Comparison of atmospheric hydrology over convective continental regions using isotope measurements from space
Outline

• Overview
• Motivation
• Isotope review
• Instrument / Methods
• Recent research
• Analysis
• Conclusions
• Next steps
The hydrologic regimes of convective continental regions are complex and difficult to represent in GCMs.

The fate of precipitation (re-evaporation, transpiration, or runoff) is considerably different across many models.

Isotopes offer a unique view into these processes via fractionations occurring during evaporation and condensation, and via non-fractionating transpiration events.

The isotopic composition of airborne water vapor has historically been modeled using precipitation as a constraint.
Motivation and science questions

Isotopes provide a unique way of looking at the hydrologic cycle since different processes lead to different isotope signals.

• Which local processes change isotopic ratios over different continental regions?

• What is the contribution from upstream sources?

• How well does Rayleigh distillation predict isotopic change?

• Can the isotopes be used as a fingerprint of the seasonal hydrology?
Isotope Review

\[ \frac{[\text{HDO}]}{[\text{H}_2\text{O}]} \text{ observed} \text{ is compared to mean ratio in ocean water, and expressed as} \]

\[ \delta D \text{(permil)} = \left( \frac{[\text{HDO}]/[\text{H}_2\text{O}]_{\text{obs.}}}{[\text{HDO}]/[\text{H}_2\text{O}]_{\text{ocean}}} - 1 \right) \times 1000 \]

\[ [\text{HDO}]/[\text{H}_2\text{O}]_{\text{ocean}} = 311.52 \times 10^{-6} \]

<table>
<thead>
<tr>
<th>Condensation</th>
<th>Evaporation</th>
<th>Transpiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor becomes depleted as heavy isotopes “prefer” condensed state</td>
<td>Lighter isotopes preferentially evaporate from open water (unless complete)</td>
<td>No net fractionation from soil water to vapor</td>
</tr>
</tbody>
</table>
Rayleigh Theory

Rayleigh distillation

\[ R = R_o F^{\alpha-1} \]

\[ \delta D = (\delta D_o + 1)F^{(\alpha-1)} - 1 \]

where \( R = \text{[HDO]/[H}_2\text{O]} \), \( F = \) fraction of initial moisture content remaining in air parcel, and \( \alpha = \) effective fractionation factor (temp. dependent)

Delta form. \( \delta D_o \sim -70\) permil above ocean water

Dansgaard’s effects

**Latitude effect** – Moisture moving poleward encounters colder temperatures, which causes condensation and therefore isotopic depletion

**Altitude effect** – Rising moisture cools and condenses, causing isotopic depletion at altitude

**Distance-from-coast effect** – As moist air parcels move inland and away from their primary moisture source (the ocean), isotopic depletion occurs via condensation.
The Amount Effect

Isotopic depletion correlate with high rainfall totals in monsoonal locations Seen in Andean and Himalayan ice cores, and several GNIP studies (e.g. Vuille (2005) and Matsuyama (2005))

Dansgaard (1964) and Rozanski (1993)

• High fractional removal of heavy isotopes during intense condensation, and subsequent rainout

• Evaporation of rain drops below cloud base \[ f (\text{RH, drop size}) \]

• Continuous isotopic exchange over time between falling rain drops and water vapor

For water vapor, is it simply that heavy isotopes condense and rainout, or something more?
Tropospheric Emission Spectrometer
- Fourier transform spectrometer
- Thermal infra-red (650 – 3050 cm⁻¹)
- Individual lines resolved (0.06 cm⁻¹)
- Primary mission O₃, CO, CH₄
- Joint retrieval algorithm allows partial cancellation of errors common to both HDO and H₂O

~6 x 8 km “footprint”
~200 km sampling (w/ special obs)
~ 1 d.o.f. in vertical for HDO/H₂O

Worden, Bowman, Noone, et al. (2006)
Recent research


- Anomalously high $\delta D$ values in air over tropical continents (evapotranspiration?)
- Anomalously low $\delta D$ values in moist, tropical air (amount effect?)
- Attributed low $\delta D$ values to evaporation of rainfall beneath cloud base
TES data

• TES data used comes from 249 dates (orbits) from August 2004 → December 2006

• Each orbit produces 400-3000 profiles of quality HDO/H₂O data

• TES HDO/H₂O retrievals are more successful over open ocean and in the tropics

• Inversions and highly reflective surfaces (snow, deserts, sea ice) cause trouble

• Signal to noise ratio needs to be high
**Temperature:**
Zonally symmetrical

**H2O:** Highest over known convective regions (Pacific Warm Pool, Amazon)

**dD:** Latitude effect. Tropical balance between convection and condensation
**Temperature:**
Some zonal asymmetry from on land/sea contrasts, conv. zones.

