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Advection (non-climate) impact on the South Pole Ice Core

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Abstract

The South Pole Ice Core (SPICEcore), which spans the past 54,300 years, was drilled far from an ice divide such that ice recovered at depth originated at a location upstream of the current core site. If the climate is different upstream, the climate history recovered from the core will be a combination of the upstream conditions advected to the core site and the temporal changes we seek to recover. Here, we evaluate the impact of ice advection on two fundamental records from SPICEcore: accumulation rate and water isotopes. We determined the past locations of ice deposition based on GPS measurements of the modern velocity field spanning 100km upstream where ice of ~20 ka age would likely have originated. Beyond 100km, there are no velocity measurements, but ice likely originates from Titan Dome, an additional 90km distant. Shallow radar measurements extending 100km upstream from the core site reveal large (~20%) variations in accumulation but no significant trend. Water isotope ratios, measured at 12.5km intervals for the first 100km of the flowline, show a decrease with elevation (and distance upstream) of -0.008‰ m^{-1} for $\delta^{18}O$. Advection therefore adds approximately 1‰ for $\delta^{18}O$ to the LGM-to-modern change. Assuming a lapse rate of 10°C per km of elevation, the LGM-to-modern temperature change is ~1.5°C greater than if the ice had been deposited at a fixed location.

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Introduction

Ice cores provide unique and detailed records of past climate (e.g. Alley et al., 1993; Petit et al., 1999; NorthGRIP, 2004; Marcott et al., 2014). Such records are most useful if they represent the change in climate at a fixed geographic location and elevation. Two important non-climatic influences on ice core records are changes in ice-sheet elevation (Vinther et al., 2009; Steig et al., 2001; Stenni et al., 2011; Parennin et al., 2007; Cuffey and Clow, 1997) and changes in the location of ice origin due to flow (Whillans et al., 1984; Huybrechts et al., 2007; NEEM, 2013; Steig et al., 2013; Koutnik et al., 2016). Many ice cores are drilled near an ice divide to minimize both of these effects: ice thickness changes less in the interior than on the margins (Cuffey and Paterson, 2010) and there is little lateral ice flow near a divide. The change in ice thickness can be evaluated with ice-flow models (Parrenin et al., 2007; Golledge et al., 2014; Briggs et al., 2014) or measurements from the ice core itself (Martinerie et al, 1994; Steig et al., 2001; Vinther et al., 2009; Waddington et al., 2005; Price et al., 2007). The focus of this work is the impact of ice flow on the South Pole Ice Core (SPICEcore). We will use the term "advection impact" to refer to the variations in the ice-core histories that are due to deposition upstream in different climate conditions, as opposed to temporal changes in the climate at the ice-core site.

Ice cores are often drilled far enough from divides that lateral advection is important because of site characteristics (NorthGRIP, 2004; EDML, EPICA 2006; WAIS Divide, Morse et al., 2005; NEEM, 2013), logistical considerations (Camp Century, Gow et al., 1968; Dye-3, Dansgaard et al., 1969; Byrd, Hammer et al., 1980; Vostok, Lorius et al., 1985), or concern about divide migration over the drill site (Waddington et al., 2001). The importance of advection on ice core records depends on both the velocity of the ice and the gradient in the parameter of interest. For well-mixed atmospheric gases, such as carbon dioxide and methane, there is no direct impact on the histories. Instead, the affected histories are primarily those recovered from the ice phase: accumulation rate, water isotopes, surface temperature, and aerosols. Of the cores that have been drilled away from ice divides, the horizontal velocities range from approximately 1 m a^{-1} (EDML) to 12 m a^{-1} (Dye 3) and all require correction to obtain the climate history for a fixed geographic location (Whillans et al., 1984; Steig et al., 2001; Huybrechts et al., 2007; Vinther et al., 2009; NEEM, 2013; Steig et al., 2013; Koutnik et al., 2016).

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The 1750 m long SPICEcore was obtained at the South Pole between 2014 and 2016. SPICEcore was sited, in part, to take logistical advantage of South Pole station where the surface velocity is 10 m a^{-1} in the direction of 40°W (Hamilton, 2004; Casey et al., 2014). Lilien et al. (2018) inferred the flowline out to 100 km upstream and concluded that Titan Dome is the likely source region for ice reaching the SPICEcore site. Previous measurements of water isotope values upstream of South Pole are primarily from surface snow samples, which do not provide reliable time-averaged values (Masson-Delmotte et al., 2008; Dixon et al., 2013). A shallow ice core near Titan Dome (US-ITASE 07-4) provides a single estimate of accumulation (0.074 m ice equivalent a^{-1}; Dan Dixon, personal communication). Here, we assess the advection impact on the accumulation-rate, water-isotope, and surface-temperature histories of SPICEcore using new measurements in the upstream catchment.

