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The impact of glacier retreat from the Ross Sea on local climate: Characterization of mineral dust in the Taylor Dome ice core, East Antarctica

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ABSTRACT

Recent declines in ice shelf and sea ice extent experienced in polar regions highlight the importance of evaluating variations in local weather patterns in response to climate change. Airborne mineral particles (dust) transported through the atmosphere and deposited on ice sheets and glaciers in Antarctica and Greenland can provide a robust set of tools for resolving the evolution of climatic systems through time. Here we present the first high time resolution radiogenic isotope (strontium and neodymium) data for Holocene dust in a coastal East Antarctic ice core, accompanied by rare earth element composition, dust concentration, and particle size distribution during the last deglaciation. We aim to use these combined ice core data to determine dust provenance, with variations indicative of shifts in either dust production, sources, and/or transport pathways. We analyzed a series of 17 samples from the Taylor Dome (77°47′47″S, 158°43′26″E) ice core, 113–391 m in depth from 1.1–31.4 ka. Radiogenic isotopic and rare earth element compositions of dust during the last glacial period are in good agreement with previously measured East Antarctic ice core dust records. In contrast, the Holocene dust dataset displays a broad range in isotopic and rare earth element compositions, suggesting a shift from long-range transported dust to a more variable, local input that may be linked to the retreat of the Ross Ice Shelf during the last deglaciation. Observed changes in the dust cycle inferred from a coastal East Antarctic ice core can thus be used to infer an evolving local climate.

1. Introduction

Fluctuations in the amount and/or extent of sea ice and ice shelves alter wind speed and direction, as well as local storm trajectories (Vihma, 2014; Francis et al., 2009). Modeling the interaction between ice sheets and local climate demonstrates that air is cooled locally over an ice sheet, affecting the atmospheric flow response (Liakka and Nilsson, 2010). The high albedo and altitude of ice sheets can induce zonal anomalies in surface temperature, which can modify large-scale atmospheric circulation (Cook and Held, 1988; Beghin et al., 2014). Furthermore, several studies have implied that an ice sheet is capable of changing the position of the subtropical jet, in turn altering storm trajectories (Hall et al., 1996; Kageyama and Valdes, 2000; Laîné et al., 2008; Rivière et al., 2010). The change in storm trajectories will undoubtedly result in changes in precipitation pathways and the ice accumulation rates over ice sheets (Beghin et al., 2014). It is possible that variations in the extent of glaciation, sea-ice and ice shelves are capable of driving significant atmospheric climatic variations on seasonal, decadal, millennial and glacial–interglacial cycles.

Ice cores from the Antarctic ice sheet provide records of past climate extending over hundreds of thousands of years (Jouzel et al., 1995; Petit et al., 1999). Chemical and mineralogical characterization of dust particles transported through the atmosphere and deposited on ice sheets and glaciers allow for the reconstruction

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of regional and global climate patterns. The dust concentration and composition of long timescale ice cores varies with air temperature as recorded by stable isotopes: previous studies have established that dust concentration is one-to-two orders of magnitude greater during glacial versus interglacial periods. The increased dust deposition may be attributed to higher dust availability at source areas and higher wind speeds caused by a stronger equator to pole temperature gradient (Hammer et al., 1985; Delmonte et al., 2004a), or stronger wind gusts in dust source regions during periods of steepened meridonal temperature gradients (McGee et al., 2010). Provenance of dust deposited in ice can be characterized using radiogenic isotopes, including strontium ($^{87}Sr/^{86}Sr$), neodymium ($^{143}Nd/^{144}Nd$), hafnium ($^{176}Hf/^{177}Hf$) (Grousset and Biscaye, 2005; Basile et al., 1997; Delmonte et al., 2004a, 2004b, 2008; Lupker et al., 2010), and REE concentration (Wegner et al., 2012). The isotopic composition of ice core dust compared to Potential Source Areas (PSAs) of windborne material indicate variations in the dust provenance (Delmonte et al., 2004a; Wolff et al., 2006), which may be used to resolve past climate changes. The longest timescale ice core records are from interior East Antarctica (Petit et al., 1999), yet ice cores from coastal East Antarctic sites (i.e. Talos Dome) are capable of providing undisturbed, detailed records of the last climatic cycle in a region of the East Antarctic ice sheet with distinctive climate conditions (Delmonte et al., 2010).

Previous work on central and coastal east Antarctic ice cores identify southern South America (SSA) as the most likely source of windblown mineral dust during late Quaternary glacial periods. The size distribution and chemical composition of dust from interglacial periods is more variable and in coastal ice cores may potentially originate from local sources, although analytical limitations have made correlating interglacial ice core dust to source area challenging (Delmonte et al., 2007, 2010; Gabrielli et al., 2010).

In 1992, a ~554 m deep ice core was retrieved at Taylor Dome (TYD) (M3C1 ice core, 77°47′47″S; 158°43′26″E, 2365 m a.s.l.), a local ice-accumulation area for the Taylor Glacier. TYD is located on the eastern margin of the East Antarctic ice sheet (Fig. 1), in close proximity to the current position of the Ross Ice Shelf and seasonal sea ice of the Ross Sea. The TYD core was the third ice core (following Vostok and the first Dome C core) to provide a stratigraphically intact record of the Holocene through the last glacial cycle, going back to ~130 ka (Grootes et al., 1994; Steig et al., 2000).

