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Inconsistent relationships between major ions and water stable isotopes in Antarctic snow under different accumulation environments

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ABSTRACT

Major ions, stable oxygen isotopes ($\delta^{18}O$), and accumulation rates are analyzed using high temporal resolution data from shallow ice cores and snow pits from East and West Antarctica. Seasonal cycles of major ions and $\delta^{18}O$ are well preserved at sites with an accumulation rate threshold of >100 kg m^{-2} a^{-1} and calm wind conditions. The seasonal cycle is unclear at sites with high wind speeds, even if the accumulation rate is greater than the threshold. To eliminate the influences of different source regions on major ion and $\delta^{18}O$ signals in ice cores, we calculate correlation coefficients between annually averaged major ion concentrations and $\delta^{18}O$, and then compare these with accumulation rates and other geographical variables such as latitude, elevation, and distance from the coast. We find that accumulation rates are highly correlated with elevation and the 10-m snow temperature, and that major ions and $\delta^{18}O$ are negatively correlated at low accumulation sites in inland Antarctica. Negative correlations could reflect inconsistent accumulation due to a large inter-annual variability in the accumulation rate. The results show that the relationships between major ions and $\delta^{18}O$ may not reflect climatic signatures, and could be a result of the unique characteristics of this arid environment.

1. Introduction

Deep ice cores from inland Antarctica have contributed to a better understanding of global paleoclimate. Water stable isotopes in ice cores can be used as proxies for in situ and moisture source temperatures (Petit et al., 1999; Johnsen et al., 2001; Uemura et al., 2012). Major soluble ions are widely used as proxies of past climate, including ions from sea salt (Na^+ and Cl^-), which are thought to be a proxy for sea ice extent (e.g., Wolff et al., 2006; Fischer et al., 2007). Shallow ice cores from humid environments, where the accumulation rate is more than 300 kg m^{-2} a^{-1} (e.g., Fernandoy et al., 2010), provide high temporal resolution paleoclimate information on regional and/or global scales. In coastal regions, variations in the concentrations of $CH_3SO_3^-$ and non-sea-salt (nss) SO_4^{2-} are used as proxies for marine biological activity, which has been shown to vary with sea ice extent during the Holocene (Curran et al., 2003; Sneed et al., 2011).

Recent advances in analytical technologies have enabled ice core researchers to analyze polar ice cores at a high temporal resolution on annual to seasonal time scales (Steig et al., 2005; Iizuka et al., 2006; de Angelis et al., 2013). However, minimum temporal resolutions are constrained by the sampling interval and the annual accumulation rate.

Deep ice cores covering several glacial cycles, such as Vostok, Dome C, and Dome F, have been drilled in arid environments, where the accumulation rate is less than 50 kg m^{-2} a^{-1} (e.g., Johnsen et al., 2001; EPICA, 2004; Masson-Delmotte et al., 2011; Uemura et al., 2012). It is well known that the original isotopic (and thus temperature) signals are smoothed by isotopic diffusion in firn and ice (Johnsen, 1977; Pol et al., 2010), but it is not well understood how surface snow changes over time after deposition. Recently post-depositional alteration of water stable isotopes in surface

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snow has been studied using in situ data (Ekaykin et al., 2002; Hoshina et al., 2014) and simulations (Neumann and Waddington, 2004; Town et al., 2008). Studies of the post-depositional alteration of major ions have shown that gaseous ions (Cl^-,NO_3^-, and $CH_3SO_3^-$) tend to be lost by volatilization from the upper firn to the atmosphere (Wagnon et al., 1999; Delmas et al., 2003a). By comparing three ice cores around Law Dome, Curran et al. (2002) showed that $CH_3SO_3^-$ from summer layers could relocate to winter layers. Additionally, chloride from sea salt is replaced by sulfate after deposition by transportation from the ocean toward inland areas (Delmas et al., 2003b; Iizuka et al., 2012).

It is difficult to obtain high temporal resolution data from polar ice cores drilled in extremely arid environments. Because of insufficient understanding of post-depositional alteration, it is also unclear whether the interpretation of chemical signals in coastal (high accumulation) ice cores can be applied to cores retrieved from low accumulation sites in central Antarctica. Previous studies dealing with post-depositional alteration and the validity of major ions as climate proxies have focused on individual sites rather than discussing spatial variations (e.g., Curran et al., 2002; Göktas et al., 2002; Karlöf et al., 2005). In this study, we consider how accumulation rates constrain the temporal variation of chemical and isotopic signals, and affect the relationship between major ions and $\delta^{18}O$ (and thus temperature) preserved in Antarctic snow.

