The added value of water isotopic measurements for process-oriented evaluation of atmospheric and land surface hydrological processes in climate models

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Seminar at Tsinghua University, April 24, 2013
Inter-model spread in hydrological projections

- CO2 increase
- Temperature increase
- Climate feedbacks
Inter-model spread in hydrological projections

Key uncertainties in climate models:
- clouds
- atmospheric convection
- boundary layer

Climate feedbacks

CO2 increase → temperature increase
Inter-model spread in hydrological projections

**Key uncertainties in climate models:**
- boundary layer
- atmospheric convection
- clouds
- atmospheric general circulation models

**CO2 increase** → **temperature increase** → **regional precipitation changes**

precipitation change by 2100 (%)<2/3 agree on sign

*IPCC AR4*
Inter-model spread in hydrological projections

precipitation change by 2100 (%)  
$\square <2/3$ agree on sign

evapo–transpiration change by 2100 (mm/d)  
$\times <70\%$ agree on sign

Key uncertainties in climate models:
- clouds
- atmospheric convection
- boundary layer

atmospheric general circulation models

Introduction
Inter-model spread in hydrological projections

Key uncertainties in climate models:
- clouds
- atmospheric convection
- boundary layer

atmospheric general circulation models
- sensitivity of surface fluxes to soil moisture
- soil/groundwater storage
- spatial heterogeneities

land surface models

CO2 increase → temperature increase → regional precipitation changes → land surface hydrological changes → land use change

climate feedbacks

land–atmosphere feedbacks

precipitation change by 2100 (%)
□ <2/3 agree on sign

evapo–transpiration change by 2100 (mm/d)
× <70% agree on sign

Introduction 2/27
Water isotopic composition

- $H_2^{16}O$, $HDO$, $H_2^{18}O$, $H_2^{17}O$, fractionation
Water isotopic composition

- $H_2^{16}O$, $HDO$, $H_2^{18}O$, $H_2^{17}O$, fractionation
- records phase changes
Water isotopic composition

- $H_{2}^{16}O$, HDO, $H_{2}^{18}O$, $H_{2}^{17}O$, fractionation
- records phase changes

![Diagram showing the cycle of water isotopes involving evaporation, continental recycling, condensation, and precipitation.]

- Present-day climate variables
- Meteorological variables
- Isotopic variables
- Physical processes
- Future climate
Water isotopic composition

- $H_2^{16}O$, HDO, $H_2^{18}O$, $H_2^{17}O$, fractionation
- records phase changes

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Evaporation

Continental recycling

Condensation

Convection

Precipitation

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$H_2^{16}O$

$HDO$

Present-day climate

Meteorological variables

Isotopic variables

Physical processes

Future climate

Evaluate processes "isotopic test"

Evaluate credibility
Water isotopic composition

- $H_2^{16}O$, $HDO$, $H_2^{18}O$, $H_2^{17}O$, fractionation
- records phase changes

Present-day climate

Meteorological variables

Isotopic variables

Physical processes

Evaluate processes "isotopic test" "paleo-test"

Future climate

Evaluate credibility

Past climates

Isotopic proxies

Introduction
Overview of my activities

1. evaluation of atmospheric processes
   ▶ processes controlling humidity
   ▶ atmospheric deep convection
Overview of my activities

1. evaluation of atmospheric processes
   - processes controlling humidity
   - atmospheric deep convection

2. evaluation of land surface processes
   - partitionning of water fluxes at land surface
   - land-atmosphere feedbacks, continental recycling
Overview of my activities

1. evaluation of atmospheric processes
   - processes controlling humidity
   - atmospheric deep convection

2. evaluation of land surface processes
   - partitionning of water fluxes at land surface
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3. evaluation of tropical precipitation changes
   - what do tropical water isotopic proxies record
   - link between past and future behavior (CMIP5)
LMDZ and ORCHIDEE models

- components of IPSL climate model

- isotope-enabled (Risi et al. 2010a) + water tagging
- nudging capability $\rightarrow$ realistic dynamical context
- zoom capability down to 30km

- isotope-enabled + water tagging
Available measurements

- GNIP
- in-situ measurements
  - GNIP-vapor, various campaigns
  - aircraft
  - ship
  - water vapor
  - precip

