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Seasonally Resolved Holocene Sea Ice Variability Inferred From South Pole Ice Core Chemistry

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Key Points:

- Millennial-scale Holocene variations in sea salt sodium at the South Pole primarily originate from changes in winter sea ice extent
- Antarctic Holocene sea salt values have increased, especially from 8,000 to 10,000 years ago, reflecting a zonally symmetric change in sea ice
- We infer reduced Atlantic sector winter sea ice from 5,000 to 6,000 years ago, possibly related to North-South Atlantic Ocean heat redistribution

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Variability in sea ice is a critical climate feedback, yet the seasonal behavior of Southern Hemisphere sea ice and climate across multiple timescales remains unclear. Here, we develop a seasonally resolved Holocene sea salt record using major ion measurements of the South Pole Ice Core (SPC14). We combine the SPC14 data with the GEOS-Chem chemical transport model to demonstrate that the primary sea salt source switches seasonally from open water (summer) to sea ice (winter), with wintertime variations disproportionately responsible for the centennial to millennial scale structure in the record. We interpret increasing SPC14 and circum-Antarctic Holocene sea salt concentrations, particularly between 8 and 10 ka, as reflecting a period of winter sea ice expansion. Between 5 and 6 ka, an anomalous drop in South Atlantic sector sea salt indicates a temporary sea ice reduction that may be coupled with Northern Hemisphere cooling and associated ocean circulation changes.

Plain Language Summary Sea ice variability has a dramatic effect on regional and global climate. Because sea ice extent has such a large summer to winter difference, seasonally specific records of past sea ice conditions are necessary to properly interpret sea ice/climate relationships. Here, we present a sea salt record from the South Pole Ice Core, which represents Southern Hemisphere sea ice changes during the last 11,400 years. We use an atmospheric chemistry model to show that wintertime sea salt in the South Pole Ice Core comes mostly from salty snow originating from sea ice. Wintertime sea ice variations are responsible for most of the long-term variability in the South Pole sea salt record. Ice core data across Antarctica show increasing sea salt concentrations since 11,400 years ago, representing cooling and sea ice expansion, particularly between 8,000 and 10,000 years ago. Between 5,000 and 6,000 years ago, a drop in sea salt indicates an abrupt reduction in sea ice cover in the South Atlantic. Interestingly, paleoclimate data suggest that sea ice was more extensive in the North Atlantic at this time, indicating a linked and opposing sea ice signal in the North and South Atlantic most likely due to changing ocean circulation.

1. Introduction

Sea ice in the Southern Ocean exhibits some of the most pronounced seasonality in the global climate system. During late winter, Antarctica is surrounded by an average of 18.5 million km^2 of sea ice, diminishing to 3.1 million km^2 during summers (Parkinson, 2014; Shepherd et al., 2018). Despite rising global temperatures, Southern Ocean sea ice had remained remarkably stable until 2016, despite model projections predicting declining Antarctic sea ice (Turner & Comiso, 2017; Turner et al., 2015). Since 2016, the Southern Ocean has exhibited abrupt reductions in sea ice extent (Parkinson, 2019). However, consistent observations of Antarctic sea ice are restricted to the short satellite era (since 1979), which hinders our ability to disentangle anthropogenic changes from natural variability, to understand multi-decadal variability, or to investigate feedbacks with climate more broadly.

The recently drilled South Pole ice core (SPC14; Casey et al., 2014) provides a new opportunity to advance our understanding of Holocene sea ice variability in the Southern Ocean. Recent studies have conclusively

demonstrated connections between South Pole and low latitude climate (Clem et al., 2020; Jones et al., 2016; Turner et al., 2020). The breadth and duration of meteorological and aerosol data from the South Pole (e.g., Clem et al., 2020; Lazzara et al., 2012; Sheridan et al., 2016) is unique among ice coring locations. SPC14 has the only ice core chronology on the East Antarctic plateau that allows seasonal partitioning of chemistry records during the Holocene (Winski et al., 2019). Here we use this seasonal Holocene chronology and major ion chemistry data to provide new insights into winter sea ice variability and Southern Hemisphere climate during the Holocene.