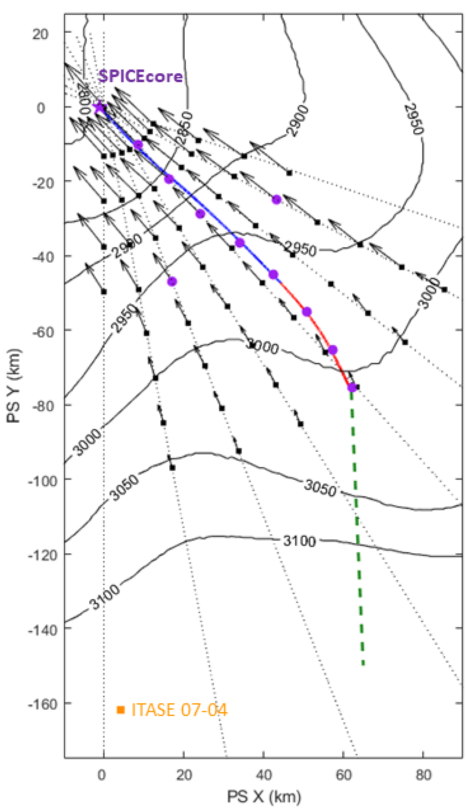

Figure 1: Map of the area upstream of the South Pole. SPICEcore location is purple star. 10m core locations are purple circles. Stake locations (black squares) were surveyed with GPS and plotted with velocity vectors. Flowline was inferred from the velocity measurements for past 10 ka (blue, from Lilien et al., 2018) and 10 ka to 21 ka (red). Unconstrained flowline for 21 ka to 55 ka is dashed green. Surface topography contours are from BedMap2 (Fretwell et al., 2013). ITASE 07-04 core at Titan Dome is orange square. Note that Titan Dome is a broad ridge and the geometry is not well defined in BedMap2 and the elevation does not match the 3090 m measured by Dixon et al. (2013).

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Methods

To assess the impact of advection on the SPICEcore climate histories, we measured ice velocity, accumulation rates, water isotopes, and firn temperatures in the upstream catchment. The surface ice-flow velocities, inferred flowline, and spatial pattern of accumulation were described by Lilien et al. (2018; http://www.usap-dc.org/view/dataset/601100) and we provide only a brief review below.

Surface Ice-flow Velocity and Flowline Determination

Determining the ice-flow velocity near South Pole is more difficult than many other locations in Antarctica; there is little satellite coverage due to the geometry of satellite orbits which creates a "pole hole." Rignot et al. (2011) used synthetic aperture radar to compute the surface velocity, but utilized a substantially tilted satellite view, resulting in velocity measurements that are not sufficiently precise to define the flowline. To obtain improved velocity measurements in the region, we performed repeat surveys of stakes with GPS during four consecutive field seasons. We installed 56 stakes at 12.5km intervals along lines of longitude from 110°E to 180°E at 10° intervals (Lilien et al., 2018). The 110° and 180° lines were measured only to 50 km from South Pole; the others were measured to 100 km (Figure 1). The measured velocities range from 3 to 10 m a^{-1}, with errors of ±0.02 to 0.25 m a^{-1} in each horizontal direction. We used the measured velocity field to determine the modern flowline. Starting at the SPICEcore drill site, we recursively stepped upstream in one-year intervals in the direction opposite the velocity vectors to obtain annual positions along the flowline. We assume that the surface velocity is constant for the upper 1750m of the ice column (the depth of SPICEcore), because the warmer ice below 1750m contributes nearly all of the deformation driving the surface velocity.

Accumulation

The accumulation rate along the flowline is derived from radar layers imaged from approximately 20 m to 100 m depth with a 200 MHz radar (details can be found in Lilien et al., 2018). The depth of a radar layer is converted to an accumulation rate using the density profile and depth-age relationship of a core drilled on the flowline 50 km upstream from SPICEcore. The firn depth-density profile is assumed to be unchanging along the flowline. The firn density affects the derived accumulation rate history both through the inferred depth of the layer due to the radar-wave propagation speed and through the conversion to ice-equivalent thickness. These two uncertainties oppose each other but do not necessarily cancel. Using four additional density profiles near South Pole, Lilien et al. (2018; Figure S4) found the spread in accumulation has a standard deviation of 2.3% for a layer at ~20m depth. Deeper layers have a smaller spread because the density is most variable near the surface. All accumulation rates are given in m a^{-1} of ice equivalent.

Water Isotopes

Water isotopes ratios of $\delta^{18}O$ and δD were measured in cores of approximately 10 m depth at 12.5 km spacing along the flowline, as well as at two sites 15 km perpendicular to the flowline 50 km upstream of SPICEcore, for a total of 10 firn cores. We also report the deuterium excess, using the log definition (d_{ln}; Markle et al., 2017). The cores were sampled at 0.5 m intervals in the field and allowed to melt in plastic bottles. The measurements were performed at the University of Washington's Isolab with a Picarro L-2120i. The average $\delta^{18}O$ and δD values (vs Vienna Standard Mean Ocean Water) for each core are presented here. The cores were not dated and thus the water isotopes cannot be averaged over the same ages; averaging using only the upper 5 m for each core instead of the full core produced negligible differences. One outlier from 0.5-1 m depth at site 25km was excluded.

10 m Temperatures

The temperature at approximately 10 m depth was measured in each borehole left by the shallow-core extraction. We averaged the values measured by four thermistors surrounded by a copper shield. The thermistors were left in the borehole for different lengths of time ranging from 28 minutes to 48 hours.

Results

Gradients in Upstream Climate Parameters

Accumulation

The accumulation rate along the 100 km flowline for four different internal layers is shown in Figure 2. The youngest layer is 151 years before 2017 (~20m depth) and was used by Lilien et al.

