From precipitation to ice core: On the importance of surface processes for stable water-isotope records in East Antarctica

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Stable water-isotope records from Antarctic ice cores allow the reconstruction of past temperature variability. However, accurate interpretation of the isotopic signal requires comprehensive understanding of the processes leading to its archiving in snow and ice, which can be documented by in situ measurements.

In the history of paleoclimate research, Antarctic ice cores have been largely used to unveil past variability of the Earth’s climate. As an example, the EPICA ice core drilled at Dome C in East Antarctica provided the longest record of past atmospheric conditions up to 800,000 years back in time (EPICA community members 2004). Within the ice matrix of the cores, the stable water isotopes are traditionally used as a proxy for past local temperatures. This is based on the observed correlation between the local atmospheric temperature and the surface snow $\delta^{18}O$ across spatial transects in Antarctica (see review by Masson-Delmotte et al. 2008 and references therein).

A first challenge to the interpretation of isotopic records of snow and ice is related to the large-scale dynamics of the water cycle that vary through time, but are well constrained in global climate models (e.g. Cauquoin and Werner 2021). Along their trajectory from evaporation to precipitation, the air masses reaching the interior of the Antarctic continent are modified by precipitation and sublimation of snow that modulates the isotopic composition of the water vapor. In addition, on the East Antarctic plateau, snow accumulation is the result of a few precipitation events often associated with warm-air intrusions (Genthon et al. 2016). This leads to a discontinuous and temperature-biased recording of the stable water-isotope signal in the accumulating snow.

The ability to infer past temperatures from ice cores is also based on the assumption that the precipitation isotopic composition is preserved from snowfall to deeper burial in the snowpack. However, post-depositional processes taking place at the snow-atmosphere interface have been identified to modify the snow isotopic composition after precipitation. At Dome C, the daily-to-seasonal variations observed in the snow isotopic composition cannot be explained by precipitation only, demonstrating the existence of further processes involved in the formation of the snow isotopic signal (e.g. Casado et al. 2018).

Surface processes
At the ice sheet’s surface, the snow is affected by three kinds of physical processes: (i) wind redistribution of the snow; (ii) water-vapor exchanges between the snow and the lower atmosphere; and (iii) diffusion of water vapor within the snow. At very dry and low accumulation sites, such as the East Antarctic Plateau, the snow is exposed for long periods of time before being isolated from the influence of the atmosphere. During these precipitation-free periods, the first two processes mentioned above play a role in the resulting isotopic signal found in the snow.

A large variety of meteorological conditions are encountered on the plateau, but because of its location high up on the ice sheet, and the very small local slope, Dome C is not affected by strong katabatic winds (Genthon et al. 2021). Nevertheless, surface winds are sometimes strong enough to erode and redistribute the snow (Libois et al. 2014), which causes an inhomogeneous distribution of the water isotopes at the surface.

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Figure 1: Contribution of the different reservoirs to the isotopic composition of the snow. $R$ stands for the isotopic composition of the vapor ($R_v$), vapor at equilibrium with snow ($R_s$), precipitation ($R_p$), snow ($R_i$) and firm ($R_f$). The two water vapor transport mechanisms are mapped: sublimation/condensation at the surface, and molecular diffusion within the snow. Figure modified from Casado et al. (2018).
The surface snow and the atmosphere above also exchange moisture through sublimation of snow or condensation of water vapor onto the surface (Fig. 1). This sublimation process is driven by temperature and humidity gradients between the snow and the atmosphere. This mixing process is significant for understanding post-deposition climate variability, their quantitative interpretation in terms of temperature has been challenged by recent studies that revealed the impact of several processes at the surface of the ice sheet, modifying the isotopic composition of the snow after precipitation. Research is still ongoing to disentangle and quantify the impact of these different processes, which may take place during the snowfall, on the isotopic signal found in ice cores. For this reason, field measurements are performed, and provide some of the keys to understanding the dynamics of the water isotopes at the surface of the Antarctic Ice Sheet.

**Summary**

While water-isotope records from ice cores can provide invaluable information on past climate variability, their quantitative interpretation in terms of temperature has been challenged by recent studies that revealed the impact of several processes at the surface of the ice sheet, modifying the isotopic composition of the snow after precipitation. Research is still ongoing to disentangle and quantify the impact of these different processes, which may take place during the snowfall, on the isotopic signal found in ice cores. For this reason, field measurements are performed, and provide some of the keys to understanding the dynamics of the water isotopes at the surface of the Antarctic Ice Sheet.

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