2. Study Site

The South Pole has a relatively high modern snow accumulation rate (8 cm water equivalent yr^{-1}; Lilien et al., 2018; Mosley-Thompson et al., 1999; Winski et al., 2019), providing the unique opportunity to develop a seasonally resolved ice core chemistry record from East Antarctica. Surface winds at the South Pole originate primarily from slightly (grid) east of the prime meridian but with contributions from both the Ross and Weddell sectors of Antarctica (Clem et al., 2020; Lazzara et al., 2012; Sheridan et al., 2016). Previous studies have thoroughly characterized the South Pole aerosol climatology in relation to meteorological conditions, finding that sources of marine and temperate air to the South Pole are varied, but aerosols primarily arrive within the mid-to-upper troposphere between grid northwest and southwest, between the Ross and Weddell Seas (Arimoto et al., 2008; Harris, 1992). For both terrestrial and marine aerosols, delivery to the South Pole requires cyclonic activity to penetrate the polar cell, bringing relatively warm, moist and aerosol-laden air to the South Pole in what have been referred to as 'salt storms' (Bodhaine et al., 1986; Hogan et al., 1997; Parungo et al., 1981; Shaw et al., 1988). In these cases, typically occurring during winter months, a strong influx of lower-latitude air is needed to overcome the strong subsidence over the South Pole and prevailing katabatic winds. Whereas the flux of particulate matter to the South Pole is highest during summer months, sea salt aerosols exhibit winter peaks in both the atmosphere (Bodhaine et al. 1986, 1987; Parungo et al., 1981; Sheridan et al., 2016; Tuncel et al., 1989) and snowpack (Bergin et al., 1998; Cole-Dai & Mosley-Thompson, 1999; Ferris et al., 2011; M. R. Legrand & Delmas 1984; M. Legrand & Kirchner 1988; Whitlow et al., 1992). At the South Pole, both wet and dry deposition of ionic impurities occur in roughly equal measure (Legrand & Delmas 1987, 1988; Legrand & Kirchner, 1988), which is supported by the lack of correlation between accumulation rate and chemical concentrations from previous South Pole ice core studies (e.g., Ferris et al., 2011).

3. Methods

SPC14 was collected between 2014 and 2016 and analyzed using the Dartmouth melter system and ion chromatography (Winski, Fudge, et al., 2019; supporting information), resulting in timeseries of the following major ions: Cl^-, NO_3^-, SO_4^{2-}, Na^+, Mg^{2+}, and Ca^{2+}. The SP19 chronology was based on the very consistent seasonal variations in Na^+ and Mg^{2+} ions, constrained with volcanic tie points (Figures 2 and 3 of Winski et al., 2019). Each summer, these ions reached their annual minimum, demarcating years within the SP19 timescale. The definition of annual horizons in the Holocene SP19 timescale based on this signal, as well as its consistency, allow us to extract information about the seasonality of Na^+ and Mg^{2+} chemistry by calculating the minimum and maximum ionic concentrations for each year. The annual minimum Na^+ and Mg^{2+} concentrations occur, by definition, on January 1st during the austral summer, while the annual maximum concentrations occur during winter or early spring (Bergin et al., 1998; Legrand & Kirchner, 1988; Whitlow et al., 1992). We use multiple well-established methods to infer sea salt and non-sea salt (crustal, volcanic, biogenic, etc.) contributions of each ion at South Pole (Figures S1–S3), all of which yield consistent results. These methods also allow us to define Na^+ originating from marine sources (ss-Na^+), which we use as our primary sea salt metric.

We use output from GEOS-Chem model (Bey et al., 2001) simulations of sea salt aerosol mobilization and transport to constrain the relative source contributions of ss-Na^+. Critical to our study, the GEOS-Chem model allows for the partitioning of Na^+ on a seasonal basis at the South Pole into two origins: open water, and sublimation of blowing snow over sea ice. The assumptions and description of the model runs used here are discussed by Jaeglé et al. (2011), Huang and Jaeglé (2017), and Huang et al. (2020).

