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Temperature reconstruction from measured bubble number-density evolution in the South Pole Ice core since the late-glacial (~19.5 ka)

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ABSTRACT

We present analyses of bubble number density (BND) data from the South Pole Ice Core (SPC14) showing warming of ~7.5°C from the Late Glacial (~19.5 ka), then relatively stable temperatures during the Holocene (< 0.5°C warming), in close agreement with results of independent paleothermometers. The BND data span from ~160 m just below pore close-off, to ~1200 m, where bubble loss by clathrate formation is significant. Measurements were made with standard bubble "thick"-section techniques and a new application of 3D micro-computed tomography (CT) imagery; the nearly identical results recommend the faster, nondestructive micro-CT. The very high BND at South Pole, typically 800 and 900 bubbles cm^{-3}, reflects the joint effects of the relatively low mean-annual temperature (−49°C) and high accumulation rate (~7.5 cm w.e. a^{-1}). High BND is physically linked to small grain sizes at pore close-off, which in turn helps explain the near-absence of brittle-ice behavior at the site, contributing to the high quality of the recovered core with implications for siting of future ice cores. The accumulation history, derived from $\delta^{15}N$-N_2 firn-column thickness estimates, correlates with the temperature history but varies somewhat more than saturation vapor pressure, suggesting dynamic controls including upstream slope variability.

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INTRODUCTION

Ice cores are incredible archives of paleoenvironmental data, containing crucial insights into past climate and supplementing and extending instrumental data (e.g., Schneider and Steig, 2008; Steig and others, 2009, Fegyveresi and others, 2011). Data from ice cores are especially valuable because they provide multiple, independent constraints on the history of key climatic variables such as temperature or snow accumulation rates (e.g., Cuffey and Paterson, 2010; Alley, 2010). Multiple ice-core proxies (e.g., stable isotopes, ice chemistry, etc.) have been used to develop indicators of past climates across multiple sites, and while these proxies are fairly well-established qualitatively, corroboration through independent data sets, as well as calibration of the geochemical paleo-thermometer, is invaluable for establishing robust and accurate paleoclimate reconstructions.

Spencer and others (2006) showed that estimates of past temperatures in polar ice can be quantitatively reconstructed from ice-core bubble number-density and site accumulation rates.

Recent applications of this model employed for the WAIS Divide site (Fegyveresi and others, 2011, 2016) validated the effectiveness and capability of this technique for establishing independent records down to the depth at which bubble loss to clathrate formation becomes significant, which in previous applications of the technique has been in Holocene ice. The use of this technique requires slow, labor-intensive bubble-section preparation and analyses.

Here, we present an independent paleoclimate reconstruction for South Pole across the most recent glacial termination, and up through the Holocene, using this bubble number-density paleoclimate indicator. We also present and compare data derived from a new 3D imaging technique developed using micro-CT technology. We show that using this new imaging technique instead of the traditional bubble-section imagery produces comparable results, with similar precision and uncertainty. In addition, this imaging technique is effectively non-destructive to the ice samples, and sample preparation and measurement is considerably more efficient, enabling faster and more-accurate future analyses.

Loss of bubbles to form clathrate hydrates in the South Pole core was insignificant in ice samples younger than ~20 ka (kyrs bf 1950), allowing the results here to give the first independent temperature reconstruction from bubble number-density through the glacial transition. This new temperature reconstruction for South Pole agrees with other independently derived reconstructions of surface temperatures for the site based on isotope proxies, diffusion length estimates, and firn densification modeling (Buizert and others, 2021; Kahle and others, 2021).

BACKGROUND

South Pole Site Specifics

The main coring of the South Pole Ice Coring Project (SPICEcore) took place over two Antarctic summer seasons between 2014 and 2016. The drilling site, located at 89.99°S, 98.16°W and approximately 2 km from the primary South Pole Station, is unique in that the mean annual temperature at the drilling location (−49°C) is more typical of East Antarctic sites, while the mean accumulation rate (~7.5 cm w.e. a^{-1}) is more typical of West Antarctic sites (Casey and others, 2014; Lazarra and others, 2012). The site has an estimated ice thickness of 2700 m, an ice velocity of 10 m a^{-1} along 40°W, is situated at approximately 2835 m above sea level, and has an estimated depth to pore close-off of about 120 m (Battle and others 1996, Casey and others 2014; Sneed and others 2011). The primary recovered core, SPC14, was drilled to a depth of 1751 meters, with the ice dated to ~54,300 years BP (Winski and others, 2019). Calculated gas-age/ice-age differences for the core were as high as 2500 years, with gas-ages at the bottom of the core of ~52,500 years BP (Epifanio and others, 2020).

