Stable Water Isotopes in the Atmosphere

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Overview

1. Stable water isotopes (SWI) illustrate the tightly coupled nature of the earth system, and are useful tools for studying climates past, present, and future.

2. Information from observing and modeling SWI complements information from observing and modeling of water alone, and can be applied to a wide variety of problems in earth system science.

3. SWI help to illuminate processes that occur at scales too small for climate models to resolve and offer tremendous potential for constraining and improving model parameterizations.

4. When used in conjunction with other isotopes (e.g., carbon dioxide or methane), SWI provide valuable information regarding couplings between the carbon and water cycles.
Part I

1. Introducing the most common stable water isotopes
2. Basic modeling of water isotopes in the atmosphere
3. Extending the basic model
4. Global modeling of water isotopes in the atmosphere
Introducing the Isotopes

Vienna Standard Mean Ocean Water

Water $^{1}H_{2}^{16}O$ 1,000,000

Deuterated Water $^{1}HD^{16}O$ 156

$^{18}O$ Water $^{1}H_{2}^{18}O$ 2,005
Stable water isotopes are held to the same budget as water, except that

1. Light isotopes preferentially evaporate
2. Heavy isotopes preferentially condense
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An isotopic “fingerprint” of a transition in the water cycle that depends on

1. the interface
2. the temperature
3. any kinetic or non-equilibrium effects
Introducing the Isotopes

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fractionation

An isotopic “fingerprint” of a transition in the water cycle that depends on

1. the interface
2. the temperature
3. any kinetic or non-equilibrium effects

fractionation can be calculated according to a temperature dependent fractionation factor $\alpha$
Introducing the Isotopes

Isotopic concentrations in vapor are often reported as a ratio relative to the amount of water vapor $q$:

$$R_i = \frac{q_i}{q}$$

or as a deviation relative to a standard ratio:

$$\delta_i = \left( \frac{R_i}{R_{i,\text{SMOW}}} - 1 \right)$$

Standards include standard mean ocean water (SMOW), Vienna standard mean ocean water (VSMOW), and standard light Antarctic precipitation (SLAP)
Introducing the Isotopes

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For vapor $V$ in isotopic equilibrium with a liquid reservoir $L$, $R_V = \alpha R_L$ (or $\delta_V = \alpha \delta_L$), with $\alpha < 1$. 

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The Craig–Gordon Model

Assume thermodynamic equilibrium conditions at the air/water interface \( RH = 1 \) and \( RV = \alpha RL \) with a constant vertical flux (i.e., no horizontal divergence in the air column) and no isotopic fractionation during turbulent mixing.

\[
R_V = RV = \alpha RL
\]

Gat et al., 2001
Clouds and Precipitation
Assume thermodynamic equilibrium conditions during condensation, with condensate (cloud water/ice) falling out immediately as precipitation.
Rayleigh Distillation

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Increasing depletion with increasing distance from the equator

Bowen and Wilkinson, 2002
The Continent Effect

Increasing depletion with increasing distance from the ocean

Bowen and Wilkinson, 2002
The Altitude Effect

Increasing depletion with increasing height above sea level

Bowen and Wilkinson, 2002
Satellite Observations

These effects are also observed in total column water vapor...

Frankenberg et al., 2010
Satellite Observations

...and in water vapor in the middle troposphere.

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Helliker and Noone, 2010

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Rayleigh Distillation

The Rayleigh distillation model underpins reconstructions of paleoclimate variables using stable water isotopes from ice cores:
Rayleigh Distillation

The Rayleigh distillation model underpins reconstructions of paleoclimate variables using stable water isotopes from ice cores:

(1) Assumes snow/ice accumulate year-round
(2) Assumes that precipitating air masses in different eras have similar histories
(3) Assumes little removal of snow/ice/water from glacier
(4) Assumes that the local topography is simple
The Water Cycle

1. Evaporation
2. Transpiration
3. Sublimation
4. Condensation
5. Transportation
6. Precipitation
7. Deposition
8. Infiltration
9. Snowmelt Runoff
10. Plant Uptake
9. Surface Flow
9. Groundwater Flow

srh.noaa.gov
A Simple Box Model of SWI

- Advection
- Evaporation
- Condensation
- Precipitation
- Re-evaporation
- Isotopic fractionation occurs