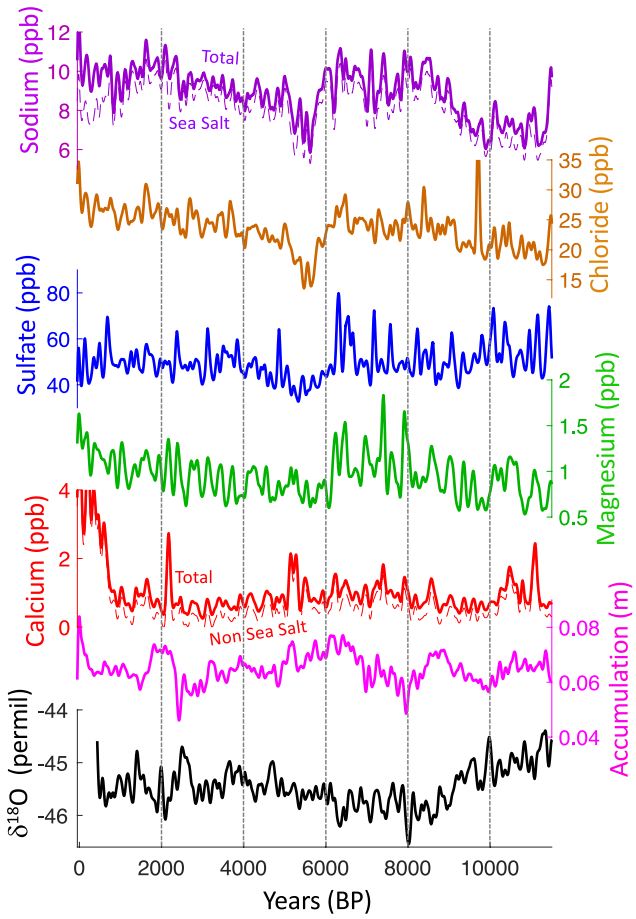

Figure 1. Concentrations of major ions in SPC14 during the Holocene. From top to bottom are plotted Na^+, Cl^-, SO_4^{2-}, Mg^{2+}, Ca^{2+}, annual accumulation rate (water equivalent) and $\delta^{18}O$. ss-Na^+ and nss-Ca^{2+} are included as dashed lines. All timeseries have undergone low-pass filtering at 200 years for clarity.

4. Results

4.1. The Holocene SPC14 Sodium Record

The Holocene SPC14 major ion records are presented in Figure 1. Consistent with other studies (e.g., Bertler et al., 2005; Fischer et al., 2007; Wolff et al., 2006, 2010), principal component analysis and ionic ratios (see supporting information) indicate Na^+, Mg^{2+} and Cl^- are dominated by marine sea salt contributions, Ca^{2+} is a mix of crustal and sea salt sources, and SO_4^{2-} likely receives contributions from volcanic emissions, marine biogenic emissions and sea salt. Consistent with prior work (Hogan et al., 1997; Shaw et al., 1988), we interpret a substantial contribution of sea salt during snow events based on the lack of a significant negative relationship between Na^+ and accumulation rate (Table S2), as would be expected if South Pole were a purely dry depositional environment (Kreutz et al., 2000).

Temporally, Na^+ and Cl^- records are predictably similar and exhibit a rising trend, most pronounced between 8 and 10 ka, but interrupted by a temporary drop from 5 and 6 ka. The early Holocene sea salt rise is most clearly evident in ss-Na^+, which increases 32% between 8-10 ka. The magnitude of the 5–6 ka event is roughly 2 ppb in Na^+ and 8 ppb in Cl^-, approximately a 20%–25% anomaly for each. This drop is not visible in Ca^{2+} (or nss-Ca^{2+}), which shows broadly elevated Ca^{2+} values during the mid-Holocene. Instead, the major feature within the Ca^{2+} and nss-Ca^{2+} record is a 4-fold rise in concentration during the last millennium. The 5–6 ka sea salt drop is not present in the SPC14 accumulation or $\delta^{18}O$ timeseries, both of which show relatively stable values near 5–6 ka BP (Figure 1). In contrast, the prominent rise in Na^+ and Cl^- during the early Holocene is associated with a concurrent drop in $\delta^{18}O$. High frequency (sub-centennial) variability is high throughout all ionic records, although the white component of the signal does not contain consistently strong frequencies.

