopause
- With new microphysical scheme, achieve better understanding of water vapor budget & microphysical processes in tropical UT/LS
- Improved model fields for better interpretation of airborne measurements
Carrying on...

- ATTREX/CONTRAST/CAST provide an extraordinarily rich database of water vapor measurements, particularly in the “gap” between the DC-8 and high-altitude platforms
- Other missions, other environments & seasons: CR-AVE, MACPEX, SEAC4RS, HIPPO
- Analysis of remote sensing data for sub-grid variability
  - CPL data
  - CALIPSO overpasses of opportunity
- Develop state-dependent PDF parameterization for large-scale models (probably not a simple top-hat)