Quantifying different climatic controls on d-excess and $^{17}$O-excess with the isotope-enabled Community Atmosphere Model

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Isotopic fractionation

Equilibrium effect
Heavy isotopes have higher binding energies

\[ \delta_D, \delta^{18}O, \delta^{17}O \]

\[ \delta = R - 1 \]
\[ R = \text{isotope ratio relative to VSMOW} \]

Non-equilibrium effect
Heavy isotopes have slower diffusion velocities

\[ d = \delta_D - 8 \cdot \delta^{18}O \]
\[ (\text{Dansgaard, 1964}) \]

\[ \Delta^{17}O = \ln R^{17}O - 0.528 \cdot \ln R^{18}O \]
\[ (Barkan and Luz, 2007) \]

\[ d_{\ln} = \ln R^D - 8.47 \cdot \ln R^{18}O + 28.5 \cdot (\ln R^{18}O)^2 \]
\[ (Uemura et al., 2012) \]
Why a logarithmic definition?

Rayleigh condensation

\[
\frac{R}{R_0} = f^{\alpha - 1} \quad \Rightarrow \quad \frac{d \ln R}{d \ln f} = \alpha - 1
\]

\[
\Rightarrow \ln R_1 - \frac{\alpha_1 - 1}{\alpha_2 - 1} \cdot \ln R_2 = \text{const.}
\]

\[\alpha = \alpha_{eq}(T)\]

\[\alpha = \alpha(T, Si)\]

\[\alpha = \alpha(T, RH)\]

- \(f\): fraction of remaining water vapor
- \(Si\): saturation ratio with respect to ice
- \(\alpha\): fractionation factor
- \(T\): temperature
- \(RH\): relative humidity
Rayleigh condensation

\[ \frac{R}{R_0} = f^{\alpha-1} \]

\[ \frac{\delta R}{R} = f^{\alpha-1} \]

\[ \ln \frac{R}{R_0} = \ln f^{\alpha-1} \cdot \left( \delta \ln R \right) = \left( \ln f - \ln f_0 \right) \cdot \left( \delta \ln f \right) \]

\[ \delta \ln R = \delta \ln f + \delta \ln (f+1) = \delta \ln f + \delta \ln (f+1) \]

\[ f = 0.02 \]

\[ T = -50.0°C \]

\[ \Delta^{17}O = \delta^{18}O - \delta^{18}O_0 \]

\[ \Delta^{18}O = \delta^{18}O - \delta^{18}O_0 \]

\[ Si = 1 - 0.002T \]

\[ Si = 1 - 0.004T \]

\[ Si = 1 - 0.006T \]

\[ \text{vapor} \]

\[ \text{condensate} \]
Modeling $d_{\text{ln}}$ and (especially) $\Delta^{17}\text{O}$ is challenging

$$Si = 1 - 0.002T$$

$$Si = 1 - 0.004T$$

$$Si = 1 - 0.007T$$

Schoenemann et al. (2014)
Modeling $d_{ln}$ and (especially) $\Delta^{17}O$ is challenging

\[ Si = 1 - \lambda T \]

Risi et al. (2013)
Microphysics scheme allows supersaturation with respect to ice (Gettelman et al., 2010, Morrison & Gettelman, 2008) → using model-predicted $Si$ for isotopes improves simulation of $d$ in Antarctica (Dütsch et al., under review)

Simulations
- Present day and last glacial maximum
- 10 years (+ 1 year spin-up)
- iCAM5 (Nusbaumer et al., 2017), iCLM4 (Wong et al., 2017), iCICE4 (Brady et al., 2019)
- Prescribed SST and sea ice concentrations (Hurrell et al., 2008, Zhu et al., 2017)
- 1.9° x 2.5° horizontal resolution

Objective
Quantify the contributions of
- evaporation from the surface
- transport
- cloud formation ... on $d_{ln}$ and $\Delta^{17}O$
$d_{ln}$ in iCAM5 and ice cores

