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How best to recover water-isotope data from ice cores

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Diffusion of water molecules in ice cores attenuates high-frequency variability of the water-isotope records, strongly affecting the interpretation of the deepest, oldest ice. Our ability to partly restore the signal depends on the measurement noise and our knowledge of the diffusion length.

Water-isotope diffusion

Stable water isotopes ($\delta^{18}O$ and δD) stored in ice sheets serve as a valuable proxy of the climate at the time of deposition as snowfall. However, over time, the water isotopes disperse, either between the porous snow and surrounding air at the top of the ice sheet (Whillans and Grootes 1985), or through other processes such as solid-ice-bulk diffusion (Johnsen 1977; Ramseier 1967) or liquid-water veins (Nye 1998) once the snow has been compacted into ice. This process is known as diffusion and attenuates the isotopic signal, primarily over the higher frequencies (shorter timescales), causing a smoothing effect. The degree of attenuation is characterized by the diffusion length, which is the average displacement of water molecules from their initial position within the ice sheet. Since this is a cumulative effect, ice thinning increases the affected timescale as the ice layers descend. Additionally, the very deepest ice close to bedrock is warm, reaching temperatures close to the pressure melting point. This greatly increases the diffusion length due to the non-linear dependence of the ice-diffusivity coefficient on temperature. Consequently, variability on centennial and even millennial timescales can be reduced significantly by diffusion in very old ice. Typical diffusion lengths in the firn range from 0–15 cm (Gkinis et al. 2021; Johnsen et al. 2000), while in the deep ice some estimates suggest values up to 60 cm (Pol et al. 2010). Knowledge of the diffusion length is important, as it enables us to determine on which timescales climate variability is preserved, and even restore some of the attenuated signal.

How diffusion affects the water-isotope signal

To visualize the potential effect of diffusion on the water-isotope signal in deep ice, we produced a virtual water-isotope record with the properties of the Beyond EPICA Oldest Ice Core (BE-OIC) currently being drilled in Antarctica. As an assumed climate record, we use the marine benthic stack (Lisiecki and Raymo 2005, "LR04 stack"), a landmark climate record based on a global collection of $\delta^{18}O$ measurements in benthic foraminifera. This record represents global ice volume and is strongly correlated on glacial-interglacial scales with Antarctic ice-core records. We adjust the age scale of this record to an age-depth model (Chung et al. 2023) of the BE-OIC, and rescale and invert the benthic $\delta^{18}O$ values using the EPICA Dome C $\delta^{18}O$ record (EPICA community members 2004), taking the peak of the Last Interglacial Period and Last Glacial Maximum as reference points.

As an example of the potential effect of diffusion, we zoom into a 25 m section in the deep part of this virtual ice core that represents 11 glacial–interglacial cycles from 1.2 Myr BP to 1.6 Myr BP (Fig. 1a). Simulated diffusion was applied to the record using three different diffusion lengths, demonstrating the potential magnitude of the smoothing effect. While a diffusion length of 10 cm (blue) simply rounds out the sharp peaks and troughs, a diffusion length of 60 cm (red) greatly attenuates the amplitude of even the glacial–interglacial cycles.

To quantify this effect, we calculate the remaining variability of a given frequency as the diffusion length is increased (Fig. 1b). We show the remaining power at decamillennial timescales (light gray, 10 kyr), as well as the dominant frequency driving