Worden et al., 2007
A Simple Box Model of SWI

Worden et al., 2007

\[ P = C - X \]
A Simple Box Model of SWI

\[ \frac{\partial q}{\partial t} = E - P + A \]

\[ P = C - X \]

- Advection
- Evaporation
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- Precipitation
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Worden et al., 2007
Only Consider Evaporation

The Craig–Gordon Model

\[ \frac{\partial \delta}{\partial q} = \frac{1}{h} \left( \delta_s' - \delta \right) + \epsilon_s \]

Different atmospheric values
Only Condensation and Precipitation

Rayleigh Distillation

\[ E = 0 \]
\[ X = 0 \]
\[ A = 0 \]
\[ \alpha \text{ varies} \]
\[ \frac{dq}{dt} < 0 \]

\[ \frac{\partial \delta}{\partial q} = \frac{1}{q}(\alpha - 1) \]

Different values of \( \alpha \)

Differences between evaporation-only and condensation-only solutions allow these processes to be differentiated
Allow Evaporation of Condensate/Precipitation

Fraction of condensate that evaporates varies

\[ \frac{\partial \delta}{\partial q} = \frac{1}{q} \left[ \alpha \left( \frac{1 - f / \alpha_e}{1 - f} \right) - 1 \right] \]

Air is moister than Rayleigh, but more depleted. Why?

(1) Evaporation below cloud base enriches precipitation
(2) Exchange by molecular diffusion into subsaturated air

Worden et al., 2007
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $<\Delta q> \left[ \frac{(q_{LSC} - q_{CTL})}{q_{CTL}} \right]$

Zonal Mean $\Delta$HDO $[\delta D_{LSC} - \delta D_{CTL}]$

change in water vapor

change in HDO

Wright et al., 2009
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $\langle \Delta q \rangle \left[ \frac{(q_{LSC} - q_{CTL})}{q_{CTL}} \right]$  

-25% -20% -15% -10% -5% 0

90S 60S 30S 0 30N 60N 90N

change in water vapor

evaporation of precipitation depletes heavy isotopes in vapor

Zonal Mean $\Delta$HDO $\left[ \delta D_{LSC} - \delta D_{CTL} \right]$  

-50% -30% -10% +10% +30% +50%

90S 60S 30S 0 30N 60N 90N

change in HDO
Turn Off Evaporation of Condensate in a GCM

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Zonal Mean \(\Delta HDO \ [\delta D_{LSC} - \delta D_{CTL}]\)

-25% -20% -15% -10% -5% 0

-50% -30% -10% +10% +30% +50%

Wright et al., 2009
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $\langle \Delta q \rangle \left[ \frac{(q_{LSC}-q_{CTL})}{q_{CTL}} \right]$

Zonal Mean $\Delta HD\bar{O} \left[ \delta D_{LSC}-\delta D_{CTL} \right]$

- less heavy isotopes
- more heavy isotopes
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $\langle \Delta q \rangle \equiv [(q_{\text{LSC}} - q_{\text{CTL}})/q_{\text{CTL}}]$

Zonal Mean $\Delta \text{DHO} \equiv [\delta D_{\text{LSC}} - \delta D_{\text{CTL}}]$

lighter rain isotopes

less heavy isotopes

lighter vapor isotopes

heavier rain isotopes

more heavy isotopes

heavier vapor isotopes

Wright et al., 2009
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $\langle \Delta q \rangle \left[ \frac{(q_{LSC} - q_{CTL})}{q_{CTL}} \right]$

Zonal Mean $\Delta$HDO $[\delta D_{LSC} - \delta D_{CTL}]$

-25%  -20%  -15%  -10%  -5%  0

-50%  -30%  -10%  +10%  +30%  +50%

lighter

heavier
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $<\Delta q> \equiv \frac{(q_{LSC} - q_{CTL})}{q_{CTL}}$

Zonal Mean $\Delta HDO \equiv \frac{\delta D_{LSC} - \delta D_{CTL}}{\delta D_{CTL}}$

heavier

lighter
Turn Off Evaporation of Condensate in a GCM

Zonal Mean $\langle \Delta q \rangle \left[ \frac{q_{LSC} - q_{CTL}}{q_{CTL}} \right]$

Zonal Mean $\Delta$HDO $[\delta D_{LSC} - \delta D_{CTL}]$

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Stronger precipitation falls faster through the atmosphere, with less time to equilibrate with vapor – stronger precipitation is more depleted in heavy isotopes.