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(2018); the 743-year layer is the deepest (~90 m) layer resolved. Although the layers are relatively young, there can still be a horizontal offset of hundreds of meters to kilometers from where the layer was deposited on the surface. In Figure 2A, the accumulation rates in the upper panel are plotted at the position of the radar trace. The impact of horizontal advection can be observed as the older layers appear shifted to left (closer to SPICEcore) compared to the younger layers.

To account for horizontal advection, the position where the accumulation rate is inferred (i.e. the location of the radar trace) is adjusted. This adjustment is made by multiplying the half-age of the layer by the surface velocity at the mid-point of its path from deposition to the current trace location (Figure 2B). The adjustment ranges from 3.7 km at SPICEcore for the 743-year layer to 0.2 km for the 151-year layer at the upstream end. Shifting the distance of the accumulation records (Figure 2C) better aligns the peaks and troughs among the four layers. It also highlights that older layers vary less along flow. The depth of a layer reflects the average surface accumulation rate over the distance traveled. Thus, an older layer is flatter because it averages the influence of accumulation on vertical velocity over a longer distance. This shows that simply shifting the position of the layers to account for horizontal advection does not fully recover the spatial variations in accumulation.

A more-complete treatment could solve an inverse problem to infer the surface accumulation rate along the flow line that best matches the observed layer thicknesses (e.g., Waddington et al., 2007). We do not address this problem here because we focus on the advection impact on the SPICEcore record and not a formal evaluation of the surface accumulation patterns consistent with available layers. Lilien et al. (2018, supplement) showed that the 151-year layer was sufficiently deep to record real climate variations, and not noise, but shallow enough to not be significantly affected by lateral flow.

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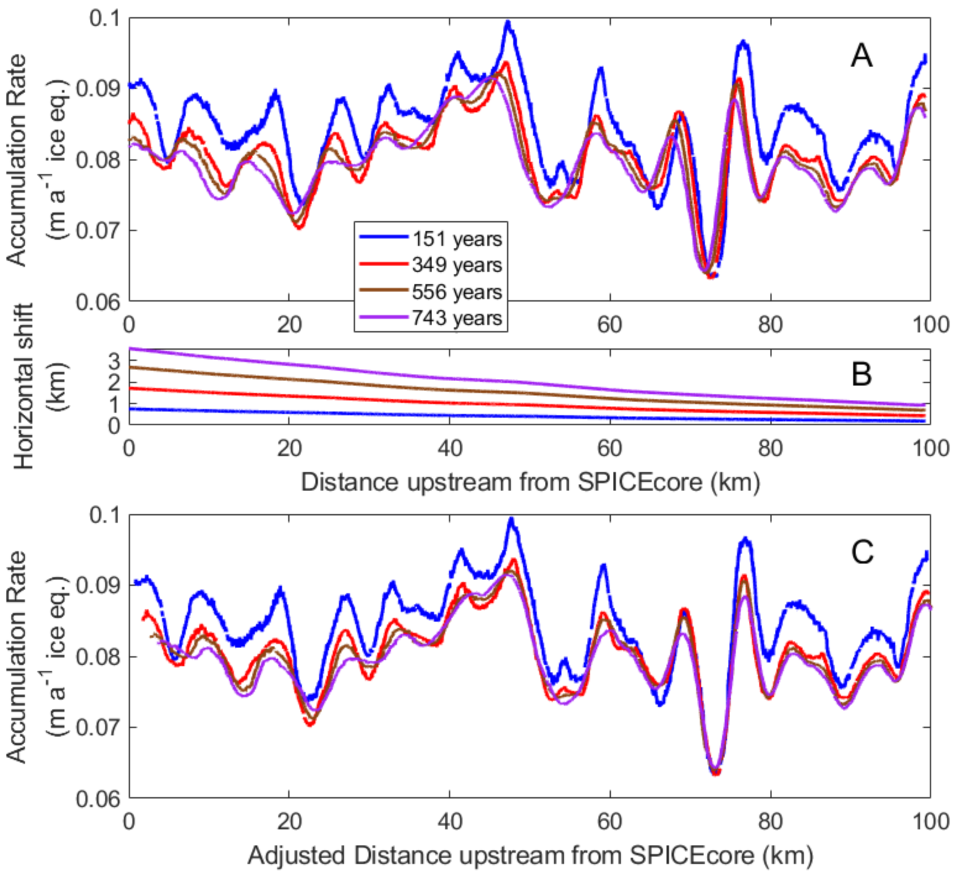

Figure 2: **Accumulation rate along flowline.** Panel A shows the accumulation rate for four radar layers, with ages in years before 2017. Panel B shows average horizontal distance traveled. Panel C shows same inferred accumulation as in Panel A, except the position is adjusted to account for the horizontal distance traveled.

The average accumulation rate of the oldest (743-year-old) layer is 0.080 m a^{-1} and there is a negligible spatial linear trend of -4×10^{-6} m a^{-1} km^{-1}. The spatial variations are approximately ±20% compared to the average value, much larger than the linear trend. Beyond the 100km of mapped flowline, the only accumulation-rate information is from the US-ITASE 07-04 core near Titan Dome, where an accumulation rate of 0.074 m a^{-1} was inferred (Daniel Dixon, personal communication, 2013). This is within the range of accumulation rates identified along the

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flowline, but it is smaller than the 0.080 m a^{-1} average along the first 100km of the flowline. With only a single point measurement, we cannot resolve whether this accumulation rate near Titan Dome is representative of a mean value for a wider area.

