New insights into the hydrological cycle from IASI δD distributions across the globe

Lacour Jean-Lionel - LATMOS
Risi Camille - LMD
Flamant Cyrille - LATMOS
Coheur Pierre-François - ULB
Clerbaux Cathy - LATMOS/ULB

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Water isotopologues

- Water isotopologues — \( H_2^{16}O, HDO, H_2^{18}O \) — have different vapour pressures
- \( H_2^{16}O \) preferentially evaporates
- HDO preferentially condenses
- Every phase change is recorded in the isotopic ratio \( \delta D \)

\[
\delta D = 1000 \times \left( \frac{HDO}{H_2^{16}O} \right)_{SMOW} - 1
\]

*Standard Mean Oceanic Water*

The isotopic ratio tells us:
- about the degree of rainout of an airmass from its origin above the ocean
- about different sources of water vapour (oceanic/continental)
- about the different processes affecting the airmasses

Constraints on the hydrological cycle uncertainties
\[ \delta D = 1000 \times \left( \frac{HDO}{H_2^{16}O} \right)_{SMOW} - 1 \]

- \( \delta D = 0 \text{‰} \) in the ocean
- \( \sim -80 \text{‰} \) above the ocean
- \( \sim -500 \text{‰} \) at the tropopause

Introduction
Remote sensing of δD – The challenge

- Variability of water vapour is large!
- Small variations of the isotopic ratio!

We need a methodology that is **sensitive** over the wide dynamical range of water variations and **precise** to capture isotopic variations.

- Depending on the altitude range, a precision between 10 and 50 ‰ is needed
- 10 ‰ ~ a variation of 1 % of H₂O
OEM with a constraint on log(HDO/H2O)

[Worden et al., 2006; Schneider et al., 2006]

- Short spectral range 1195-1253 cm⁻¹
- Full inversion on the 10 first layers of the atmosphere
- Temperature profiles from EUMETSAT L2
- Cloud flag < 10%

$\delta$D profiles with 1-2 DOFS

$\rightarrow$ Vertical sensitivity is limited (generally in the free troposphere)

Error of 38 permil for an individual measurement

[Lacour et al., 2012]
Cross validation

- Cross-validated against TES and ground-based FTIRs (MUSICA) [Lacour et al., 2015 AMT]
- Cross validation of H2O, δD but also of the relationship H2O- δD

- With a better spectral resolution (0.1cm⁻¹) TES can provides estimates of δD in the boundary layer
- IASI Sensitivity to δD decreases for high water vapour contents
Interpretation of δD et H2O observations
- Simple models [Noone et al., 2012]
Interpretation of δD et H2O observations
-> Simple models [Noone et al., 2012]
Interpretation of $\delta D$ and H2O observations

$\rightarrow$ Simple models [Noone et al., 2012]
Applications of IASI δD retrievals

Interpretation of δD et H2O observations

-> Simple models [Noone et al., 2012]

Re-evaporation of rain drops
North Atlantic – Influence of the Sahara

Temporal variations at Izana – North Atlantic

Added value of IASI 6D observations
Dynamical state of the atmosphere

\[ \delta D \text{ seasonal cycle is controlled by:} \]
- Change in water sources
- Transport pathways
- Turbulent mixing
- Dynamical state of the atmosphere
- Intensity of the Saharan Heat Low

Corresponds to a deep turbulent boundary layer (up to 6 km)
South Pacific: influence of low clouds

- Low clouds enrich the free troposphere
- Clear signature of the free tropospheric moistening by low clouds
- Climate sensitive areas where a small change in water vapour has an exponential impact on radiative budget
In convective areas, $\delta D$ is sometimes enriched, sometimes depleted. What could explain this different behaviours? Intensity of convection? Depth of convection?
Tropics: isotopic signature of convection’s depth

- $D_{rl} =$ Deviation from what would be predicted by a Rayleigh model
- $r(\log(H_2O) - \delta D) =$ gives indication on the processes -> $r<0 =$ amount effect

For a given source:
- $D_{rl} = 0 =$ advection
- $D_{rl} > 0 =$ enriching mechanisms
- $D_{rl} < 0 =$ depleting mechanisms