Several studies have been published recently reconstructing glaciological, chemical, and temperature histories for the South Pole site using the primary SPC14 core. These include analyses of accumulation (Fudge and others, 2016; Kahle and others, 2021), advection and ice-provenance trends (Lilien and others, 2018; Fudge and others, 2020), oxygen isotope trends (Markle and others, 2018; Steig and others, 2021; Markle and Steig, 2022), and trapped gas trends (Epifanio and others, 2020; Morgan and others, 2022; Epifanio and others, 2023). The temperature reconstructions published thus far for the South Pole site have used several proxies, including the well-known water stable isotope thermometer (Markle and Steig, 2022), isotope diffusion lengths (Kahle and others, 2021), and the history of firn densification at the site (Buizert and others, 2021). These reconstructions for South Pole have all revealed a general temperature increase across the recent glacial transition of between ~7°C and ~10°C.

An investigation of the visual stratigraphy was also carried out for the site (Fegyveresi and others, 2019a). Seasonal coarse-grained and depth-hoar layers were used to identify the annual layers (also see Gow, 1965), and the results reveal accumulation trends that could indicate past climatological or glaciological changes at the site. Specifically, one 1600-year interval from 6700 to 5100 years BP (years bf 1950) experienced a higher-than-average accumulation rate (~8.1 cm w.e. a^{-1}), while one 700-year interval from 3100 to 2400 years BP (years bf 1950) experienced a lower-than-average accumulation rate (~6.4 cm w.e. a^{-1}); several analyses have suggested these temporal patterns in the core are related to upstream spatial patterns in accumulation and redistribution of snow (Winski and others, 2021, Morgan and others 2022).

Over 1900 individual wind or iced crusts were also observed and documented, as well as one visible tephra layer at a depth of 306.6 m in the core (~3560 years BP and likely tied to an eruption of Candlemas Island in the South Sandwich Islands; Palais and others, 1987). These data contributed to the accumulation-rate reconstruction that is needed in the BND temperature-reconstruction technique, and demonstrated, not surprisingly, that the core is ordinary bubbly ice suitable for that reconstruction.

Bubble Number-Density Paleothermometry

Even with the demonstrated success of known ice-core paleoclimate proxies (such as $\delta^{18}O_{ice}$), it is essential that any such proxy or its associated reconstruction technique or model be continually tested, refined, and improved to ensure that they are spatially and temporally robust across sites with differing paleo-histories and conditions. It is also valuable to develop complementary paleoclimate reconstructions using methods reliant on entirely independent variables, so as to better corroborate those reconstructions and affirm that they represent the most accurate temperature histories. A recent study showed that borehole thermometry in interior East Antarctica yields Last Glacial Maximum (LGM) temperature estimates significantly warmer than those estimated from the traditional use of water stable isotope ratios (Buizert and others, 2021), providing a need for independently calibrated temperature proxies to resolve this discrepancy.

Based on the modeling in Alley and Fitzpatrick (1999), Spencer and others (2006) developed a technique that allows for the reconstruction of either paleotemperatures or paleo-accumulation rates by fitting a semi-empirical steady-state model to measured number-densities of bubbles in ice cores. Polar firn densification is primarily driven by temperature and accumulation rate (Gow, 1968); however, during burial following pore close-off, ice grain sizes quickly become unreliable indicators of firnification conditions due to various processes that depend on other factors such as ice deformation rate (Spencer and others, 2006). Given that the geometry of firn at pore-close off is essentially self-similar (Gow, 1968), the integrated effects of temperature and accumulation rate on density and grain growth are therefore recorded in the number-density of bubbles formed as the firn is transformed into ice at the pore close-off depth (Spencer and others, 2001; 2006). Furthermore, due to slow gas diffusion between ice-core bubbles, bubble number-densities in ice can reliably preserve information about firnification conditions over longer periods (Alley and Fitzpatrick, 1999).

Conserved number-density then allows for the use of the firn-densification and grain-growth models to invert for either the firnification paleotemperature or paleo-accumulation rate, provided the other parameter is known. This method was updated and applied successfully using ice-core data from the WAIS Divide site, revealing an overall ~1.7°C Holocene cooling—with notable smaller climatic trends contained therein—that also agreed with $\delta^{18}O$ reconstructions (Fegyveresi and others, 2011; 2016).