We also calculate the accumulation rate for the intervals between successive layers (Figure 3) which allows temporal trends to be more clearly evaluated. The uncertainty in the accumulation rate is greatest for the 151-year layer because the density measurements are least certain in the lower-density surface snow, and surface firn conditions are more spatially variable. We calculate the uncertainty for an interval based on the density profiles of five different firn cores (the core we drilled at 50km and four cores from near South Pole; Severinghaus et al., 2001; Christo Buizert, personal communication). The uncertainty shading shown in Figure 3 is the range between the maximum and minimum accumulation rates using the five density profiles. The spatial average of the three older intervals are within uncertainty of each other. The spatial average of the 0 to 151-year interval is always greater than the older three intervals. Because the spatial average of the minimum accumulation rate (based on firn density) for 0 to 151-year is greater than the spatial average of the maximum for the older intervals, we have confidence that the accumulation rate has increased in the past 151 years. The accumulation increase is 8±4% compared to the previous 592 years (151 to 743 years before 2017).

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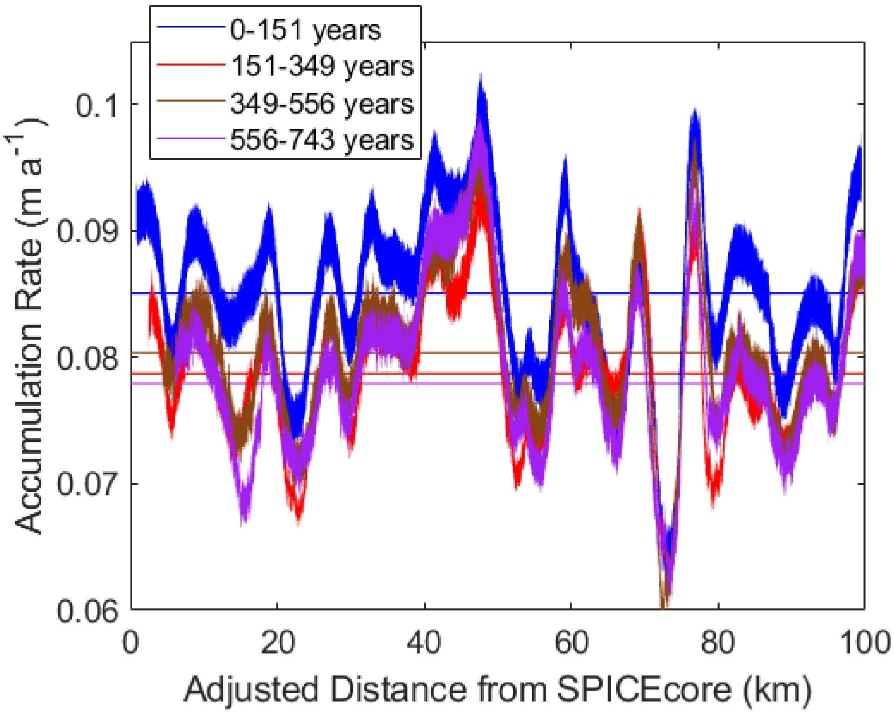

Figure 3: Temporal average accumulation rate for ages between radar layers. Shading indicates uncertainty based on five firn-density profiles. Distance from SPICEcore has been adjusted as in Figure 2 and described in main text. Horizontal lines indicate spatial average of the accumulation rate using the density profile measured on the firn core at 50km.

Table 1: Accumulation Increase in past 151 years relative to previous periods

Interval	Mean	Minimum	Maximum
151-349	8%	4%	12%
349-556	6%	1%	11%
556-743	9%	3%	13%
151-743	**8%**	**4%**	**12%**

Mean increase uses density profile from the core at 50km for all layers
Minimum (maximum) increase uses density profile which yields the minimum (maximum) accumulation rate for the 0-151 interval and the density profile which yields the maximum (minimum) for the older layers.

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Water Isotopes

Measurements of water isotopes require the collection of ice samples and thus have much more limited spatial resolution than the accumulation-rate measurements. There is considerable scatter (Figure 4) in the 0.5 m resolution samples, which have durations of a few years of time (i.e. 2-4 years) per sample; the differences among 0.5 m samples are likely driven by interannual variations. Using the mean values, a decrease with distance from South Pole is observable in both $\delta^{18}O$ and δD. The d_{ln} values show no significant trend upstream.

