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Constraining the timing of West Antarctic Ice Sheet changes using East Antarctic ice cores

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Ice sheet collapse under a warming world poses threat to humanity as a whole since approximately 38% of global population lives within 100 km of the coast (UNEP, 2014). The West Antarctic Ice Sheet (WAIS) is grounded on bedrock currently below sea-level and therefore vulnerable to ocean warming (Mercer, 1968; Hughes, 1973). Observations over the past decades have confirmed accelerated mass losses from West Antarctica (Rignot et al., 2019). Yet, accurately quantifying future contributions to sea-level rises from the WAIS remains challenging. One way to reduce the uncertainty of future sea-level predictions is to investigate the sensitivity of ice sheets to past temperature changes. For example, the Last Interglacial (LIG) between 129 ka and 116 ka ago has gained considerable interest. The LIG is a geologically recent interval with an average global temperature 0℃ to 2℃ higher than the pre-industrial level (Otto-Bliesner et al., 2013). The LIG thus represents a "geologic analog" for anticipated near-future warming and could potentially shed light on the response of the WAIS to future warming.

Global sea-level was likely 5 m to 10 m higher in the LIG than the present (IPCC, 2022), but the magnitude of individual ice sheet changes cannot be precisely quantified by global sea-level reconstructions. Geophysical modeling suggests that the WAIS contributed to at least 3-m global eustatic sea-level rise in the LIG (Pan et al., 2021). However, geological observations are currently lacking, because terrestrial evidence is often erased by subsequent glaciation, and marine records thus far do not have enough temporal resolution to precisely pinpoint the timing of WAIS changes during the LIG (McKay et al., 2012).

Ice cores provide continuous, well-dated records of local, regional, and global environments (Hou, 2022) and have emerged as a promising archive of not only climate information but also past ice sheet behaviors. It might seem intuitive at first to use ice cores as an ice sheet indicator, in view of the very fact that ice cores are part of the ice sheets. However, no ice cores from the West Antarctica reach the LIG so far other than some exposed ice near Mt. Moulton and Patriot Hills (Figure 1), both located near the ice sheet margin (Korotkikh et al., 2011; Turney et al., 2020). A deep ice core drilled at the WAIS Divide (Figure 1), for example, dates back to 68 ka near the bottom (WAIS Divide Project Members, 2013). This is a telling observation, but it must be underscored that the absence of LIG ice records from West Antarctica does not necessarily mean that there was no ice in West Antarctica at that specific time.

Researchers thus turned into East Antarctica, the gargantuan ice mass that remained stable during the LIG. Whether or not a collapsed WAIS would leave some discernable signatures in the nearby ice, particularly the stable water isotopes, was first formally investigated by Steig et al. (2015). The results were promising and, along with subsequent studies, Steig et al. (2015) identified Hercules Dome (Figure 1) as a site sensitive to the

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presumptive WAIS collapse (Goursaud et al., 2021). An ice coring project there was funded in 2020 by the United States National Science Foundation. Actual drilling is expected to begin in late 2025 at the earliest.

