C. R. Geoscience xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

External Geophysics, Climate (Glaciology)

Surface studies of water isotopes in Antarctica for quantitative interpretation of deep ice core data

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ARTICLE INFO

Article history:
Received 2 May 2017
Accepted after revision 11 May 2017
Available online xxx

Handled by François Chabaux

Keywords:
Ice core
Water isotopes
Antarctica

ABSTRACT

Polar ice cores are unique climate archives. Indeed, most of them have a continuous stratigraphy and present high temporal resolution of many climate variables in a single archive. While water isotopic records (δD or $\delta^{18}O$) in ice cores are often taken as references for past atmospheric temperature variations, their relationship to temperature is associated with a large uncertainty. Several reasons are invoked to explain the limitation of such an approach; in particular, post-deposition effects are important in East Antarctica because of the low accumulation rates. The strong influence of post-deposition processes highlights the need for surface polar research programs in addition to deep drilling programs. We present here new results on water isotopes from several recent surface programs, mostly over East Antarctica. Together with previously published data, the new data presented in this study have several implications for the climatic reconstructions based on ice core isotopic data: (1) The spatial relationship between surface mean temperature and mean snow isotopic composition over the first meters in depth can be explained quite straightforwardly using simple isotopic models tuned to d-excess vs. $\delta^{18}O$ evolution in transects on the East Antarctic sector. The observed spatial slopes are significantly higher (~ 0.7–0.8‰·°C^{-1} for $\delta^{18}O$ vs. temperature) than seasonal slopes inferred from precipitation data at Vostok and Dome C (0.35 to 0.46‰·°C^{-1}). We explain these differences by changes in condensation versus surface temperature between summer and winter in the central East Antarctic plateau, where the inversion layer vanishes in summer. (2) Post-deposition effects linked to exchanges between the snow surface and the atmospheric water vapor lead to an evolution of $\delta^{18}O$ in the surface snow, even in the absence of any precipitation event. This evolution preserves the positive correlation between the $\delta^{18}O$ of snow and surface temperature, but is associated with a much slower $\delta^{18}O$-vs-temperature slope than the slope observed in the seasonal precipitation. (3) Post-deposition effects clearly limit the archiving of high-resolution (seasonal) climatic variability in the polar snow, but we suggest that sites with an accumulation rate of the order of 40 kg.m^{-2}.yr^{-1} may record a seasonal cycle at shallow depths.

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http://dx.doi.org/10.1016/j.crte.2017.05.003
1631-0713/

Please cite this article in press as: Landais A, et al. Surface studies of water isotopes in Antarctica for quantitative interpretation of deep ice core data. C. R. Geoscience (2017), http://dx.doi.org/10.1016/j.crte.2017.05.003

1. Introduction

Polar ice cores are unique archives of multiple sources of information on past changes in climate and environment. Indeed, most polar ice cores have a continuous stratigraphy, and allow extracting highly resolved records, reaching seasonal resolution in Greenland and coastal Antarctica. Today, the ice core spanning continuously the longest period is the EPICA Dome C ice core, drilled on the East Antarctic plateau and covering the last 800 ka, hence eight climatic cycles (EPICA Community Members, 2004). Earlier discontinuous records have been extracted from blue ice fields (Higgins et al., 2015). The International Partnership for Ice Core Science is searching drilling sites where records spanning the last 1.5 million years could be extracted (Fischer et al., 2013). In central Greenland, where accumulation rates are at least 10 times larger than in the East Antarctic plateau, the longest continuous climatic record from NorthGRIP is limited to the last 120 ka (NorthGRIP-community-members, 2004), but information back to 130 ka has been extracted from an undisturbed section of the NEEM ice core (NEEM community members, 2013).