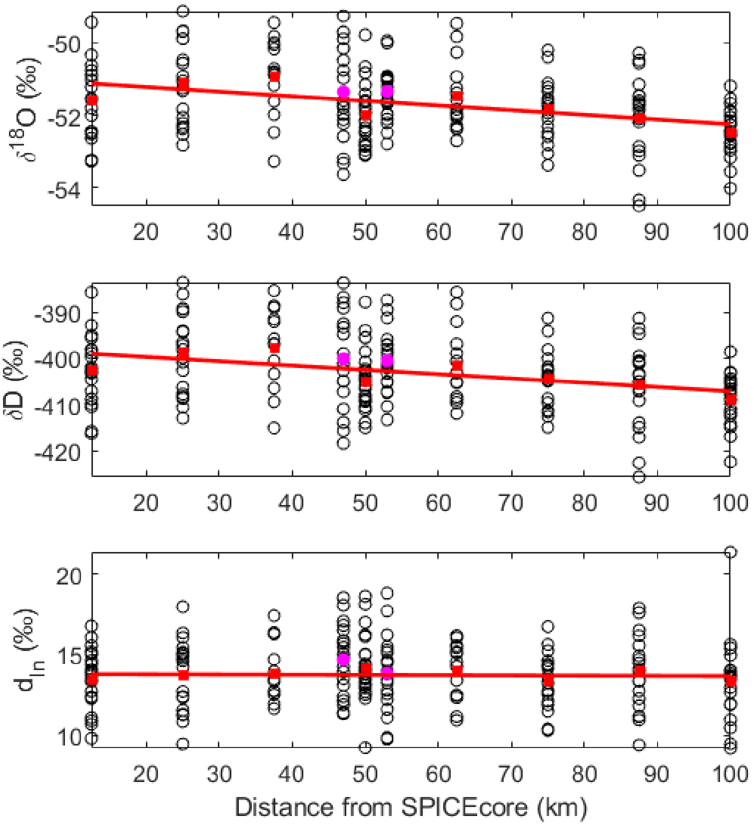

Figure 4: Water-isotope values (black circles) and averages (red squares) for shallow cores along the flowline upstream of South Pole. Cores at 50km upstream on 120E and 160E are plotted at 47km and 53km (magenta circles). Linear slope (thick red line) is from the average values along the flowline only.

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The $\delta^{18}O$ and δD values are also shown in Figure 5 but are plotted by elevation rather than distance upstream. Linear fits to $\delta^{18}O$ and δD yield slopes of -0.0080 ± 0.0055 ‰ m^{-1} and -0.0579 ± 0.04 ‰ m^{-1} respectively (95% confidence levels). Including the average $\delta^{18}O$ value from the upper 1.2m of the firn core at Titan Dome (-53.15‰) in the linear regression changes the slope to -0.0073‰ m^{-1}, which is in good agreement with the mean slope. Because the Titan Dome value is an average of only the upper 1.2m and not directly comparable in time to our 10m-average measurements, we use the mean slope of 0.008 ‰/m^{-1} from the 10m cores for the advection correction described in the subsequent section.

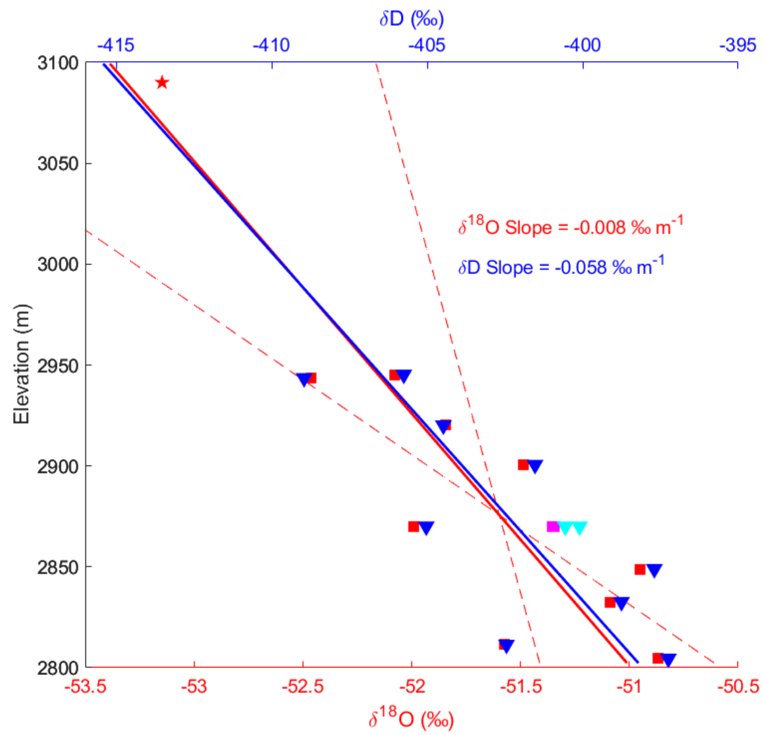

Figure 5: Average $\delta^{18}O$ (red squares) and δD (blue triangles) values from the 10m cores along the flow line and SPICEcore. Average $\delta^{18}O$ and δD from cores off of the flowline at 50km upstream (pink squares and cyan triangles). $\delta^{18}O$ of US-ITASE 07-04 core at Titan Dome (red star). Linear fit of 10m cores along the flow line for $\delta^{18}O$ (red thick line) and δD (blue thick line) do not include Titan Dome or cores from off the flowline. 95% confidence intervals of the $\delta^{18}O$ fit (red dashed lines) are shown. Confidence intervals of δD overplot those of $\delta^{18}O$ and are not shown.

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Surface Temperature Gradient

The ~10 m temperatures are shown in Figure 6. Unfortunately, a variety of differences in the measurement procedure were made because of time constraints of the field work, and these prevented a determination of the gradient in mean annual temperature. Based on cooling curves (not shown) from two boreholes, measurements that equilibrated for less than 1.5 hours yielded warmer temperatures that those left in boreholes for longer times, and we consider those measurements less reliable. Measurements that were made after leaving the thermistors in the boreholes for longer than six hours are consistent with a dry adiabatic lapse rate of 10°C km^{-1}, but we cannot reject a wide range of other values for the lapse rate.