15km
Available measurements

Introduction
Available measurements

Introduction 6/27
Available measurements

- Remote-sensing of water vapor
  - Ground-based: NDACC, TCCON, IAS, SCIAMACHY, GOSAT
  - Satellite: IASI, TES
- In-situ measurements
  - GNIP–vapor, various campaigns
  - GNIP
  - GNIR
  - MIBA
  - satellite remote-sensing of water vapor
  - ground-based remote-sensing of water vapor

Introduction
Available measurements

- ODIN
- ACE MIPAS
- IASI
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- satellite remote-sensing of water vapor
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- aircraft
- water vapor
- ship
- precip
- leaves
- stems
- soil water
- rivers
- in-situ measurements

- for remote-sensing: focus on spatio-temporal variations
- account for sampling and instrument sensitivity
Evaluation of LMDZ water vapor and precip

TES data

\[ \delta D_{vapor} \ (\%) \ 800\text{hPa (anomaly relatively to the tropical average)} \]

GNIP data

LMDZ

\[ \delta^{18}O_{precip} \ (\%) \]

Introduction
Evaluation of ORCHIDEE land surface isotopes

- Le Bray (France, Wingate et al 2009)

![Graph showing isotopic data for Le Bray, France, 2007]

<table>
<thead>
<tr>
<th>Observed isotopic forcing</th>
<th>Soil water (surface)</th>
<th>Stem water</th>
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<tbody>
<tr>
<td>vapor</td>
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Evaluation of ORCHIDEE land surface isotopes

- Le Bray (France, Wingate et al 2009)

Le Bray, France, 2007

Observed isotopic forcing

- vapor
- precipitation

Soil water (surface) data

Stem water data

$\delta^{18}O$ (‰)

time (month)

depth (cm)

$\delta^{18}O$ (%)
Evaluation of ORCHIDEE land surface isotopes

- Le Bray (France, Wingate et al 2009)

\[
\delta^{18}O \text{ (permil)} = \frac{\text{isotope}}{\text{water}} \times 10^3
\]

### Observed isotopic forcing
- vapor
- precipitation

### Soil water (surface)
- data
- ORCHIDEE

### Stem water
- data
- ORCHIDEE

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**Le Bray, France, 2007**

- Time (month)
- Depth (cm)

**Soil profiles, August**

- \(\delta^{18}O\) (permil)
Evaluation of LMDZ-ORCHIDEE precipitation and rivers

**Introduction**

**GNIR and GNIP data**

**LMDZ-ORCHIDEE-iso**

$$\delta^{18}O_{river} - \delta^{18}O_{precip} (\%o)$$
I) Using water vapor measurements to evaluate atmospheric processes

- what controls the water vapor composition
- 3 examples
Atmospheric processes controlling isotopic composition

- observational studies (Risi et al 2008b), in particular at intra-event time scales (Risi et al 2010c, Tremoy et al 2012)
- modeling studies (Risi et al 2008, 2010b, 2012b)
q-δD complementarity

100hPa

convective detrainment
compensating subsidence

large-scale ascent
vertical diffusion

unsaturated downdrafts

Rayleigh mixing

δD (‰)

0  2  4  6  8  10  12

q (g/kg)

100hPa  800hPa
1) Processes controlling subtropical humidity

- condensate detrainement
- dehydration in clouds
- large-scale circulation
- lateral and vertical mixing
- boundary layer mixing
- rain evaporation

Observers:
- Wright et al. 2009
- Sherwood et al. 1996
- Pierrehumbert 1998
- Couhert et al. 2010
- Folkins and Martin 2005
1) Processes controlling subtropical humidity

LMDZ–iso (Risi et al 2010a):
- control: AR4 version (19 levels)

- condensate detrainment
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- rain evaporation
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AIRS data

relative humidity (%)
1) Processes controlling subtropical humidity

LMDZ–iso (Risi et al 2010a):
- control: AR4 version (19 levels)

3 reasons for a moist bias

- condensate detrainement (Wright et al 2009)
- dehydration in clouds (Sherwood et al 1996)
- large-scale circulation (Pierrehumbert 1998)
- lateral and vertical mixing (Couhert et al 2010)
- rain evaporation (Folkins and Martin 2005)

