Sublimation origin of negative deuterium excess observed in snow and ice samples from McMurdo Dry Valleys and Allan Hills Blue Ice Areas, East Antarctica

Motivation

- The use of stable isotopes of oxygen and hydrogen in polar ice to infer past temperature is built upon the assumption that post-deposition processes do not alter the isotopic composition of snow (Friedman et al., 1991; Petit et al., 1999).
- This assumption has been increasingly challenged by observations of vapor-snow exchange (Steen-Larsen et al., 2014; Ritter et al., 2016; Madsen et al., 2019; Hughes et al., in press), but it is not clear if sublimation alone is capable of causing isotopic fractionation. However, if it does, deuterium excess (d-excess = δD - 8*δ18O) should decrease.
- While most of the d-excess values observed in present-day Antarctic surface snow are positive (Masson-Delmotte et al., 2008), a notable exception can be found in the McMurdo Dry Valleys and the nearby (~100 km away) Allan Hills Blue BIA where conditions are persistently dry and windy. Surface snow samples consistently show negative d-excess values (Dadic et al., 2015; Gooseff et al., 2006; Masson-Delmotte et al., 2008). These sites provide an opportunity to investigate whether ice sublimation causes isotopic fractionation in the field.

Model setup

- Isotope-enabled Community Earth System Model (iCESM) was used to simulate snowfall d-excess values at Allan Hills and Dry Valleys, using prescribed sea-surface temperature and sea-ice observations from 1977–2012 with 25 regions tagged.
- Mixed-Cloud Isotope Model (MCIM), a component of the iCESM, was used independently to evaluate under what conditions negative d-excess in precipitation can occur.

Results and Discussion

1. iCESM

- Modeled d-excess is systematic lower than observations.
- In Taylor Dome near the Dry Valleys region, the model underestimates d-excess by 6%.
- Adding this 6% offset to d-excess precipitation over Allan Hills yields 4.8% d-excess.
- Measured d-excess, however, is -2.9%.

Figure 3. Climatological precipitation d-excess simulated by iCESM (1977-2012 CE) and ice core measurements (post 1840 CE).

2. MCIM

- Negative d-excess can only occur if the majority of moisture comes from Southern Ocean, which however only accounts for <50% of precipitation in Dry Valleys/Allan Hills simulated by iCESM.

Figure 4. Modeled d-excess in precipitation along moisture trajectories if moisture solely originates from (a) the Southern Ocean and (b) the Tropical ocean for three different supersaturated parameter S as a function of condensation temperature, with the maximum values of relative humidity and minimum values of SST from 1977 to 2012 over the regions using the Mixed-Cloud Isotope Model.

3. Rayleigh-distillation model (* homogenization occurs through solid-state-diffusion)

Figure 5. Quantifying the effect of sublimation on d-excess (a) and δ18O (b) in the remaining snow using a Rayleigh-distillation model under interglacial (red) and glacial (blue) conditions. Depending on RH, 3 to 24% of the surface snow is lost due to sublimation to yield a negative d-excess of -5%.

Summary

- Negative d-excess in precipitation over Allan Hills and the Dry Valleys cannot be realistically reproduced by current-generation climate models.
- To yield negative deuterium excess in Antarctic precipitation, unrealistically high moisture contribution from high-latitude oceans is required.
- Sublimation fractionation must contribute to negative deuterium excess.

References