TRMM heating profiles
Tropics: isotopic signature of convection’s depth

- For any given convection intensity, the depth of convection is determinant in the isotopic composition of water vapour
  - Water vapour is more enriched when associated with shallow heating/convection
  - Water vapour is more depleted when associated with deep heating/convection

- Amount effect is more frequent in deep convective environment

Convection’s depth gives to water vapour a particular isotopic signature
Climate implication:

- In GCM, shallow convection versus deep convection = result of multiple parametrizations specific to each model
- With consequences on:
  - Water vapour,
  - Chemical and aerosol transport,
  - Cloudiness (Cloud feedback)
  - Latent heating profiles – large scale circulation

- Sherwood et al., [2014] traced the uncertainty on climate sensitivity to the different ratios of deep and shallow convection in models

IASI δD observations could serve to evaluate the representation of shallow vs deep convection in climate models
Distributions of $\delta D$ at IASI resolution show well marked isotopic effects

Many processes can be analysed under « the isotopic eye »

Much more information in $\delta D$ (record) than in $H_2O$
(Evapotranspiration, convection, air mass mixing, transport,...)

→ Powerfull tool to evaluate GCMs (about 10 isotope-enabled GCMs)
→ For weather forecasting?

By assimilating $\delta D$ observations [Yoshimura et al., 2014] showed that the assimilation of such observations constrain dynamic fields. The degree of improvement is proportional to the number of inputted data points.

Climate (past and future) applications

Retrieval of $\delta D$ in the tropics (one orbit) is now operationnal
With an improved retrieval scheme
Recent progress in remote sensing of $\delta D$

- 2004: Zakharov et al., *GRL* IMG/ADEOS
- 2006: Worden et al., *Nature* TES/AURA
- 2009: Frankenberg et al., *Sciences*, SCIAMACHY/ENVISAT
- 2012: Lacour et al., *ACP* IASI/MetOp
- 2011: Schneider et al., *ACP* IASI/MetOp
- 2009: Herbin et al., *ACP* IASI/MetOp
- 2013: Frankenberg et al., *AMT* GOSAT/SWIR
- 2013: Boesch et al., *AMT* GOSAT/SWIR
- 2016: Scheepmaker et al., *AMT* TROPOMI
δD seasonal cycle is controlled by:
- Change in water sources
- Transport
- Turbulent mixing
- Dynamical state of the atmosphere
- Intensity of the Saharan Heat Low
• Isotopic composition of water vapour is sensitive to many processes: convection/transport/evapotranspiration/mixing ...
• The capacity of a model to restitute $\delta D$ reflects its ability to represent all these processes

• Model evaluation against water vapour observations can be limited as
  • Different processes can have the same impact on H2O
  • Compensating effects in the models

$\delta D$ to evaluate global climate models
Yoshimura et al., 2015:

- First assimilation experiment of δD observations (TES, SCIAMACHY, GNIP, in situ)
- Positive score on T, P, wind fields

"From OSSE, IASI’s impact is much larger than those of TES, SCIAMACHY, and GNIP-vapor for not only δD, but also environmental variables (temperature, wind speed, pressure, etc.)"
$\delta^{18}O(\%o)$ in atmospheric column

Air Temperature (K) at bottom

Zonal Wind (m/s) at bottom

Surface Pressure (Pa)
Tropics: isotopic signature of convection’s depth

- The mechanism responsible of the amount effect in precipitation has long been debated
- 3 mechanisms are commonly used to explain the depletion of the precipitations:
  - In the water vapour:
    - Amount effect is more frequent in deep convective environment
    - The anti-correlated pairs corresponds to very humid free troposphere
    - The rain re-evaporation more efficient when RH increases

→ In the vapour, the amount effect is found associated with deep convective environment with high RH → rain re-evaporation mechanism
• MJO = principal mode of intra seasonal variability (30-60 days)
• Influence on global water cycle
• Persistent difficulties to simulate the water cycle in this region

H₂O

Source = rain drops re-evaporation, water vapor is depleted

δD

Source = enriched water vapor from the boundary layer.

Tuinenburg et al., JGR 2015