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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 δ^{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 onto the ice sheet, 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.

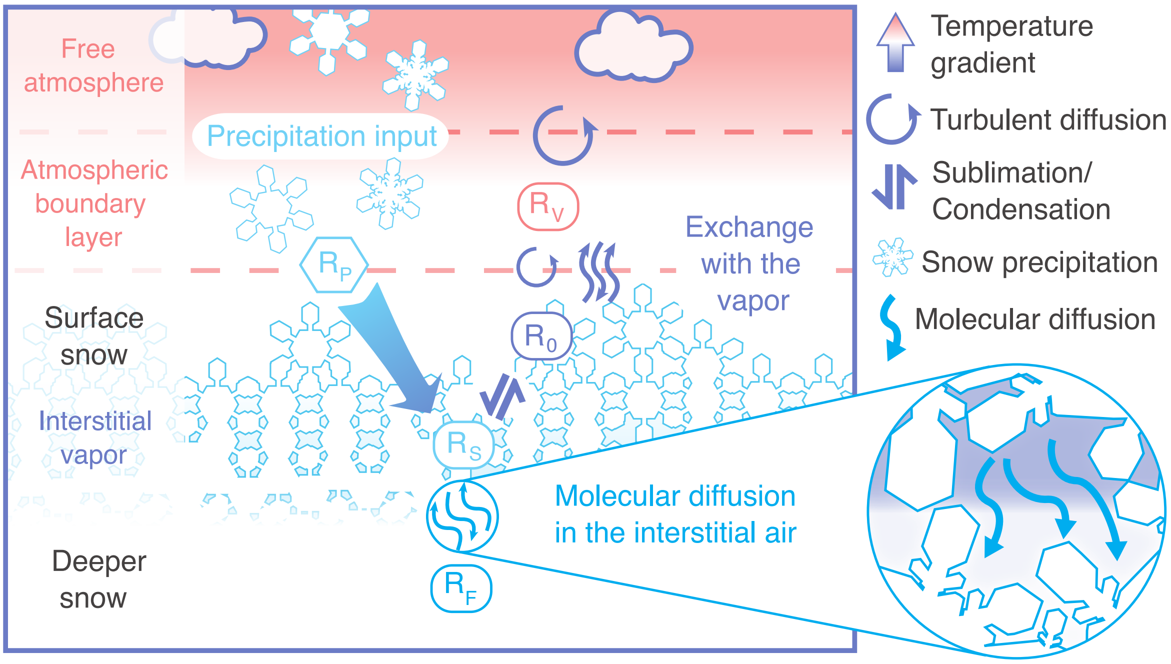

Figure 1: Contribution of the different reservoirs to the isotopic composition of the snow. R stands for the isotopic composition of the vapor (R_V), vapor at equilibrium with snow (R_0), precipitation (R_P), snow (R_S) and firn (R_F). The two water vapor transport mechanisms are mapped: sublimation/condensation at the surface, and molecular diffusion within the snow. Figure modified from Casado et al. (2018).