Katabatic-driven movements of cold interior Antarctica air masses approaching from the southwest largely influences the weather at TYD (Morse et al., 1998), whereas warmer, precipitation-laden air masses approach TYD from the south (Morse, 1997). The latter air masses are linked to cyclones originating near Marie Byrd Land (Fig. 1), traveling over the Ross Ice Shelf and across the Transantarctic Mountains before deposition at TYD (Harris, 1992).

During the Last Glacial Maximum (LGM), the accumulation rate at TYD drastically decreased, suggesting a change in atmospheric circulation during the late ice age period (Morse et al., 1998). Morse et al. (1998) hypothesized that moisture-bearing storms arrived at TYD from the north (rather than the south as they do presently), a result of changing ice cover in the Ross Embayment. The elevated topography in the Ross Embayment (e.g. from the Ice Shelf or Ross 'Ice Sheet') and northward displacement of the Ross Low combined to displace the storm tracks northward through the Transantarctic Mountains north of the Royal Society Range (Morse et al., 1998) (Fig. 1). Terrestrial and marine geological evidence indicates that grounded ice advanced far into the Ross Sea during the Last Glacial Period (LGP), reaching its greatest thickness and extent between 12.8–18.7 ka (Hall et al., 2015). The recession of the ice sheet began about 12.8 ka, and it retreated from the McMurdo

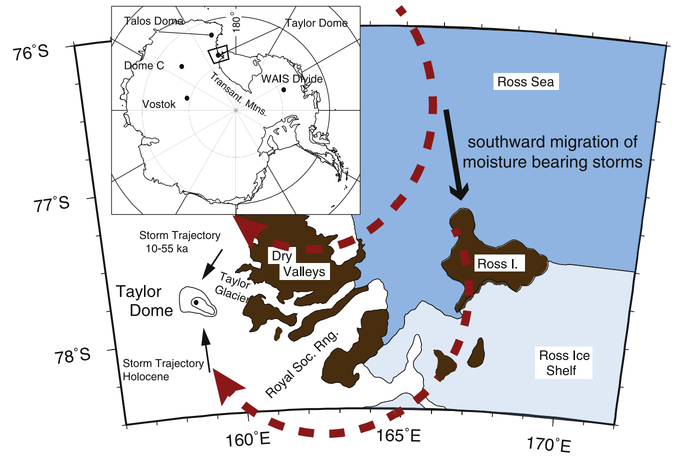

Fig. 1. Map of Taylor Dome and surrounding area, with major ice core drilling sites and the hypothesized Last Glacial Maximum (top dashed arrow) and current Holocene (bottom dashed arrow) storm trajectory (figure adapted from Morse et al., 1998).

Sound area over the period 11.5–6 ka (Anderson et al., 1992; Licht et al., 1996), aligned with the proposed timeline for southerly storm trajectories.

We utilize the TYD ice core dust record to examine the changes in local weather and storm trajectories during and following the retreat of the Ross Ice Shelf during the last deglaciation. Dry and windy conditions throughout the LGP are likely to have established the dominance of dry-deposited dust on TYD, as opposed to sea-salt aerosol. The dust accumulation rates should have decreased throughout the last deglaciation, and the sources and transport pathways of dust may have remained similar to those from the LGP (Hinkley and Matsumoto, 2001) or alternatively could have been completely restructured due to the major climate shift. The retreat of the Ross Ice Shelf, 11.5–6 ka, should have had a significant impact upon the dust record, consistent with the dust record at Talos Dome (Delmonte et al., 2010) as hypothetically, storm trajectories and dominant winds would migrate southward to approach TYD from the southeast (Fig. 1).

Sea salt aerosol, is yet another indicator of sea ice and ice shelf extent (Wolff et al., 2003; Lupker et al., 2010); it originates from sea ice covered with brine, frost flowers and bubble bursting over seawater. Here we measure the isotopic and elemental characteristics of the soluble fraction (<0.2 μm) of the TYD ice core for comparison to the insoluble fraction, which is comprised of dust between 0.2 and 30 μm in diameter. Particles larger than 30 μm in diameter were not measured due to the low dust availability and instrumental detection limitations.

This work presents the first detailed Sr and Nd isotopic dataset of coastal Antarctic ice core dust during the last deglaciation. We employ a newly developed mass spectrometry technique utilizing 10^{13} Ohm resistors which can effectively measure variations in Nd isotope composition of extremely small samples to the fourth decimal place (Koornneef et al., 2014). The goals of the study are: (1) to provide the first high-resolution record of dust deposited in East Antarctica during the last deglaciation and into the Holocene, (2) identify and compare the geochemical (radiogenic isotope compositions and rare earth element concentrations) and physical characteristics (dust concentration and particle size) of ice core dust to PSAs from SSA and the Ross Sea sector (e.g. McMurdo Dry Valleys), (3) explore the effects of the retreating Ross Ice Shelf upon regional storm trajectories using the dust record preserved in the TYD ice core, and (4) establish the likely sources of dust to TYD during the LGP and the Holocene.