**H₂O:** Highest over continents, with downstream advection

**dD:** Sensitive to land surfaces

Monsoon locations show different signals
Local Effects

• Wet seasons for all 3 regions show dD decreases with increasing RH and precipitation rate (condensation effects)

• Most regions show dD increases with increased vertical mixing (convective effects)

• Asian Monsoon and Australia regions show signs of subsidence (lowest dD with warm, dry, and stable conditions)

• Local advection component indicates depleted source for wet A. Monsoon and N. Aust. Regions (upstream condensation?)

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>T, δD</th>
<th>RH, δD</th>
<th>P, δD</th>
<th>Γ, δD</th>
<th>Vq, δD</th>
<th>Multi-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>DJF (wet)</td>
<td>0.02</td>
<td>-0.39</td>
<td>-0.21</td>
<td>-0.15</td>
<td>0.10</td>
<td>0.55</td>
</tr>
<tr>
<td>N. Australia</td>
<td>DJF (wet)</td>
<td>-0.10</td>
<td>-0.34</td>
<td>-0.27</td>
<td>-0.32</td>
<td>-0.26</td>
<td>0.51</td>
</tr>
<tr>
<td>Asian Monsoon</td>
<td>JJA (wet)</td>
<td>-0.03</td>
<td>-0.32</td>
<td>-0.16</td>
<td>-0.06</td>
<td>-0.16</td>
<td>0.37</td>
</tr>
<tr>
<td>Amazon</td>
<td>JJA (dry)</td>
<td>0.07</td>
<td>-0.13</td>
<td>-0.02</td>
<td>-0.24</td>
<td>-0.04</td>
<td>0.29</td>
</tr>
<tr>
<td>N. Australia</td>
<td>JJA (dry)</td>
<td>-0.12</td>
<td>0.16</td>
<td>0.00</td>
<td>-0.28</td>
<td>0.02</td>
<td>0.32</td>
</tr>
<tr>
<td>Asian Monsoon</td>
<td>DJF (dry)</td>
<td>-0.35</td>
<td>0.28</td>
<td>-0.08</td>
<td>-0.21</td>
<td>0.27</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Not only does one need to consider the local controls

but also the history of processes acting during transport from some source location, and the distribution of isotopic composition of vapor at the source.
**Trajectory Model**

3D using NCEP data interpolated in time and space (20 minute time steps) over 5 days.

Running the highest and lowest dD values aids in deciphering changes enroute.

The histories of the air parcels aid in distinguishing upstream isotope effects those occurring locally.
Seasonal Histograms

Amazon and Asian Monsoon regions show wet season depletion and dry season enrichment.

Australia shows wet and dry season enrichment.

**Rayleigh prediction** for Amazon and Asian Monsoon wet season depletion.

Amazon 37/32

Asian Monsoon 48/29
Amazon region parcel histories

DJF (wet)

JJA (dry)
N. Australian region parcel histories

DJF (wet)

JJA (dry)
Asian Monsoon region parcel histories

DJF (dry)

JJA (wet)
### Upper and Lower Quartiles

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>lowest 25%</th>
<th>highest 25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>wet</td>
<td>-79</td>
<td>+12</td>
</tr>
<tr>
<td>Australia</td>
<td>wet</td>
<td>-30</td>
<td>+79</td>
</tr>
<tr>
<td>Asian M.</td>
<td>wet</td>
<td>-89</td>
<td>+1</td>
</tr>
<tr>
<td>Amazon</td>
<td>dry</td>
<td>-15</td>
<td>+73</td>
</tr>
<tr>
<td>Australia</td>
<td>dry</td>
<td>0</td>
<td>+77</td>
</tr>
<tr>
<td>Asian M.</td>
<td>dry</td>
<td>+4</td>
<td>+87</td>
</tr>
</tbody>
</table>

- Twice the depletion of Rayleigh model
- Similar depletion to Rayleigh model
- No net change \( \rightarrow \) subsidence
- Significant enrichment primarily through advection
- Significant enrichment primarily through convection
Regional Conclusions

**Wet season**

*Amazon*: Generally strong condensation, both upstream and locally. Local convection mixes in significant amount of boundary layer water (transpiration?).

*Australia*: Hydrology is a mix of upstream, condensing parcels combined with local injection of water through convection.

*Asian Monsoon*: Strong upstream condensation. Large amount effect, indicating that the microphysics of rainout are important

**Dry season**

*Amazon*: Significant condensation and very active convection drive the hydrologic cycle.

*Australia*: Largely subsident conditions, vertical mixing, and quenching through advection.

*Asian Monsoon*: Largely subsident conditions, light vertical mixing, and quenching through advection.
Next steps

1) A global Lagrangian approach with the satellite data

2) Use isotopes and GNIP to find contribution of evapotranspiration to Amazonian water cycle. How will deforestation disrupt the hydrology, and what will the $\delta^D$ values be when it does?

3) Use knowledge gained from research to add constraints to isotope-enabled GCMs
Acknowledgments

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