Various proxies are measured in ice cores enabling the reconstruction of climatic and environmental variables. While concentration of greenhouse gases (CO_2, CH_4, NO_2) is directly measured by the extraction of the air trapped in the ice, other proxies are more indirect, such as chemical proxies to infer changes in distal climatic conditions, atmospheric circulation, atmospheric chemistry, sea ice extent or fire records (e.g., Legrand et al., 2016; Wolff et al., 2010). Similarly, while high-resolution water isotopic records (δD or δ^{18}O) in ice cores are often taken as references for past atmospheric temperature variations, their quantitative interpretation is not straightforward and may be associated with large uncertainties. The initial method of temperature reconstruction from water isotopes is based on the present-day spatial relationship between δD or δ^{18}O and surface temperature on polar transects. This spatial slope is then used as a surrogate for the relationship between changes in water isotopic composition and temperature from past to present ("temporal slope"). In East Antarctica, the amplitude of temperature change over glacial–interglacial transitions was mainly estimated based on water isotopes with an associated error of –10 to +30%. In West Antarctica, the amplitude of the last deglaciation has been estimated to +11.3 °C based on measurements of isotopic composition of air isotopes, i.e. 2 to 4 °C larger than the water isotopes estimated amplitude of the last deglaciation in East Antarctica (Cuffey et al., 2016). At the glacial-interglacial scale, most atmospheric General Circulation Models equipped with water isotopes suggest that temporal slopes are close to spatial slopes (Jouzel et al., 2007; Risi et al., 2010; Stenni et al., 2010) with one exception (Lee et al., 2008) producing smaller slopes attributed to evaporative recharge over the Southern Ocean. For inter-annual variations under present-day climate or for simulated climates warmer than today due to increased greenhouse gas concentration, several studies produce temporal slopes up to twice smaller than the spatial ones, mostly because of precipitation-temperature covariance effects through precipitation intermittency (Schmidt et al., 2007; Sime et al., 2009). Temporal slopes lower than spatial slopes for climates warmer than pre-industrial ones (early Holocene, earlier interglacial periods) are also supported independently by investigations of isotope–temperature–accumulation relationships (Cauquoin et al., 2015).

Sources of uncertainties in the use of the spatial slope as a surrogate for temporal slopes emerge from (1) past changes in moisture source regions and the corresponding climatic variations, affecting the isotopic composition of the water vapor that will finally precipitate in polar regions (e.g., Lee et al., 2008), (2) past changes in the trajectories of water masses toward the polar regions affecting water isotopes in precipitation independently of changes in local condensation temperature (Helsen et al., 2006), (3) past changes in precipitation intermittency including seasonal effects (Krinner and Werner, 2003; Laepple et al., 2011; Masson-Delmotte et al., 2006; Sime et al., 2009) causing a distortion between the ice core signal (precipitation-weighted) and annual mean temperature; and finally (4) post-deposition effects leading to a modification of the isotopic composition of the surface snow after its deposition and before it is buried (Johnsen et al., 2000; Neumann and Waddington, 2004; Town et al., 2008).

In Greenland, the diffusion of the δ^{18}O seasonal signal can be corrected (e.g., Steen-Larsen et al., 2011) and other post-deposition effects have long been estimated to be of second order because of the high accumulation rate. However, recent studies claim that post-deposition processes could represent a significant contribution to the isotopic signal (Steen-Larsen et al., 2014). Still, alternative temperature measurements have been developed such as borehole temperature measurements (Dahl-Jensen, 1998) or direct quantification of the amplitude of temperature changes through air isotopic measurements (Landais et al., 2004a, b; Orsi et al., 2014; Severinghaus and Brook, 1999). These methods allow estimating temperature changes with an accuracy estimated at ±3 °C for Dansgaard–Oeschger abrupt events (Buizert et al., 2014; Kindler et al., 2014). These analyses reveal that, in Greenland, temporal isotope–temperature slopes are systematically lower than spatial slopes, with marked regional characteristics (e.g., Guillevic et al., 2013).

In the central East-Antarctic plateau, low accumulation rate and slow past temperature make borehole temperature reconstructions more difficult to interpret (Salamatin et al., 1998) and preclude the use of air isotopic measurements for quantitative temperature reconstructions (Landais, 2011). In this region, there is thus a strong need to better understand and quantify the processes potentially affecting the relationship between water isotopes and temperature, and specifically post-deposition processes that may have a strong influence when surface snow is exposed to exchanges with air during long time periods.

These facts have motivated the development of two types of surface polar programs in addition to deep drilling programs. The first type of surface program is focused on investigating the surface characteristics of a deep drilling

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