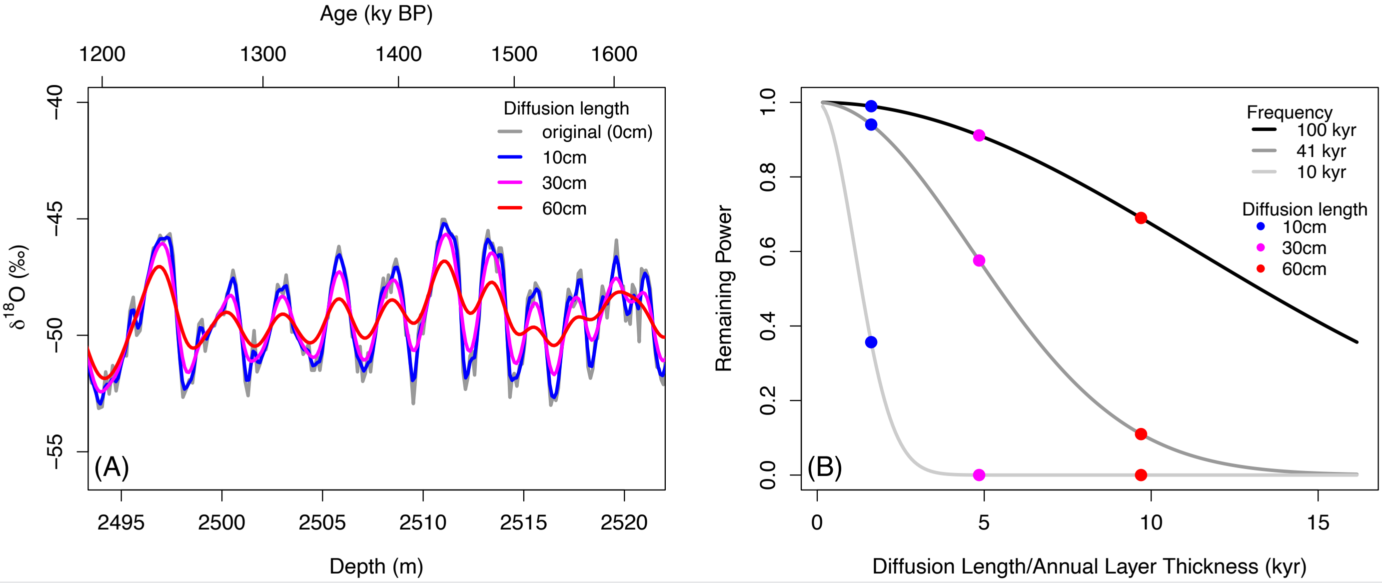

Figure 1: (A) Effect of diffusion length on the simulated deep ice-core record. **(B)** Remaining power at specific timescales against diffusion length in time units, converted from depth units by dividing by the average annual layer thickness across the depth range shown in (A). The three frequencies represent decamillennial variability (light gray, 10 kyr), Earth's obliquity cycle, dominant before the MPT (dark gray, 41 kyr) and Earth's eccentricity cycle, dominant after the MPT (black, 100 kyr). The colored dots represent the diffusion lengths shown in (A).