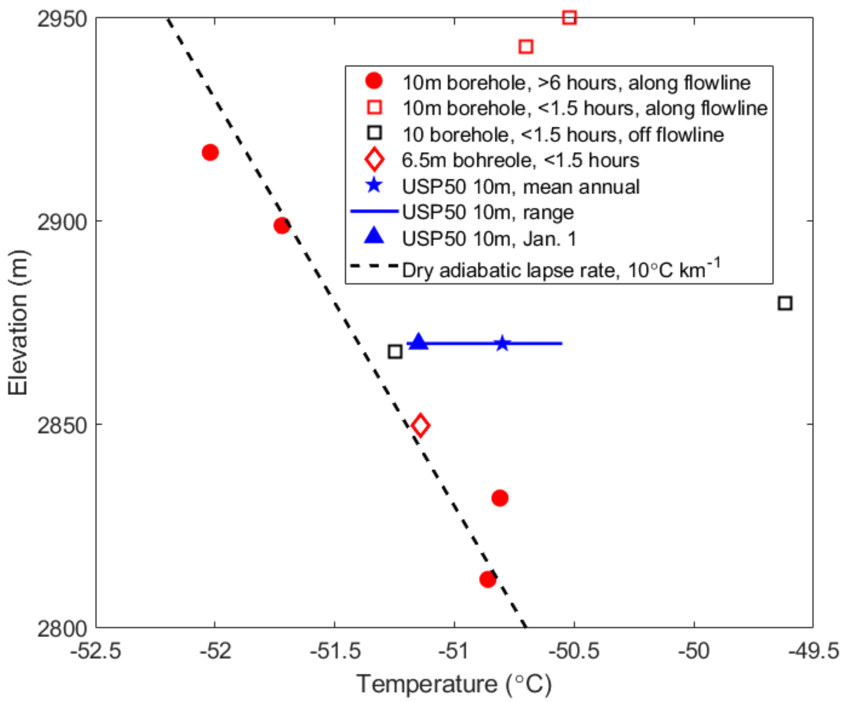

Figure 6: Temperature measurements. Filled symbols equilibrated for more than 6 hours; open symbols equilibrated for less than 1.5 hours. Red symbols are along the flow line; black symbols are off the flowline. Diamond is a measurement at 6.5 m depth, which is likely ~0.7°C colder due to the winter cold wave than if measured at 10 m depth. Blue symbols are from a single thermistor installed at 10 m depth in a back-filled borehole with measurements recorded more than 1 year; star is mean annual temperature, triangle is initial temperature after equilibration and horizontal line is the range of temperature recorded. Black dashed line shows a lapse rate of 10°C km^{-1}.

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Determination of Flowline Position and Age

The location where ice in SPICEcore fell on the surface is well constrained for the past 10 ka by Lilien et al. (2018). For ice older than 10 ka, the spatial variations in the accumulation rate cannot be clearly correlated with the layer thickness variations in SPICEcore. This is likely because: 1) uncertainty in the flowline position accumulates with distance (age); 2) the relative uncertainty in the surface velocity increases as the velocity decreases with distance upstream; 3) the surface-velocity measurement stakes are farther apart; and 4) the temporal variations in accumulation are likely larger during the isotopic maximum at ~11 ka and the glacial-interglacial transition (Veres et al., 2013; Fudge et al., 2016).

We divide the reconstruction of the flowline into three segments based on the data available. The first segment is the flowline inferred by Lilien et al. (2018) which includes the inference of a 15% speed-up during the past 10 ka. The first segment covers 70 km from SPICEcore.

The second segment of the flowline spans from 70 km to the limit of the surface velocity measurements at 100 km from the SPICEcore drill site. To determine the flowline, we assume that the direction of ice flow was not different than what is measured today. We also assume the 15% lower velocity at 10 ka found by Lilien et al. (2018) is appropriate for older ages. We recognize that velocity changes during the glacial-interglacial transition, when the accumulation rate roughly doubled, are likely; however, it is unclear what the effect is for this region. If the velocity was determined by the amount of accumulation (i.e. balance velocity), we might expect the 20 ka speed to be approximately half of the 10 ka speed, mirroring the glacial-interglacial change in accumulation rate. However, results from a full ice-sheet model (Pollard and DeConto, 2009) show surface velocities 20% faster at 20ka compared to 10 ka. On the other hand, an updated version of the same model (Deconto and Pollard, 2016), shows 25% slower velocities at 20 ka compared to 10 ka. Since there is no unambiguous estimate of velocity change during the glacial-interglacial transition, we make the simplest assumption of holding the inferred 10 ka velocity constant for older ages. Thus, ice of 21.6 ka age would have originated 100km from SPICEcore with older ice originating beyond the measured flowline.