As noted, the South Pole site experiences a unique combination of environmental variables for an Antarctic site, most notably its relatively high mean-annual accumulation rates for its relatively low mean-annual temperature (Casey and others, 2014). Both of these site conditions favor slower grain growth with depth, and therefore smaller mean grain and bubble sizes, as well as higher bubble number-density values (Gow, 1968). Combined with a higher-resolution annual stratigraphy as compared to other East Antarctic sites, it places South Pole into a “sweet spot” with respect to bubble number-density, allowing for both a greater depth of resolvable annual layers, as well as the potential reconstruction of temperature histories back through the most-recent glacial termination into the Pleistocene (the Spencer model has not yet been successfully applied to any ice core containing bubbly ice older than Holocene-aged). It is worth noting that the South Pole site is located in a flank-flow setting, and therefore the climatic record from deeper in the core represents conditions from farther upglacier, introducing the need for ice-flow corrections to answer certain paleoclimatic questions, with the associated uncertainties in ice flow (Fudge and others, 2016; Lilien and others, 2018) .

During field recovery of the SPC14 core, it was also observed that the core exhibited very minimal brittle-ice behavior, even at brittle-ice zone (BIZ) depths traditionally associated with extreme instability, fracturing, and spalling (Souney and others, 2021; Fegyveresi and others, 2019a). Later inspection of thin sections prepared from the core also revealed a nearly complete lack of any chessboard subgrain structures, likely arising in large part from the small grain sizes which in turn are controlled by the high accumulation rate and low temperature of the site. Recent work by Fitzpatrick and others, (2024) and Barnett and others (2023) suggests that brittle behavior involves fracturing along the chessboard subgrain boundaries. This diminished brittle-ice behavior has implications for site-selection for future ice cores. It also was extremely favorable for more continuous and accurate bubble number-density measurements, as bubble-section preparation was less affected by cracking during the ice cutting and microtoming processes, resulting in more-pristine (and defect-free) imagery.

Because of the higher bubble number-density counts, lack of overall brittleness, and smaller grains, the South Pole core is excellent for both applying and refining the Spencer model, and for testing new measurement techniques and methods. As noted by Fegyveresi and others, (2011; 2016), measurement of bubble number-density on bubble-sections introduces small uncertainties due to the 2D stereological projection of 3D bubbles, which might be avoided with three-dimensional measurement techniques that capture true volumetric data and imagery, such as X-ray microtomography.

Over the past two decades, micro-computed tomography, or simply *micro-CT*, has been shown to be an effective tool for measuring three-dimensional properties of glacier ice without significant degradation to the sample (e.g., Hagenmuller and others, 2013; Dadic and others, 2019; Bagherzadeh and others, 2023). Micro-CT technology generates three-dimensional images composed of an integrated collection of two-dimensional projections, or "slices," of the target specimen. At high enough resolution, this technique can therefore generate not just true 3D counts of trapped bubbles in a given volume, but also volumetric size estimates of those bubbles. Here, we prepared 11 unique micro-CT samples at 100-m intervals (and from equivalent depths to those of traditional bubble-section sampling) as a way to test the efficacy and accuracy of the technology for measuring bubble number-density and mean bubble sizes. Our primary objective was to determine if this technique could be used as a viable alternative for ascertaining bubble counts, and ultimately, bubble number-density. We show that this new technique is viable and indeed non-destructive of the prepared samples, and can greatly reduce sample preparation and imaging processing time for future ice-core measurements.

METHODS AND DATA

Bubble Number-Density

To obtain both the ice-core bubble-sections and micro-CT sections, samples were first cut from the appropriate core depth sections in the National Science Foundation Ice Core Facility's -26°C ice preparation room. Following Fegyveresi and others (2011; 2016) we used a band saw to first cut thick bubble sections ~10 cm long by ~6 cm wide by 5 mm thick, at 20-meter depth intervals ranging from 160-1200 m depth in the core. One face of each sample was smoothed with a sledge-type microtome and then affixed to a glass slide using a combination of silicone oil and tinkered water-ice. These samples were then microtomed to ~1.5 mm overall thickness and recorded with several overlapping high-resolution images using the on-site digital camera stage. Final imagery was stitched using *Adobe Photoshop* software to produce the high-resolution bubble-sections (e.g., Figure 1). Estimates of bubble number-density were calculated—with appropriate bubble-cut corrections—following Fegyveresi and others (2011; 2016), and using the *QIA-64* (formerly *Fovea Pro*) image analysis plug-in for *Adobe Photoshop*.