DF: Dome F (Fujita and Abe, 2006; Touzeau et al., 2016)
EDC: EPICA Dome C (Jouzel et al., 2007; Stenni et al., 2010)
EDML: EPICA Dronning Maud Land (EPICA Community Members, 2006; Stenni et al., 2010)
SIP: Siple Dome (Brook et al., 2005; Schoenemann et al., 2014)
SP: South Pole (Steig, unpublished data)
TAY: Taylor Dome (Steig et al., 1998; Schoenemann et al., 2014)
TAL: Talos Dome (Buiuron et al., 2012; Landais et al., 2015; Stenni et al., 2011)
VOS: Vostok (Vimeux et al., 2001; Landais et al., 2008, 2012; Risi et al., 2013)
WD: WAIS Divide (Markle et al., 2017; WAIS Divide Project Members, 2013, 2015)
$\Delta^{17}\text{O}$ in iCAM5 and ice cores

**DF:** Dome F (Fujita and Abe, 2006; Touzeau et al., 2016)

**EDC:** EPICA Dome C (EPICA Community Members, 2004; Stenni et al., 2004, 2010; Winkler et al., 2012)

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**WD:** WAIS Divide (Markle et al., 2017; WAIS Divide Project Members, 2013, 2015)
Contributions of different processes to $d_{in}$ and $\Delta^{17}O$

\[
\begin{align*}
    d_{in,precip} &= d_{in,evap} + (d_{in,cloud} - d_{in,evap}) + (d_{in,precip} - d_{in,cloud}) \\
    \Delta^{17}O_{precip} &= \Delta^{17}O_{evap} + (\Delta^{17}O_{cloud} - \Delta^{17}O_{evap}) + (\Delta^{17}O_{precip} - \Delta^{17}O_{cloud})
\end{align*}
\]
Contributions of different processes to $d_{\text{ln}}$ and $\Delta^{17}\text{O}$ (PD)

$\Delta^{17}\text{O}_{\text{evap}}$ = evaporation

$\Delta^{17}\text{O}_{\text{precip}} - \Delta^{17}\text{O}_{\text{evap}}$ = transport + cloud formation

$\Delta^{17}\text{O}_{\text{precip}} = \Delta^{17}\text{O}_{\text{precip}} - d_{\text{ln, evap}} + d_{\text{ln, precip}}$
Contributions of different processes to $d_{\text{in}}$ and $\Delta^{17}O$ (PD)

$\Delta^{17}O_{\text{evap}}$

$\Delta^{17}O_{\text{cloud}} - \Delta^{17}O_{\text{evap}}$

$\Delta^{17}O_{\text{precip}} - \Delta^{17}O_{\text{cloud}}$

$\Delta^{17}O_{\text{precip}}$
Contributions of different processes to $d_{ln}$ and $\Delta^{17}O$ (LGM –PD)

$\Delta^{17}O_{\text{evap}}$

$\Delta^{17}O_{\text{cloud}} - \Delta^{17}O_{\text{evap}}$

$\Delta^{17}O_{\text{precip}} - \Delta^{17}O_{\text{cloud}}$

$\Delta^{17}O_{\text{precip}}$

= +

evaporation

transport

cloud formation

$\Delta^{17}O_{\text{evap}}$

$\Delta^{17}O_{\text{cloud}}$

$\Delta^{17}O_{\text{precip}}$

= +
Zonal mean contribution of processes

\[ d_{\text{in}} (\%) \]

\[ d_{\text{out}} (\%) \]

\[ 17O \text{ (ppm)} \]

\[ 17O \text{ (ppm)} \]

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- evaporation
- transport
- cloud formation
iCAM5 can simulate $\Delta^{17}O$ (and $d_{\text{ln}}$) in present day climate and during the last glacial maximum

- $d_{\text{ln}}$ in iCAM5 is lower in present-day climate and slightly higher during the last glacial maximum than in ice cores
- $\Delta^{17}O$ in iCAM5 is mostly lower than in ice cores

$\Delta^{17}O$ and $d_{\text{ln}}$ change significantly on the way from the moisture source to the precipitation site

- The effects of transport (including rainout and mixing) and cloud formation partially compensate each other, but not everywhere

Evaporation from the surface increases both $\Delta^{17}O$ and $d_{\text{ln}}$, transport and cloud formation have opposite effects on $\Delta^{17}O$ and $d_{\text{ln}}$

- Potential for combined metric to isolate the effect of moisture source conditions?