AIRS data
1) Processes controlling subtropical humidity

LMDZ–iso (Risi et al 2010a):
- control: AR4 version (19 levels)
- diffusive vertical advection

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AIRS data

relative humidity (%)
1) Processes controlling subtropical humidity

LMDZ–iso (Risi et al 2010a):
- red: control: AR4 version (19 levels)
- green: diffusive vertical advection
- blue: $\sigma_q/10$

3 reasons for a moist bias

- condensate detrainment (Wright et al 2009)
- dehydration in clouds (Sherwood et al 1996)
- large-scale circulation
- lateral and vertical mixing (Pierrehumbert 1998)
- boundary layer mixing (Coutbert et al 2010)
- rain evaporation (Folkins and Martin 2005)

AIRS data
1) Processes controlling subtropical humidity

LMDZ–iso (Risi et al 2010):
- control: AR4 version (19 levels)
- diffusive vertical advection
- $\sigma_q/10$
- $\epsilon_p/2$

3 reasons for a moist bias

condensate detrainement

dehydration in clouds

large-scale circulation

lateral and vertical mixing

boundary layer mixing

rain evaporation

AIRS data
What causes the moist biases in GCMs?

Sensitivity tests: with LMDZ:
- Control
- Excessively diffusive vertical advection
- Excessive condensate detrainment
- Insufficient in-situ condensation
- AIRS/ACE data

400 hPa, 15°N-30°N mean

JJA-DJF $\Delta \delta D$ (%) vs. relative humidity (%)
What causes the moist biases in GCMs?

Sensitivity tests:
with LMDZ:
- Control
- Excessively diffusive vertical advection
- Excessive condensate detrainment
- Insufficient in-situ condensation
- AIRS/ACE data

SWING2 models:
- ECHAM
- CAM2
- MIROC
- GISS
- HadAM
- GSM

● frequent reason for moist bias = excessively diffusive advection

1) Atmospheric processes
2) Upper tropospheric convective moistening

MIPAS data at 200hPa, annual

LMDZ control

$\delta D \, (\%_0)$
2) Upper tropospheric convective moistening

MIPAS data at 200hPa, annual

LMDZ control

Difference 15°S-15°N minus 30°S-30°N at 200hPa

MIPAS: 50 ± 20%o

control
vertical advection more diffusive
stronger condensate detrainment
less in-situ condensation
less in-situ precipitation

I) Atmospheric processes
2) Upper tropospheric convective moistening

MIPAS data at 200hPa, annual

LMDZ control

Difference 15°S-15°N minus 30°S-30°N at 200hPa

MIPAS: 50 ± 20%

- MIROC
- CAM
- HadAM
- GISS
- ECHAM
- GSM

**Legend**
- red: control
- green: vertical advection more diffusive
- blue: stronger condensate detrainment
- blue: less in-situ condensation
- brown: less in-situ precipitation

I) Atmospheric processes
3) Interplay convection - large-scale schemes

I) Atmospheric processes
3) Interplay convection - large-scale schemes

- $P_{LS}/P_{tot}$ arbitrary, but influences cloudiness, intra-seas. variability, chemical tracer transport

I) Atmospheric processes
Convection vs large-scale precip

Amazon, DJF-JJA (wet-dry)

<table>
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I) Atmospheric processes
Convection vs large-scale precip

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I) Atmospheric processes
Convection vs large-scale precip

Amazon, DJF-JJA (wet-dry)

TES data
- Control
- Vertical advection more diffusive

Stronger condensate detrainment
Less in-situ condensation
Less in-situ precipitation

I) Atmospheric processes
Perspectives on convection

- Combine $q$, $\delta D$ + cloud $\Rightarrow$ better constrain large-scale precip
Perspectives on convection

- Combine $q$, $\delta D$ + cloud $\Rightarrow$ better constrain large-scale precip
- Combine $q$, $\delta D$ + chemical tracers: CO, $O_3$, $^{10}Be$ $\Rightarrow$ better characterize fluxes
Perspectives on convection