For ice in SPICEcore with ages older than 21.6 ka, no surface-velocity measurements exist to help define where the ice originated. We examined the utility of the surface topography (Fretwell et al., 2013) in defining the flow direction by tracking particles along the steepest descent. We computed two flowlines, one stepping upstream from SPICEcore and the other stepping downstream from the 10 ka location. They do not agree with each other or with the measured flowline, which is not surprising given the limited data in the surface DEM and the convergent flow. Thus, we cannot expect the surface topography to be useful in defining the x and y components of the flowline beyond 100km. Therefore, we neglect variations in the direction of flow and assume that the ice has flowed in a straight line from an ice divide (Figure 1). The position of the ice divide is not well defined and we assume it is an additional 90km distant. We also assume that the velocity decreases linearly from its value at 100km to zero at the divide, which is equivalent to assuming a balance velocity in an ice sheet with uniform ice thickness and accumulation rate and no convergence or divergence. These assumptions suggest the oldest SPICEcore ice (54.3 ka) originated ~35km downstream from the assumed divide position.

Advection Impact

The advection impact on the SPICEcore accumulation-rate and water-isotope histories are quite different from one another. The accumulation rate is sampled with high frequency but shows no long-term trend with distance and elevation. The water isotopes, on the other hand, are sampled infrequently but show a linear trend with distance and elevation. We discuss the advection impact for the two separately.

Accumulation Rate

The lack of a linear trend in the accumulation rate along the flowline indicates that no trend should be removed from the SPICEcore accumulation history. However, the variation in accumulation upstream has a major impact on the SPICEcore history. Lilien et al. (2018) were able to isolate the influence of km-scale upstream variability for the past 10 ka, which explains a majority of the variance in the SPICEcore accumulation history. Thus, little of the variability in the accumulation history for the past 10 ka is due to climate. While the residual variance of the SPICEcore accumulation history (the accumulation history after removing the advection impact) might reflect temporal changes in climate, the residual variance is also affected by multiple

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sources of uncertainty such as the assumptions of a constant spatial pattern of accumulation, a fixed flowline, a linear speed up, and a spatially homogeneous firn-density profile. These uncertainties are sufficiently large and difficult to quantify that we do not interpret the residual as a temporal history of accumulation.

Beyond 10 ka, it is important to understand the potential influences of spatial variations in order to avoid erroneous conclusions about temporal variations in the accumulation rate over the past 55 ka. Since there is no overall trend, we are primarily interested in how the spatial variability could be imprinted in the ice-core history. Spectral analysis shows that there is significant power at a wavelength of 5 to 10 km. The temporal imprint of the spatial variations is then determined by the ice-flow velocity, which is 4 m a^{-1} for ice of 10 ka age and decreases to 1 m a^{-1} for ice of 55 ka age. The timescales affected in the accumulation history are ~1 to 3 ka during the deglacial transition (10-20 ka) and get longer, reaching 10 ka, for the oldest SPICEcore ice. The advection impact on the deglacial transition may affect the specific timing of accumulation-rate change, but not the overall temporal trend. For older ages, the advection impact has a similar timescale to millennial-scale climate variations. We thus expect that the advection impact will decrease the coherence between the accumulation-rate history and the temperature history inferred from water isotopes.

Water Isotopes

The water isotopes are not sampled at a high enough spatial resolution to perform an analysis of millennial-scale variations as was done for the accumulation rate; however, the $\delta^{18}O$ and δD both show linear trends with elevation and distance. Because $\delta^{18}O$ and δD are similar, we will discuss only the advection correction for $\delta^{18}O$ in this section (both are provided in the supplemental spreadsheet). A correction for advection becomes important, particularly for questions such as the magnitude of the glacial-interglacial change. We use a linear fit to elevation data as the base for the advection correction (Figure 7). The linear fit is continued beyond 100km at the same slope, reaching an elevation similar to the US-ITASE 07-04 core at 190km upstream of SPICEcore. We use the linear fit to avoid meter-scale elevation variability being added through the advection correction.

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The advection correction reaches a maximum of -1.7‰ at 54 ka. A negative value indicates the ice recovered in the core fell at a location where the water isotopes are more depleted than at South Pole in the current climate. Thus, the SPICEcore ice at 54 ka would be 1.7‰ more enriched if it had fallen at South Pole instead of ~150 km upstream at ~220 m higher elevation. Because the elevation change is linear with distance, the curvature of the advection impact is determined by the change in ice velocity and the advection impact increases the most rapidly at the youngest ages. The difference over the Holocene (past 10 ka) is 0.7‰ while the difference over the previous 10 ka (10 to 20 ka) is 0.36‰. The advection impact for the oldest ice is only about 0.1‰ per 10 ka. Overall, the impact on the LGM-modern change is a little more than 1‰ compared to modern, although only about 0.6‰ compared to mid-Holocene values (i.e. 5 ka).