~(Figure 1)

Micro-CT samples were cut at 100-meter intervals ranging from 200-1200 m depth. These samples measured 2.5 cm square, by 8 cm long and were split in half for replicate measurements. All micro-CT measurements were made on site in a -10°C cold room at the Cold Regions Research and Engineering Lab in Hanover, NH. We used a Bruker SkyScan 1173 desktop micro-CT scanner with a Hamamatsu 130/300 tungsten X-ray source and flat-panel sensor camera detector, with samples mounted in standard plastic measurement containers (see e.g., Figure 2). The X-ray source of the SkyScan 1173 produces a fixed conical, polychromatic beam that operates a distortion-free X-ray detector with a source spot size of < 5 µm, a spatial resolution detectability of < 4 µm, and contrast resolution of < 7 µm. For our measurements, we set the maximum accelerating voltage of the X-ray beam at 40 kV, with a current of 200 µA. Samples were rotated 180° in 0.35° steps, with 5-frame averaged attenuation images captured at each step using a camera exposure of 400 ms. We used a 2 x 2 binning protocol to create final X-ray radiographs of 1120 x1120 pixels. Reconstructions and analyses of these radiographs were carried out use the native Bruker software package NRECON, which uses a modified Feldkamp cone-beam algorithm to produce a vertical stack of gray-scale cross-section images. As part of the image post-processing, we performed ring artifact reduction, post-alignment and beam hardening corrections, and a two-pixel Gaussian kernel smoothing to reduce noise. The resulting images had a spatial resolution of 15 µm per voxel (e.g. Figure 3). We selected a smaller internal volume of interest (VOI) for analyses, measuring ~10,000 mm^3, in order to eliminate sample edge effects and gaps. We performed three-dimensional analyses on the resulting segmented images using Skycan CTAn software. Standard binary thresholding and 5-voxel despeckling algorithms were first applied to reduce image noise and eliminate non-bubble defects. Final returned data included all measured feature (bubble) counts and sizes. Overall measurement errors reflect a combination of analytical instrument uncertainty and the one sigma (1σ) standard of replicate samples.

~(Figures 2 and 3)

Bubble number-density is the number of bubble centers in a given volume of ice, but because of the finite size of bubbles, parts of some bubbles with centers outside of a sample will be observed in a sample. Standard correction methods have been developed for these “cut bubbles”, and were followed here (see Underwood, 1970; Saltykov, 1976; Martinerie and others, 1990; Fegyveresi and others, 2011). We also followed Lipenkov (2000) and Ueltzhoffer and others (2010) in identifying and eliminating any “microbubbles” from our bubble counts. In ice from especially cold sites such as South Pole, microbubbles can account for up to 20% of total observed bubbles (Lipenkov, 2000), although in our measured samples, they were never greater than 5%. Consequently, the highest concentration of microbubbles we eliminated in any of our samples was 5% of the total bubble count, and errors in identification are a small fraction of that. Similar to WAIS Divide (Fegyveresi and others, 2016), for the purpose of using bubble number density as a climate indicator, this small concentration was negligible.

We measured bubble number-density using the bubble-sections and micro-CT samples, with typical values ranging between 800 and 900 bubbles cm^{-3} over the clathrate-free portion of our sampling interval—with a maximum value of 938 bubbles cm^{-3} measured at depth of 500 m (Figure 4). These number-densities are notably higher than published values from other ice-core sites (see e.g., Spencer and others, 2006; Fegyveresi and others, 2011), reflecting the combined effects of the relative colder mean temperatures, and higher mean accumulation rates at South Pole. The onset of clathrates did begin to notably affect our data below ~1100 meters, so for the purposes of our paleoclimate reconstruction, modeled temperatures from below this depth were considered unreliable. The glacial-interglacial transition, occurring between ~1100-800 m in depth, is not immediately obvious in the raw BND data. This is because the colder temperatures and lower accumulation rates during glacial periods have opposite effects on BND.

~(Figure 4)

Accumulation-Rate History

As noted above, reconstruction of paleotemperatures from bubble number-density data requires paleo-accumulation rates. Here, we describe our accumulation history after a short review of earlier work illustrating important characteristics of the site.

Beginning in 1965, several shallow firn and ice cores were drilled near South Pole Station (e.g., Gow 1965; Giovinetto and Schwerdtfeger 1965; Kuivinen 1983; Mosley-Thompson and others 1999), each resulting in slightly different modern mean accumulation-rate estimates, ranging between 5.0 and 8.5 cm w.e. a^{-1} (see also van der Veen and others 1999; Casey and others 2014). During the 2002-2003 field season, the International Trans-Antarctic Scientific Expedition (ITASE) drilled a 207 m core approximately 8 km from the South Pole Station as part of their array of Antarctic cores. Visual stratigraphy was measured on this core in the field, yielding an accumulation rate of approximately 7.6 cm w.e. a^{-1} when averaged over the 207 meters (A. Gow, pers. comm., 2015; Sneed and others 2011). The most recent estimate of modern mean-accumulation rate derived from the SPC14 core is ~7.4 cm w.e. a^{-1}, ranging between ~7.0 and ~9.0 cm w.e. a^{-1} through the Holocene (Fegyveresi and others, 2019a; Winski and others, 2019).