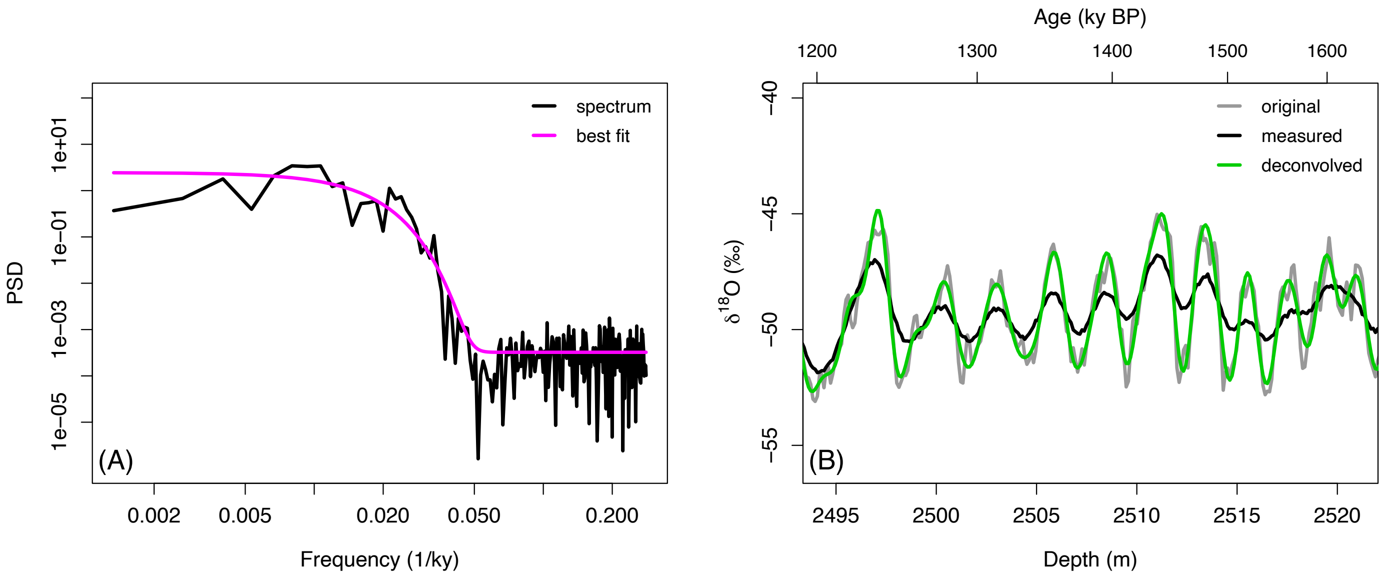

Figure 2: (A) Power spectrum of the diffused virtual isotope record from Figure 1a, assuming 60 cm diffusion and noise (black) and best fit (magenta). **(B)** Time series of the 60 cm diffused record (black) and deconvolved using Wiener deconvolution (green). Also shown is the original record before diffusion (gray). The amplitudes of the original glacial–interglacial cycles are restored, but with negligible sub-millennial variability remaining.

glacial–interglacial variability both before (dark gray, 41 kyr) and after (black, 100 kyr) the Mid-Pleistocene Transition (MPT) (Clark et al. 2006). Significant decamillennial variability only remains for a diffusion length of 10 cm, while on the 100-kyr timescale less than a third of the power is lost, even for a 60 cm diffusion length. The glacial–interglacial cycles in Figure 1a mostly follow a 41-kyr cycle trend, represented by the dark gray curve in Figure 1b. The striking difference in the smoothing of this glacial–interglacial variability for different diffusion lengths is intuitive, once compared with the three diffusion lengths marked on the 41-kyr curve. While approximately 94% of the power remains when diffused with a 10 cm diffusion length, less than 11% survives once the diffusion length is increased to 60 cm.

Recovery of the water-isotope record

For a better reconstruction of past climate evolution, we would like to be able to recover some of the diffused information. To achieve this, we need to know how much variability has been lost at every frequency. Thus, we need to know the diffusion length. It is possible to statistically estimate the diffusion length by analyzing the power spectrum of a water-isotope record. Using the spectral representation of diffusion outlined in Johnsen et al. (2000) enables us to apply a fit to the power spectrum of the water-isotope record to empirically derive the diffusion length (Fig. 2a).

Once a diffusion length has been obtained, we are able to back-diffuse the isotope record through a process called deconvolution. This technique amplifies the variability of the diffused frequencies to the expected initial amplitude, reversing the smoothing process. If water-isotope measurements were taken flawlessly, with perfect precision and no noise introduced by sampling preparation, handling and analytical uncertainty, then it would be possible to almost perfectly reconstruct the signal originally archived in the upper firn layers. In practice, measurement noise is a significant limiting factor for deconvolution. At the highest, most diffused frequencies, this noise often greatly exceeds the remaining climate signal. Amplifying these frequencies will also blow up the noise, destroying the signal. To resolve this, we can filter out the frequencies with a signal-to-noise ratio (SNR) below one, through the use of a Wiener filter (Wiener 1949). As we are losing the fastest variations, the recovered signal is still smoother than the original, undiffused LR04 stack record (Fig. 2b).

In addition to minimizing the measurement noise, it is also important to obtain an accurate diffusion length, in order to calculate the magnitude of attenuation for each frequency, and to correctly identify at which frequency the SNR drops below one. Deconvolving with an incorrect estimate will either over-amplify lower frequencies if the diffusion length is too large, or amplify the higher noisy frequencies if the diffusion length is too small. Therefore, improvements to diffusion-length estimation methods and models are indispensable for high-quality signal reconstructions of this kind.

Summary

The loss of high-frequency variability in water-isotope records due to diffusion in ice cores poses a significant challenge when attempting to infer past climate. This problem is especially pronounced in deep ice cores where, due to densification and geothermal heat flux, layers are extremely thin and much warmer in the deepest, oldest ice. Statistical methods exist for estimating the diffusion length, which can be used not only to better interpret these smoothed water-isotope records, but also restore variability across certain attenuated timescales. Improved reliability and effectiveness of deconvolution techniques is possible through refining diffusion-length estimation methods, and optimizing measurement processes to minimize the measurement noise. It is also crucial for obtaining as much information as possible from future deep ice-core projects.

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