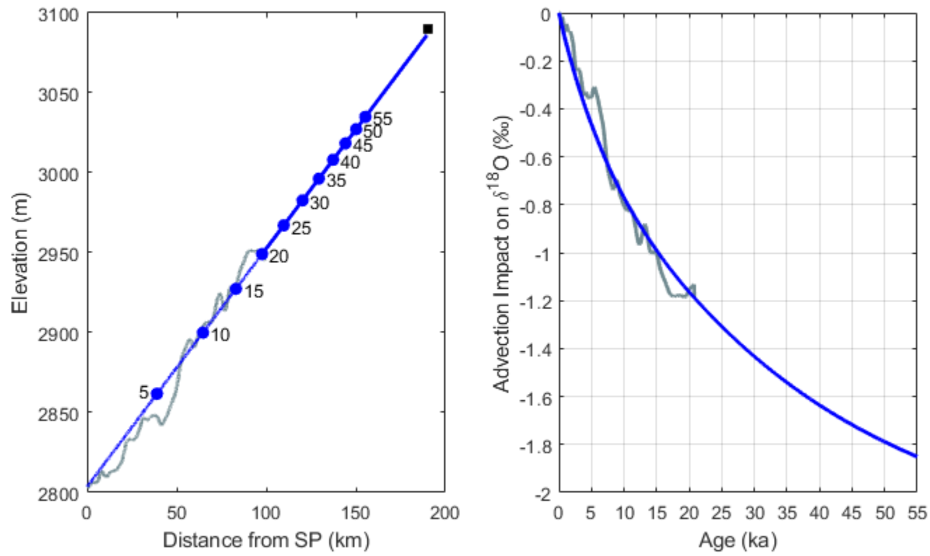

Figure 7: Advection Impact for $\delta^{18}O$. Left Panel: Elevation profile (gray) and linear fit (blue) used in advection correction. Elevations at 5 ka intervals shown by blue dots.
Right panel: Advection correction using elevations in left panel. Blue is smooth (linear elevation) correction; gray is if the modern, measured elevations were used. A negative value indicates the ice recovered in the core fell at a location where the water isotopes are more depleted than South Pole in the current climate.

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Discussion

Advection has enhanced the glacial-interglacial $\delta^{18}O$ change at SPICEcore by 1‰ because ice in the core originated at higher elevations with more depleted isotopic values. The total LGM (18 to 22 ka) to modern (past 1 ka) $\delta^{18}O$ change is approximately 6‰ (Steig et al., in prep.). Accounting for advection reduces the fixed-location glacial-interglacial change to 5‰. Advection has the opposite impact at WDC, where advection increases the glacial-interglacial change by 1‰ (Steig et al., 2013), to 8‰. Understanding the advection impact is important for comparing the magnitude of isotopic change among Antarctic ice cores; WDC has a 1‰ greater LGM-modern change than SPICEcore in the raw records, but a 3‰ greater change after accounting for advection. Because SPICEcore and WDC have similar source regions and distillation pathways (e.g. Sodemann and Stohl, 2009), the difference between the two cores has the potential to yield insight into relative elevation change between the West and East Antarctic ice sheets. A full interpretation of relative isotopic change between SPICEcore and WDC is beyond the scope of this paper, but the advection impact is a critical input for future analysis.

The advection impact on the accumulation history is distinct from that for the water isotopes. There is no linear trend in accumulation in the upstream catchment, and thus no trend to remove from the SPICEcore accumulation history. However, high spatial resolution of the modern upstream accumulation pattern has revealed that the majority of the accumulation variability in the past 10 ka (Lilien et al., 2018) is caused by advection and not temporal changes. While the upstream pattern and SPICEcore history cannot be correlated for ages older than 10ka, the spatial pattern is still expected to impact the accumulation history. The dominant timescales affected increase from ~1 ka in the Holocene to ~10 ka at 50 ka age. These timescales are similar to that of millennial climate change and thus, we expect that the coherence between isotopic and accumulation records to be decreased. Overall, changes in accumulation of less than 20% on millennial timescales should not be interpreted as a climate signal.

The different characters of the advection impact for water isotopes and accumulation arise because there is no coherent relationship between water isotopes and accumulation rate. This may be because the water isotopes are largely controlled by the condensation temperature (Jouzel et al., 1997), whereas the accumulation rate is affected by wind redistribution and the

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local surface topography (Hamilton, 2004). In fact, the curvature (second derivative) of the elevation profile along the flowline explains a third of the variance in the modern spatial pattern of accumulation, similar to areas in Greenland (Miege et al., 2013; Hawley et al., 2014).

We could not determine the temperature lapse rate from our 10m borehole temperatures; however, we can estimate the temperature impact of advection based on a dry adiabatic lapse rate of 10°C km^{-1}, which is consistent with our measurements. The LGM ice fell at 150m higher elevation and likely would be ~1.5° colder than if it had fallen at the current elevation of South Pole.

Conclusion

The relatively fast ice speed at South Pole today causes ice at depth in SPICEcore to have originated at elevations up to ~250m higher and at locations ~150 km away in the direction of Titan Dome. Our measurements in the upstream catchment define the flow direction and speed as well as spatial gradients in the accumulation rate and water isotopes. These measurements identify the non-climate impact of advection on the SPICEcore records. The accumulation rate has no spatial trend, but shows 20% variations on length scales of 5-10km; $\delta^{18}O$ shows a -0.008‰ m^{-1} depletion which enhances the measured LGM-Holocene change in the ice core by 1‰. This work facilitates accurate interpretation of the SPICEcore records as temporal histories of climate at a fixed location.

Data Availability

Velocity and radar data are available at http://www.usap-dc.org/view/dataset/601100. Water isotope, accumulation rate, and advection corrections will be posted upon publication.

Author Contributions

All authors contributed to the analysis and writing of the manuscript. HC, DL, MS, and MK performed the field work. AS, TF, and ES performed water isotope analysis.

Competing Interests

The authors declare no competing interests.

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