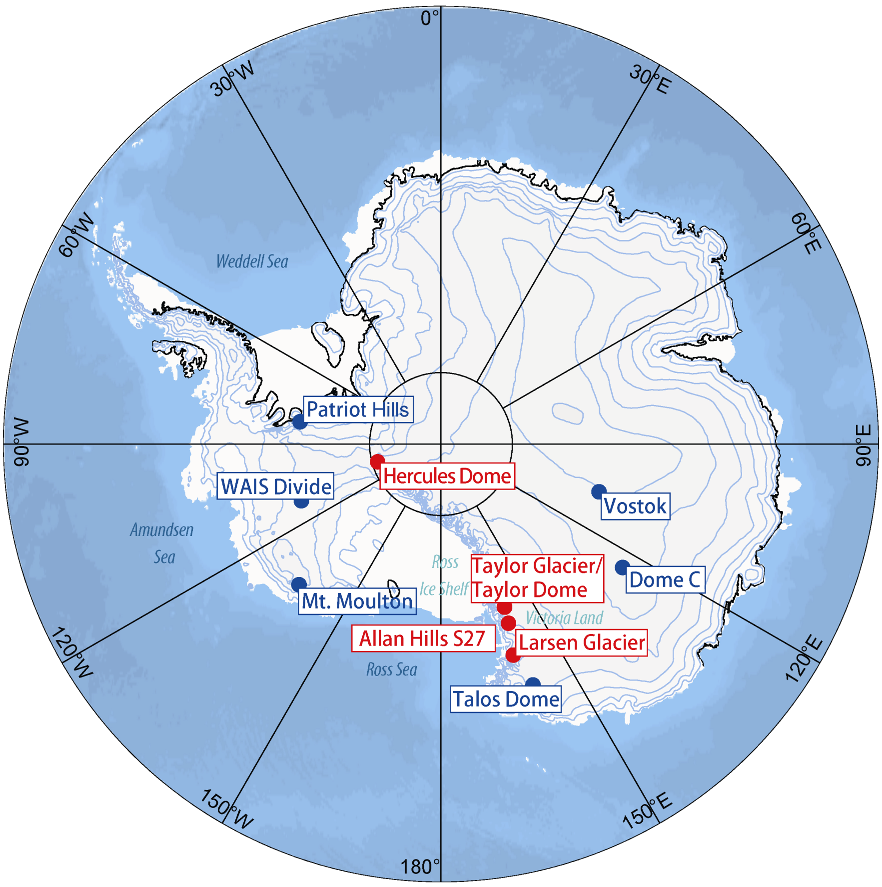

Figure 1 Locations of key ice coring sites and geographic features of Antarctica (Bindschadler et al., 2011). The proposed trans-Antarctic ice core array along the Ross Sea coast is shown in red.

While the Hercules Dome project is several years away, efforts in other parts of Antarctica, which were not intended to study past WAIS changes, might have provided some useful information. One region is Victoria Land (Figure 1), situated at the margin of the East Antarctic Ice Sheet near the Ross Sea. The possible connection between WAIS and this site was not entirely new: the position of West Antarctic ice bodies (including Ross Ice Shelf) was invoked to explain the radar stratigraphy at Taylor Dome, East Antarctica more than two decades ago (Figure 2; Morse et al., 1998). The same principle has also been recently used to account for LGM-Holocene changes in the nature of dust deliveries to the nearby Taylor Glacier (Aarons et al., 2016). Aarons et al. (2019) further investigated the dust transport into the Taylor Glacier during the LIG using a 4-m shallow ice core, and suggested "a pronounced shift in wind directions". However, the authors in that work did not discuss why the wind trajectory shifted and what the implications for the stability of WAIS would be.

In the meantime, the recovery of a 225-m ice core at Site 27 (S27; Figure 1) from the Allan Hills Blue Ice Area (BIA), also in Victoria Land, provides a continuous, high-resolution climate record between ~110 ka and ~250 ka (Spaulding et al., 2013). Allan Hills (76.73°S, 159.36°E) is a nunatak, the extruded portion of a subglacial topographic barrier situated to the northwest of the McMurdo Dry Valleys, about 80 km away from the coastline. Ice in this region flows slowly (< 0.5 m·a^{-1}) to the northeast into the Mawson Glacier from the southwest, and eventually drains into the Ross Sea. The proximity of the S27 ice core to the present-day north edge of the Ross Ice Shelf makes it a "sentinel" for past ice shelf and ice sheet changes.

Yan et al. (2021) calculated the snow accumulation rate recorded in the S27 ice core based on the age difference of the ice and the trapped air at the same depth. The respective timescales were synchronized to the well-dated EPICA Dome C (Figure 1) ice core. An order-of-magnitude increase in S27 accumulation rates across the penultimate deglaciation with a peak at 129 ka during the maximum LIG warming was found (Figure 3). By comparison, in other East Antarctic ice cores accumulation rates typically