- Combine $q$, $\delta D + $ cloud $\Rightarrow$ better constrain large-scale precip
- Combine $q$, $\delta D + $ chemical tracers: CO, $O_3$, $^{10}Be$ $\Rightarrow$ better characterize fluxes
- MJO project: cause of models’ difficulties? $\Rightarrow$ Relate MJO biases to specific problems in parameterizations, isotopes as additional diagnostic.
Perspectives on convection

- Combine $q$, $\delta D$ + cloud $\Rightarrow$ better constrain large-scale precip
- Combine $q$, $\delta D$ + chemical tracers: CO, $O_3$, $^{10}Be$ $\Rightarrow$ better characterize fluxes
- MJO project: cause of models’ difficulties? $\Rightarrow$ Relate MJO biases to specific problems in parameterizations, isotopes as additional diagnostic.
- IASI data: daily global coverage $\Rightarrow$ convective organization, life cycle

![Graph showing IASI and LMDZ data for atmospheric processes](image)
II) Using soil water, river water and water vapor measurements to evaluate land surface processes

- 4 examples
1) Surface water budget

![Diagram of surface water budget]

- control
- stomatal resistance /5
- no drainage, only surface runoff
- soil capacity /2
- less vegetation cover
- root extraction depth /4

- soil water isotopic measurements -> bare soil evaporation ratio

II) Land surface processes
2) Diffusion/infiltration in soils

August 2007
Le Bray

$\delta^{18}O$ (%)

depth (cm)

precip Sensitivity to soil properties

control
lower tortuosity $\rightarrow$ piston flow
2) Diffusion/infiltration in soils

- August 2007 Le Bray
- December 2007 Le Bray

δ¹⁸O (%0)

depth (cm)

Sensitivity to soil properties
Sensitivity to infiltration processes

control
lower tortuosity
preferential pathways

piston flow
3) Pathways from precipitation to rivers

Observations
- precipitation
- river

Vienna

$\delta^{18}O$ (%)
3) Pathways from precipitation to rivers

![Diagram of water cycle](image)

**Observations**
- precipitation
- river
- LMDZ–ORCHIDEE–iso
- control

Vienna

**Graph**

δ\(^{18}\)O (%) vs. Months

- J F M A M J J A S O N D

δ\(^{18}\)O values:
- High in June
- Low in December

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II) Land surface processes
3) Pathways from precipitation to rivers

Vienna

Observations
- precipitation
- river
LMDZ–ORCHIDEE–iso
- control
- all surface runoff

II) Land surface processes
3) Pathways from precipitation to rivers

Vienna

Observations
- precipitation
- river
- LMDZ–ORCHIDEE–iso
- control
- all surface runoff
- slower underground reservoirs

II) Land surface processes
4) Continental recycling

Water tagging:

II) Land surface processes
4) Continental recycling

Water tagging:

II) Land surface processes
4) Continental recycling

Water tagging:

PDF of vapor composition monthly, all tropical land points

% vapor from continental evapo-transpiration ($r_{con}$)
Continental recycling feedbacks

II) Land surface processes
Continental recycling feedbacks

\[ D1 = \frac{\ln\left(\frac{1}{1-r_{con}}\right)}{\ln(W)} \text{ (\%) } \]
Continental recycling feedbacks

II) Land surface processes

- use D1_iso to evaluate role of cont recycling (Risi et al in rev)
Evaluating continental recycling feedbacks

II) Land surface processes
Does LMDZ underestimate the role of continental recycling?

Or atmospheric problems?
Perspectives on land surface

- isotopes in 11-layer hydrology of ORCHIDEE ⇒ better simulation of soil profiles, more physical runoff-drainage partitioning
- use d-excess signal in the vapor to constrain evaporation/transpiration partitioning?
- link between present-day representation of the water cycle and simulated hydrological response to climate changes
Perspectives on land surface

- isotopes in 11-layer hydrology of ORCHIDEE ⇒ better simulation of soil profiles, more physical runoff-drainage partitioning
- use d-excess signal in the vapor to constrain evaporation/transpiration partitioning?
- link between present-day representation of the water cycle and simulated hydrological response to climate changes
- irrigation changes using water tagging
Potential of isotopic measurements to evaluate a broad range of processes in atmospheric and land surface models