2. Data and methods

We use major soluble ion concentrations ($CH_3SO_3^-$, Cl^-,NO_3^-,SO_4^{2-}, and Na^+) and $\delta^{18}O$ collected from three snow pits and seven shallow ice cores widely distributed across East and West Antarctica (Fig. 1). The periods analyzed are limited to between 1966 (or later) to the years in which each pit or core was collected (Table 1). The three snow pits (DF, DK, and MP), dug in the summer of 2007 by the Japanese Swedish Antarctic Expedition (JASE) (Fujita et al., 2011; Iizuka et al., 2012; Hoshina et al., 2014), were sampled at 0.02 m intervals (or 0.18–0.25 year intervals) (Hoshina et al., 2014) and were dated using crust layers and variations in Na^+ and Cl^-/Na^+ (Hoshina et al., 2014).

Two of the ice cores were collected by the Japanese Antarctica Research Expedition (JARE) at a coastal site in Dronning Maud Land; H72 was collected in 1993 (Nishio et al., 2002; Suzuki et al., 2005) and YM85 was collected in 2002 (Takahashi et al., 2009). These cores were dated by variations in $CH_3SO_3^-$ (H72; Suzuki et al., 2005) and $CH_3SO_3^-$, NO_3^-, and $nssSO_4^{2-}$ (YM85; Takahashi et al., 2009). Sampling intervals in the H72 and YM85 ice core were 0.04–0.06 m (0.10 years) and 0.02–0.06 m (0.16 years), respectively (Suzuki et al., 2005; Takahashi et al., 2009). Both cores preserved seasonal records of major ions due to their high accumulation rates (128–306 kg m^{-2} a^{-1}). We also use sub-annual records from five ice cores retrieved from West Antarctica (Fig. 1) by the United States International Trans-Antarctic Scientific Expedition (US ITASE; Dixon et al., 2004; Steig et al., 2005). These ice cores were dated using variations in $nssSO_4^{2-}$ (Steig et al., 2005; Mayewski and Dixon, 2013), and the accumulation rates and sampling intervals were 120–470 kg m^{-2} a^{-1} and 0.082 m (0.03–0.09 years), respectively.

To analyze how geographical and climatic settings affect chemical signals preserved in snow, we use accumulation rate data compiled from stake measurements every 2 km along the JARE traverse route (Fig. 1) for the period 1993–2010 (Motoyama et al., 1995, 2002, 2008; Shiraiwa et al., 1996; Azuma et al., 1997; Furukawa et al., 2002; Kameda et al., 2007; Saito et al., 2007) along with snow density data (349–427 kg m^{-3}) (Sugiyama et al., 2012). We also use 10-m snow temperature data from the JARE traverse route and US ITASE sites (Satow and Watanabe, 1992; Nishio et al., 2002; Dixon, 2007).

It is possible that the chemical components used in this study were modified during transport from their origin to the site of deposition; however, water stable isotopes from precipitation correlate well with air temperature at the sites at seasonal to

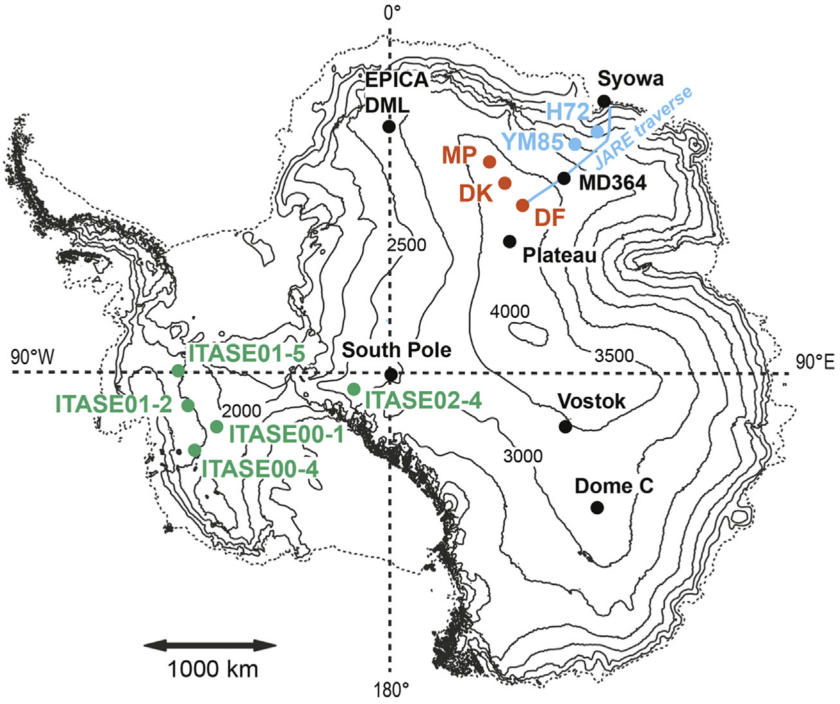

Fig. 1. Locations of ice cores and snow pits used in this study. Red, blue, and green circles denote JASE snow pits, JARE ice cores, and ITASE cores, respectively. The blue line between Syowa and DF denotes the JARE traverse along which surface accumulation has been measured. Abbreviations are listed in Table 1.