Because the South Pole site is in a region of flank flow (not on an ice divide), with notable uncertainties in flow velocities over the history of accumulation of the ice in the core, the origin of measured accumulation can be somewhat complicated (Casey and others 2014; Lilien and others, 2018). Estimated regional ice-flow velocities for South Pole range between 9.6 m a^{-1} and about 10.1 m a^{-1} (Hamilton 2004; Bamber and others 2000), and therefore the provenance of any measured ice from deep within recovered cores at the site, is likely hundreds of kilometers upstream and sourced from a very large total catchment area.

Deeper layers in the SPC14 ice core were deposited upstream of the current coring location; therefore, the effective accumulation rate (A) in the core reflects both past climatic changes and upstream patterns of snow accumulation (Lilien and others, 2018; Fudge and others, 2020). Variations in the latter appear well-correlated with the surface curvature, or second derivative of the surface elevation, along the flow path, suggesting a role of surface snow redistribution by katabatic winds (Morgan and others, 2022). The SPC14 (A) history has been reconstructed in various ways. Winski and others (2019) reconstructed Holocene accumulation rates based on annual layer thickness and a simple one-dimensional Nye ice flow model (Nye, 1963). The advantage of this method is that it allows high temporal resolution; however, it relies on a simplified and somewhat poorly constrained ice-flow model. Kahle and others (2021) used a statistical inverse approach to simultaneously reconstruct a number of glacio-climatological parameters (A, T, thinning function) using empirical reconstructions of the water isotope diffusion length and the gas age-ice age difference (Δage). The advantage of this approach is that it covers the full length of the ice core; however, the method is not optimized for reconstructing past A, and it does not incorporate firn thickness information available from the isotopic composition of N_2 ($\delta^{15}N\text{-}N_2$). Here we use an empirical method to reconstruct A based on its fundamental relationship to firn thickness and firn age (Buizert, 2021). Vertical gas diffusion within the firn pore network effectively stops at the lock-in depth L. At this depth the gravitational isotopic enrichment of gases (such as $\delta^{15}N\text{-}N_2$) halts, and the Δage is fixed (Sowers and others, 1992). The ice-equivalent lock-in depth (L_{IE}) gives the amount of ice (in meters) above L, and is given by:

$$L_{\mathrm{IE}} = \int_0^L \rho(z)/\rho_{\mathrm{ice}} dz \qquad (1)$$

Over a wide range of climatic conditions, the ratio L_{IE}/L is constant and around 0.7 (Parrenin and others, 2012). Presently at South Pole this ratio is 0.712 (Vandecrux and others, 2023). The SPC accumulation rate is therefore given by:

$$A = \frac{L_{\mathrm{IE}}}{\Delta\mathrm{age}} = \frac{L}{0.712 \times \Delta\mathrm{age}} \tag{2}$$

For SPC, the Δage has been empirically reconstructed by combining volcanic synchronization of the ice ages, and methane synchronization of the gas ages to the WAIS (West Antarctic Ice Sheet) Divide ice core that has an accurate layer-counted chronology and a small Δage (Buizert and others, 2015; Epifanio and others, 2020; Sigl and others, 2016). In our reconstruction, we add 25 years to the published empirical Δage values to account for the diffusive age of the gases and thereby estimate the true ice age of lock-in (Buizert and others, 2013). Past *L* is reconstructed directly from the SPC $\delta^{15}N$ data using the barometric equation (Sowers and others, 1992), where we apply a cubic spline for smoothness and assume a constant 4-meter convective zone thickness. We use standard error propagation techniques to estimate the uncertainty in *A* from the uncertainties in the empirical Δage (Epifanio and others, 2020) and in *L* (set to 5 m). The resulting (1σ) uncertainty ranges from 5% to 15% of *A*. The *A* values reconstructed in this manner do not reflect the instantaneous values, but rather the values averaged over a time period corresponding the lifetime of the firn layer (ice equivalent, Δage). For the purpose of interpreting bubble number-densities with respect to paleo-temperatures, this is actually the more meaningful parameter. Our accumulation record is shown in Figure 5. Errors bars represent an RMS combination of the calculated gas-age/ice-age (Δage), and lock-in depth (L_{IE}) uncertainties.

~(Figure 5)

RESULTS AND DISCUSSION

Paleotemperature reconstructions were calculated using the model developed by Spencer and others (2006) and incorporating the firn thickness accumulation record derived from the isotopic composition of N_2 ($\delta^{15}N$-N_2). We used the most recent dating of the SPC14 core that is based on volcanic ECM sulfate matching to the WAIS Divide core, together with annually resolved chemistry and visual stratigraphy (Winski and others, 2019), to convert sample depths to equivalent ages. This depth-age scale reveals that our samples do capture the entirety of the glacial-interglacial transition above the depth of clathrate-dominated ice (which affected our samples aged greater than ~20 ka (kyrs bf 1950).