Lee et al., 2007
When relative humidity is lower, more precipitation evaporates before reaching the ground – stronger precipitation is less enriched in heavy isotopes.
If condensation and transport are fixed, evaporation terms adjust to balance the water budget.

The steady state depends on precipitation efficiency.

A nudges isotopic values toward global mean value.

\[
\frac{dq}{dt} = 0
\]

\( f \) varies
\( A \) varies

\( E \rightarrow X \rightarrow C \rightarrow P \)

\( \Delta D \) (permil) vs. \( q_i \) (ppt)

\( -180 \)
Evapotranspiration
Fractionation during photosynthesis, cellulose formation, and transpiration largely cancel, so the net fractionation during transpiration is approximately zero: transpiration reflects the isotopic composition of soil water (and hence precipitation).

Evaporation from bare soil fractionates due to the effects of molecular diffusion through soil pores.
Where condensation and evaporation occur, both equilibrium and non-equilibrium processes are involved, with dependencies on:

1. the near-surface saturation deficit (i.e., RH)
2. the near-surface winds
3. evaporation of falling raindrops
4. deposition of vapor to ice
5. chemical sources and sinks
**CHALLENGE**

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**APPROACH**

Simulation of SWI distributions in global climate models allows inclusion of most relevant processes. Simulation of multiple isotopes (e.g., HDO and H$_2^{18}$O) allows study of both equilibrium and non-equilibrium processes.
Even though there is no fractionation during transport, the details of transport are fundamental in setting the spatial and temporal distributions of SWI. Interpreting isotope distributions requires knowledge of the relative impacts of both transport and fractionation processes.
**CHALLENGE**

Even though there is no fractionation during transport, the details of transport are fundamental in setting the spatial and temporal distributions of SWI. Interpreting isotope distributions requires knowledge of the relative impacts of both transport and fractionation processes.

**APPROACH**

Supplementary water tracers in the model framework provide additional information that reveals the relative importance of different processes.
SWI in GCMs

- separately treat both grid-average and in-cloud vapor, cloud liquid and ice, liquid and ice precipitation
- include dynamical transport and parameterizations of chemical sources and sinks
- established ability to test model physics and probe the mechanisms responsible for the true isotope distribution
- can be used to identify shortcomings in simulations of large-scale transport, cloud physics, or surface fluxes
- limited by robustness of the underlying model hydrology and the strength of assumptions about isotope physics
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next step: explicitly resolve cloud microphysical processes
Part II

1. Applications of atmospheric stable water isotopes
2. Interactions between the carbon and water cycles as revealed by isotopic measurements
The Subtropics

Important to the global energy budget: warm, dry, and mostly cloud-free, energy vents to space efficiently and effectively.
The Subtropics

Important to the global energy budget: warm, dry, and mostly cloud-free, energy vents to space efficiently and effectively

Water vapor is a greenhouse gas: changes in water vapor in the subtropics can strongly affect the global energy balance
Important to the global energy budget: warm, dry, and mostly cloud-free, energy vents to space efficiently and effectively.