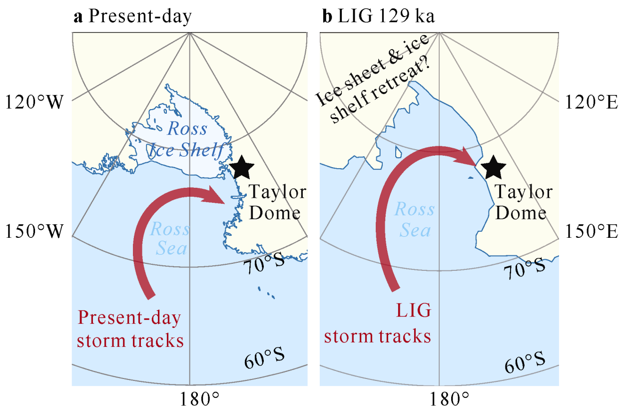

Figure 2 Schematic diagrams showing two possible scenarios of moisture delivery into the Taylor Dome area (star). The concept was first proposed in Morse et al. (1998). Map source (**a**): Alexrk2, Wikimedia Commons; licensed under the Creative Commons Attribution-Share Alike 3.0 Unported License; map source (**b**): STyx, Wikimedia Commons; licensed under the Creative Commons Attribution 3.0 Unported License).

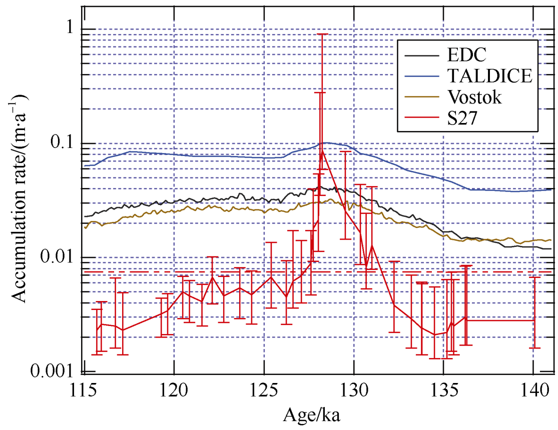

Figure 3 Accumulation rate between 115 ka and 140 ka in S27 (red), Talos Dome (TALDICE, blue), Vostok (brown), and EDC (black). The location of these cores is shown in Figure 1. Note that the y axis is plotted on logarithm scales. Accumulation rates of EDC, TALDICE, and Vostok are from Bazin et al. (2013) and the references therein. Error bars represent the 95% confidence interval for S27 accumulation rate estimates. The dashed line in red represents the present-day accumulation rate (0.0075 m·a^{-1}) in the vicinity of Allan Hills (Dadic et al., 2015).

vary by a factor of two to three on glacial-interglacial timescales (Siegert, 2003). This drastic change could be explained by possible changes in local ice mass configurations, such as more open-water conditions in the Ross Sea and a southward retreat of Ross Ice Shelf, perhaps due to the collapse of WAIS during the early LIG. Importantly, the hypothesized ice retreat in the Ross Sea makes a number of falsifiable predictions, such as a negative excursion in the deuterium excess (traditionally defined as δD–8×δ^{18}O) and changes to aerosol chemistry, which could be examined by new measurements in the future.

If S27 is a single outpost in East Antarctica to observe and record the fate of the WAIS during the LIG, it could join the proposed Hercules Dome, the southernmost sentinel, to form an array along the Ross Sea coast in East Antarctica (Figure 1). The main appeal of this array is that it could in theory document the timing of ice sheet/ice shelf retreats and advances, thanks to various geochemical markers inside the ice that allow precise timescale synchronization across different cores. Another promising site is the Larsen Glacier BIA, northern Victoria Land (Figure 1), where continuous ice archives dating back to 5–25 ka have been recently discovered (Lee et al., 2022). If ice that dates back to the LIG is present at and could be retrieved from the Larsen Glacier BIA, the northernmost sentinel, then integrating the Hercules Dome, Allan Hills, Taylor Glacier/Taylor Dome, and Larsen Glacier ice holds the potential to constrain the timing of changes in West Antarctica and the Ross Sea.

Of course, even an array of ice cores alone cannot conclusively solve the mystery of past WAIS changes, because ice core proxies are often subject to multiple interpretations (Holloway et al., 2016; Aarons et al., 2019). It is therefore necessary to integrate multiple and complementary efforts, including (but not limited to) geophysical surveys, exposure dating of the bedrock, and numerical simulations. With those powerful aids, ice cores and the wealth of information within hold tremendous potentials to help us understand how WAIS behavior would change in a warmer climate regime.

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Note Queries and discussions on this article should be made by E-mail directly with the corresponding author.

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