The published bubble number-density model of Spencer and others (2006) uses a bubble-per-grain ratio at close-off of G = 2.02 ± 0.08, from a best fit to a suite of 15 data sets from sites with different temperatures and accumulation rates in Greenland and Antarctica. Some of the variability in their best-fit relation may arise from site-specific depositional effects, impurity effects, or influences of different ice-flow strain rates. None of these effects are large in the original study, and the technique yields useful results with the general multi-site calibration; however, a site-specific calibration can largely remove any of these not-yet-quantified effects. The small difference between site-specific calibrations and the multi-site calibration means that any time-evolution of the site-specific part of the calibration has a very small effect. Given the unique conditions for South Pole, including flank flow and uncertain history of ice-flow velocities, we conducted a detailed study of targeted samples across the South Pole pore close-off depth (~120 m) to determine a site-specific bubble-per-grain ratio, yielding a value of G = 1.51 ± 0.05. While this value does not fall within the original study's published uncertainties, we feel this can be explained by the unique combination of site conditions for South Pole. This lower site-specific value of G serves primarily to shift the mean temperature of the reconstruction to more closely match estimated modern temperature at the site, with little effect on the calculated magnitude of temperature changes.

The resultant reconstruction using both the traditional bubble-section imagery and the micro-CT derived imagery reveals a warming across the late glacial-interglacial transition of ~7.5°C ± 0.87°C (Figure 6). For each sample in the study, an integrated paleotemperature (representing the average temperature over the firnification time) was therefore determined using measured bubble number-density, average accumulation rate for firnification time of the sample, and the steady state model values of Spencer and others (2006). Combined error from the updated locally tuned model, the average accumulation rates, and estimated (RMS) mean bubble counting error of bubble number-density across our 53 traditional bubble-section samples (± 17 bubbles cm^{-3}), gives an average temperature error of ± 0.85°C. Combined error across our 11 micro-CT samples (± 14 bubbles cm^{-3}) gives an average temperature error of ± 0.89°C. These results support the use of 3D micro-CT imagery in place of traditional bubble-section techniques as this approach more easily produced comparable temperature reconstructions with similar measures of uncertainty. Comparing the new empirical BND temperature estimate with water stable isotopes in the core implies an isotope-temperature regression slope of 0.97 ‰ $°C^{-1}$ for $\delta^{18}O_{ice}$ for the LGM-preindustrial difference.

~(Figure 6)

We observed other noteworthy trends in our paleoclimate reconstruction. Our data reveal a relatively stable site temperature history through the Holocene at South Pole, with only a slight (< 0.5°C) total warming—though with an upstream correction for deposition elevation the climatic temperature trend would be smaller or might disappear. This observation is consistent with several other published values for East Antarctic sites (e.g., Ciais and others, 1994; Stenni and others, 2004). Additionally, our data capture a clear Antarctic Cold Reversal (ACR) trend that closely matches the published timing estimates for a composite of six Antarctic sites by Pedro and others (2011), falling between their earliest ACR onset (14.80 ± 0.20 kyrs bf 1950) and latest ACR termination (13.02 ± 0.20 kyrs bf 1950). Lastly, and similar to our observations from WAIS Divide, the onset of clathrates became clear in samples below ~1100 m (aged greater than ~20 ka), and we therefore do not show those reconstructed paleotemperatures. Clathrates were observed in bubble-section samples in very small numbers as shallow as ~800 m, but were only abundant below ~1100 m, and therefore the presence of these clathrates did not significantly affect our analyses or reconstructions in shallower samples.

A decrease in accumulation rate often results from a decrease in temperature through dependence on the saturation vapor pressure, at ~7%$°C^{-1}$ (Denton and others, 2005; Banta and others, 2008; Frieler and others 2015). The linear regression observed in our South Pole data yields a relationship of ~13%$°C^{-1}$ (R^2 = 0.88), however using log-scaled accumulation rates and the recently published methods by Nicola and others (2023), a regression yields 11%$°C^{-1}$ (R^2 = 0.92; Figure 7). This reveals a dependence greater than for thermodynamic control alone, suggesting contributions from dynamic processes, synoptic weather patterns, or changing ice sheet surface slopes. These values are consistent with the recent model-based studies that suggest a higher value (> 10%$°C^{-1}$) in the Antarctic interior (Nicola and others, 2023).