Noone et al., 2011
Important to the global energy budget: warm, dry, and mostly cloud-free, energy vents to space efficiently and effectively. A number of processes contribute to the water balance in the subtropical free troposphere.
The Subtropics

Reanalysis model results suggest a dominant role for mixing between ocean evaporation and dry air from the extratropical upper troposphere:

Galewsky and Hurley, 2010
The Subtropics

Observations of stable water isotopes provide richer context than water vapor measurements alone:

- Mixing with ocean evaporation
- Irreversible Rayleigh distillation process
- Reversible moist adiabatic process
- Exchange during rain evaporation

Noone et al., 2011
The Subtropics

Stable water isotopes capture meteorological changes:
The Subtropics

Stable water isotopes capture meteorological changes:

Mauna Loa
The Subtropics

Stable water isotopes capture meteorological changes:

Mauna Loa
The Subtropics

Stable water isotopes capture meteorological changes:

Noone et al., 2011
The Sahel

Variability of rainfall has social and economic implications

SWI and other water tracers in a GCM deepen understanding of seasonal changes in the water budget of the Sahel

Risi et al., 2010

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The Sahel

- Large-scale subsidence associated with the Hadley circulation
- Eddy transport from mid-latitudes
- Continental recycling
- Unsatuated downdraft
- Rain reevaporation
- Isolated convection
- Organized, frequent convection associated with the ITCZ

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(20%) contribution to the intra-seasonal variability of $\delta_p$ at Niamey
Water Budget Over China

China has a monsoon climate....

Summer

Westerly

Southwest monsoon

Southeast monsoon

Winter

Polar air mass

Westerly

...what should be the seasonal signal in isotopes?
Station data indicate two seasonal minima in heavy isotopes.
Observations of the altitude and latitude effects in station data within China can also be used to infer the detailed spatial distribution of isotopes in precipitation.
Understanding Past Climates

SWI records in ice cores, moss cores, and gypsum deposits – as well as the signatures of SWI in shelled organisms – are used to reconstruct past climates and provide valuable context to current climate changes.

records of isotopes in Antarctic ice cores
Understanding Past Climates

SWI can also be used to track the evolution of recent climate changes, such as warming over the northern Tibetan Plateau.
Constraining Biases in GCMs

Many of the major uncertainties in current climate models are related to the representation of the atmospheric water cycle.
Constraining Biases in GCMs

Tools

- sensitivity tests with LMDZ
- isotopic data
- theoretical model
- additional sensitivity tests with LMDZ
- SWING2 outputs
- isotopic data

Steps of the strategy

- What is the isotopic signature associated with different reasons for a moist bias?
- Can this isotopic signature be discriminated using observations?
- Is this isotopic signature based on simple processes represented by all models?
- Is this isotopic signature robust relative to the model’s physics?
- What is the isotopic signature associated with the moist bias in each GCM?

Goals and outcomes

1) identify an observable isotopic diagnostic to diagnose the reason for a moist bias
2) check the robustness of the diagnostic
3) diagnose the reason for the moist bias in GCMs

Risi et al., 2012
Constraining Biases in GCMs

Sensitivity tests to model physics
- control
- diffusive advection
- $\sigma_h/10$
- $\epsilon_p/2$
- higher vertical resolution

Data
- AIRS and ACE

Sensitivity tests to large-scale circulation
- free control
- free, higher horizontal resolution

Sensitivity tests to isotopic representation
- no kinetic fractionation during ice condensation
- no post-condensation fractionation
- $\phi = 0.7$
Oxygen isotopes can probe the rates of carbon and water cycling in the terrestrial biosphere. SWI can be used to:

• quantify seasonality in the isotopic composition of annual precipitation
• define how the isotopic composition of precipitation relates to temperature
• find the primary environmental causes for monthly changes in the distribution of isotopes
• identify the origins of precipitating air masses
• track plant and animal responses to environmental changes
• assess interactions and feedbacks within biological communities
Soil Enzymes

Carbonic anhydrase, an enzyme in plants and soil microbes, accelerates oxygen exchange between carbon dioxide and water and enhances fractionation during evapotranspiration of water vapor and respiration of CO₂.
Water and Carbon Cycle Changes

Correlations between $^{18}\text{O}$ in CO$_2$ and hydrologic variables (cloud cover, RH, $^{18}\text{O}$ in precipitation) suggest that variations in CO$^{18}\text{O}$ during the 1990s were driven by changes in the water cycle rather than changes in the carbon cycle.

Buenning et al., 2011
Observations of carbon isotopes in glacial runoff indicate that glacial melt water is an important source of bioavailable carbon in the Gulf of Alaska, with implications for fisheries.
Summary

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