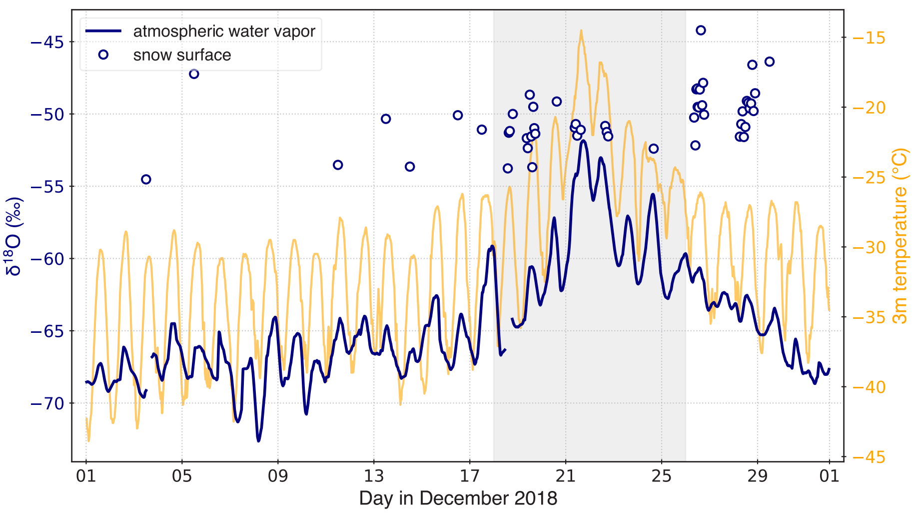

Figure 2: Observed isotopic composition of snow and atmospheric water vapor and local air temperatures at Dome C in December 2018. $\delta^{18}O$ was measured using a PICARRO laser spectrometer (atmospheric water-vapor data in Leroy-Dos Santos et al. 2021) and air temperature was measured by a sensor installed at three meters above the ground (data in Genthon et al. 2021). The atmospheric river event is marked by the gray shading.

The surface snow and the atmosphere above also exchange moisture through sublimation of snow or condensation of water vapor onto the surface (Fig. 1). The direction and magnitude of these moisture fluxes are driven by temperature and humidity gradients between the snow and the atmosphere, while wind enhances the mixing process. Although sublimation was previously thought to be a process that did not modify the snow isotopic composition, recent studies have challenged this assumption. Steen-Larsen et al. (2014) first demonstrated the existence of water-vapor exchange between the snow and the atmosphere during summer in Greenland, leading to variations in the isotopic composition of the snow, even in the absence of precipitation bringing fresh snow to the surface. Further measurements confirmed the impact of moisture fluxes on the snow isotopic composition (Wahl et al. 2021).

Diffusion, on the other hand, is a process continuously taking place inside the snowpack. At the grain scale, in the porous space of the snow below the surface, the ice crystals sublimate and the vapor is transported and re-deposited onto other snow grains (Fig. 1). This results in the movement of water molecules driven by temperature and isotopic gradients inside the snowpack, affecting the isotopic composition of the snow and firn after snowfall (Casado et al. 2021; Johnsen et al. 2000).

In situ observations

To provide observational benchmarks for isotope-enabled climate models, and to improve the understanding of post-depositional processes at the surface, measurement campaigns have been carried out for several years at Dome C.

The recent development of laser spectrometry has made it possible to measure the water-vapor isotopic composition in a very dry atmosphere. At Dome C, the analyzer installed on site (PICARRO L2130i) has provided observations of the atmospheric water-vapor isotopic composition almost continuously since November 2018 (Casado et al. 2016; Leroy-Dos Santos et al. 2021). The results obtained during the summer month of December 2018 are shown in Figure 2. The existence of diurnal cycles in the near-surface vapor isotopic composition (blue line in Fig. 2), following the diurnal cycles exhibited by the atmospheric temperature (orange in Fig. 2), demonstrates the existing link between these two atmospheric parameters. In addition, the analyzer recorded the atmospheric river event (a narrow corridor of intense moisture transport) that occurred between 18 and 26 December. This event led to ambient temperatures up to -15°C, which is much warmer than the average daily mean temperature of -31°C typically observed at this time of the year (Genthon et al. 2021). During this event, the vapor isotopic composition also increased by about 10‰, possibly due to a shift in the source region of the air mass, or less distillation along the trajectory from the source to Dome C.

Besides the atmospheric measurements, samples are regularly taken in the field to monitor the snow isotopic composition. In December 2018, the snow and atmospheric water vapor-isotopic composition at Dome C does not exhibit any clear co-variation (blue dots and blue line in Fig. 2), as observed on the Greenland Ice Sheet during the summer (Steen-Larsen et al. 2014). However, their similar isotopic composition at the peak of the atmospheric river event could suggest isotopic exchange between the two reservoirs. This is supported by the occurrence of sublimation during summer (Genthon et al. 2017), which implies isotopic exchanges between the surface snow and the atmosphere.

Lastly, precipitation samples collected in the field over several years have permitted the establishment of a temporal relationship between the snowfall $\delta^{18}O$ and the ambient temperature of 0.49‰/°C. It is significantly lower than the spatial slope of 0.8‰/°C obtained from various datasets of Antarctic snow, and traditionally used for temperature reconstructions (Masson-Delmotte et al. 2008; Stenni et al. 2016). This further highlights the importance of such measurements for the interpretation of $\delta^{18}O$ records in ice cores.

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 take place during the archiving of the snow, on the isotopic climate 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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