~(Figure 7)

Our modeled temperature history is consistent with other independent reconstructions for the site. As detailed above, our model estimates temperatures based on bubble number-density measurements from discrete depths in the core that are integrated over their respective pore close-off firn thicknesses, and corrected only for the effects of thinning. These estimates therefore represent temperatures during the time and at the place that the sample was in firn, such that older samples record conditions from farther upglacier. Temperature estimates reported by Buizert and others (2021), and Kahle and others (2021) include data that are similarly uncorrected for upstream ice advection and therefore are used here for direct comparison.

Buizert and others (2021) specifically distinguish three temperatures in their study: climatic temperature (T_{CLIM}), surface temperature (T_S), and vapor condensation temperature (T_C). In their study, they empirically reconstruct surface temperatures (T_S) by using either the isotopic composition of N_2 ($\delta^{15}N$-N_2) and empirically-reconstructed Δage as noted above, or by inverting measured borehole temperatures. Upper and lower bounds of their reconstructed paleotemperatures reflect a Monte-Carlo estimation of the uncertainty in the method reflecting: (1) the firn densification model tuning, and (2) the analytical uncertainty in the data used ($\delta^{15}N$-N_2 and empirical delta-age). As they reconstruct site temperature (T_S), their data are therefore comparable to our site temperatures estimated here. Data from Buizert and others (2021) with published uncertainties, are shown for comparison to our data in Figure 8-a. In their study, they found a glacial-interglacial temperature difference at the South Pole site (reported as a cooling of the LGM as compared to the preindustrial period), to be 6.1°C ± 1.5°C consistent with an isotope scaling of 1.19 ‰ K^{-1}. Our estimate of ~7.5°C ± 0.87°C falls within the uncertainty bounds of their estimate.

Kahle and others (2021) use a novel approach to combine isotope diffusion length and other data sets from the SPC14 core to constrain temperature, accumulation-rate, and ice-thinning histories to estimated paleo-temperatures for South Pole. Their approach reveals a best-fit linear calibration between $\delta^{18}O$ and the mean of their reconstruction using a scaling of 0.99 ± 0.03 ‰°C^{-1} (2σ). Their published reconstruction using this best-fit calibration, and destrained to correct for ice thinning, is shown for comparison in Figure 8-b. In their work, Kahle and others (2021) note that while they used a diffusion length determined from the $\delta^{18}O$ power spectrum in the reconstruction, they did not use absolute $\delta^{18}O$ values. As such, their results serve as a truly independent calibration of the traditional water-isotope thermometer, and as an excellent reconstruction for comparison here. Most notably, their site temperature reconstruction gives a glacial-interglacial temperature change at the South Pole site of 6.65 ± 0.96°C (1σ). Similar to the Buizert and others (2021) reconstruction noted above, our estimate of ~7.5°C ± 0.87°C also falls within the uncertainty bounds of this estimate.

~(Figure 8)

The close agreement among the three histories is consistent with $\delta^{18}O$ providing a useful quantitative record of surface temperature and validates the use of bubble number-density as an independent measure of paleotemperatures. All three independent methods find temporal isotope sensitivities of around 1 ‰ $°C^{-1}$ or greater, which is larger than the spatial regression slope of around 0.8 ‰ $°C^{-1}$ (Masson-Delmotte and others 2008). We therefore conclude that the spatial regression slope method, as commonly used in Antarctic temperature reconstruction, overestimates the magnitude of glacial-interglacial temperature change at South Pole and possibly other locations.

Simple calculations using published ice velocities (~3-10 m a^{-1}) for South Pole (Lilien and others, 2018) as well as estimates of surface slope (~0.0015) and dry adiabatic lapse rates (~10°C km^{-1}) indicate that almost all of the change in observed temperature across the transition is likely climatic, and not due to advection. Similar advection-corrected estimates were calculated by Kahle and others (2021) and found that upstream advection may account for at most, about 1°C of the measured difference temperature change across the transition.

Our results here also show that micro-CT measurements are comparable to those acquired through traditional methods, and therefore are appropriate for other ice-core derived estimates or reconstructions. Sample preparation and measurement via tomography is effectively non-destructive allowing for multiple and/or subsequent sample measurements. Traditional bubble-section preparation comes at the expense of significant ice loss through the microtoming process, and the resultant samples are limited to bubble-section analyses. Samples prepared for micro-CT measurement could be scanned multiple times and even repurposed for other co-registered physical, chemical, isotopic, or gas measurements. The micro-CT also allows bubble shape measurements, which may help in future studies following Fegyveresi and others (2019b) in use of bubbles as strain indicators.

Not only did the South Pole site allow the first successful implementation of the Spencer model across the glacial/interglacial transition, it also almost entirely avoids the difficulties posed by brittle ice. The South Pole ice core was remarkably stable upon recovery, exhibiting very minimal brittle-ice behavior. A subtle "brittle ice zone" was present within the SPC14 core within the depth interval of ~620-1080; however, the ice did not exhibit the typical brittle hallmarks upon recovery such as extreme cracking or spalling. (Souney and others, 2021; Barnett and others, 2023). This notable lack of brittleness, is most likely attributable to the unique site characteristics at South Pole, rather than the drilling and core handling procedures (Souney and others, 2021).

As noted above, Barnett and others (2023) and Fitzpatrick and others (2024) found that brittle ice behavior is likely connected to fractures following chessboard subgrain boundaries within the ice, which are favored by large bubble and grain sizes. Consequently, at sites with small mean grain sizes and high bubble number-densities such as South Pole, this may explain the observed lack of brittle ice behavior. Given the minimal brittle behavior of the South Pole ice core, it was an ideal candidate for the testing of the new micro-CT bubble measurements we present here, as the majority of our samples were intact and/or defect free.

CONCLUSIONS AND FUTURE WORK

We applied the ice-core bubble number-density paleoclimate model developed by Spencer and others (2006) to new samples recovered from the South Pole Ice Core (SPC14), and found ~7.5°C ± 0.87°C warming from ~19.5 ka to the present from samples measured in the upper 1200 meters of the core. This is the first successful application of this independent paleoclimate model across the most recent glacial/interglacial transition, made possible in large part by the minimal presence of brittle ice and the depth of significant clathrate onset (below ~1100 m). The data show a relatively stable Holocene (< 0.5°C of warming) and a clear Antarctic Cold Reversal signal (between approximately 15 and 13 ka). These findings agree closely with other published independent reconstructions for South Pole based on stable isotope measurements ($\delta^{15}N$ and $\delta^{18}O$), as well as published results from other East Antarctic sites (e.g., EDC). Accumulation rate and modeled temperature varied together across our data sets (~11%$°C^{-1}$), suggesting contributions from dynamic processes, synoptic weather patterns, or changing ice sheet surface slopes.

We also show that using 3D micro-CT imaging is a highly effective and comparable tool for measuring bubble number-density in core samples, and significantly reduces sample processing time when compared to traditional bubble-section techniques. This new method is also non-destructive to samples, preserving them for additional future analyses. Future analyses of bubble shape data, such as elongation orientation and aspect ratio, are planned in order to expand the work by Fegyveresi and others (2019b). We note that there currently does not exist any technique for capturing hybrid grain/bubble analyses in 3D through micro-CT (or c-axis measurements); however, new methods are being continually developed that may further the potential for more expanded ice-core physical properties measurements.

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DATA POLICY

All data presented here are available through the request of the corresponding author, or via download from USAP-DC (https://doi.org/10.15784/601880; Fegyveresi, 2025)

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Figure Captions

Figure 1: An unedited bubble-section image from the 160 m vertically oriented sample (just below pore close-off). Image shown with scale and stratigraphic core orientation.

Figure 2: Bruker SkyScan 1173 X-ray micro-CT instrument located in a -10°C cold room at the Cold Regions Research and Engineering Lab (CRREL). Scanner shown with a sample mounted in plastic specimen container on the measurement stage.

Figure 3: A volumetric 3D rendering of micro-CT imagery for the sample taken from 300 m depth. Each small feature represents a bubble measured within the sample volume of interest.

Figure 4: Measured bubble number-densities plotted against depth. Error bars represent estimated mean bubble count error across all samples. The clathrate-ice zone is shown in grey.

Figure 5: Firn-averaged accumulation (*A*) history (cm ice a^{-1}) for the South Pole site shown with combined uncertainty bands (grey) and discrete bubble number-density sampling depths (red). Published modern mean accumulation estimates are shown in ice-equivalent values.

Figure 6: Past temperatures at the South Pole site, calculated from measured bubble number-density and accumulation rates. Horizontal "error" bars represent the firnification time for each sample, and vertical error bars are the combined analytical errors, as described in the text. A LOESS smoothing line is shown to highlight major trends.

Figure 7: Estimates of log-scaled accumulation rates (cm ice a^{-1}) against the combined reconstructed temperatures (°C). Linear regression (with 95% confidence bands) yields a ~11% increase in accumulation rate per °C warming (R^2 = 0.92).

Figure 8: Modeled BND past temperatures at the South Pole site (from Figure 6) shown in panel (a) compared to surface temperatures (T_S) from Buizert and others (2021)—derived from the isotopic composition of N_2 ($\delta^{15}N$-N_2), and in panel (b) compared to surface temperatures from Kahle and others (2021)—derived from $\delta^{18}O$ stable isotopes (0.99 ± 0.03 ‰°C^{-1} scaling), and destrained to correct for ice thinning.