4.2. Seasonality of the Sea Salt Signal

The GEOS-Chem model outputs are displayed in Figure 2a, where both sea salt from the open ocean and blowing snow from sea ice exhibit a seasonal cycle with high concentrations during the late winter, consistent with observations (e.g., Sheridan et al., 2016, Figure 2a) and previous modeling studies (Levine et al., 2014). Seasonality is much higher in snow blowing from sea ice than in open ocean sources, such that the primary source of sea salt to the South Pole switches seasonally between open water and sea ice. During the austral summer, when sea salt aerosol concentrations are low, open water constitutes up to 93% of the sea salt delivered to the South Pole (Figure 2). During winters, when concentrations are highest, snow from sea ice contributes up to 55% of the South Pole sea aerosol. Multiplying seasonal SPC14 ss-Na^+ values by the GEOS-Chem percent contributions shows a seasonally consistent contribution from open ocean sources with a seasonally variable contribution from sea ice (Figure 2b). This pattern holds across all major ice core sites in Antarctica with source seasonality increasing with proximity to the coast (Figure S4). These results clarify previous work interpreting the significance of sea salt records in Antarctic ice cores by demonstrating that the mechanistic source of ss-Na^+ to interior Antarctica changes distinctly by season (Fischer et al., 2007; Iizuka et al., 2008; Wolff et al., 2006).

Because of the very consistent Na^+ seasonality over the 11,400-years record, and because this consistency was the basis for assigning annual positions in the SP19 timescale, we calculated maximum (winter) and minimum (summer) ss-Na^+ throughout the Holocene for each year (Figure 3). Both seasonal signals display similar patterns including a rise from 8 to 10 ka, a subsequent drop to a local minimum at roughly 5.5 ka and

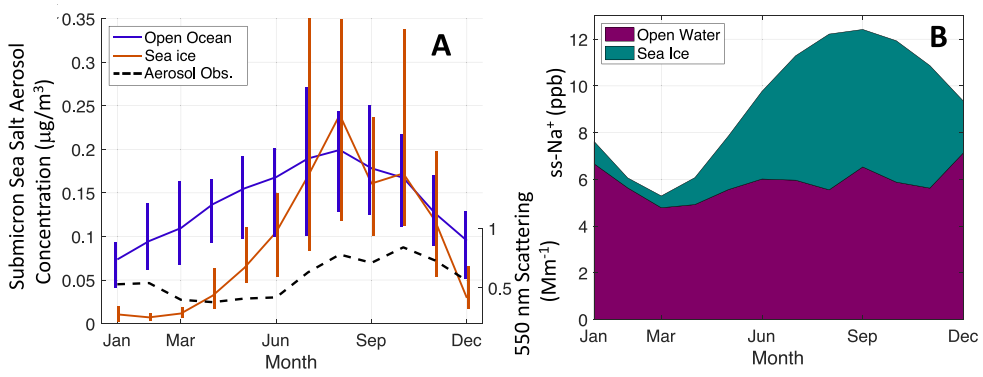

Figure 2. Mean modeled sea salt aerosol surface concentration at the South Pole as a function of month and source (a). Sources are delineated into open ocean (blue) and blowing snow from sea ice (brown). The range in monthly values among the 9 years of output is shown with vertical bars. Observational data of median monthly scattering, interpreted as sea salt aerosol (e.g., Sheridan et al., 2016), is shown for comparison (black dashed line). Seasonal concentrations of SPC14 ss-Na^+ from open ocean (purple) and sea ice (cyan) sources are shown in (b). During summer months, lower ss-Na^+ concentrations originate almost entirely from open water, whereas during winters, sea ice sources contribute up to 55% of ss-Na^+ to the South Pole during months when concentrations are highest.

rising concentrations from 2-5 ka. However, millennial-scale features are more apparent in the wintertime Na^+ data. At decadal and lower frequencies, correlations between maximum (winter) and mean annual Na^+ are high ($r = 0.91$), exceeding parallel correlations between minimum (summer) and mean annual values ($r = 0.77$) (Figure S5). The greater relative contributions, higher variance and closer correlation with mean annual values together indicate that wintertime sodium concentration is more representative of the overall annual variability. During the 5–6 ka event, maximum (winter) sodium decreases sharply by nearly a third, while minimum (summer) sodium remains comparatively stable, barely emerging from the overriding centennial scale variability. Given the GEOS-Chem results showing the wintertime importance of sea ice as a

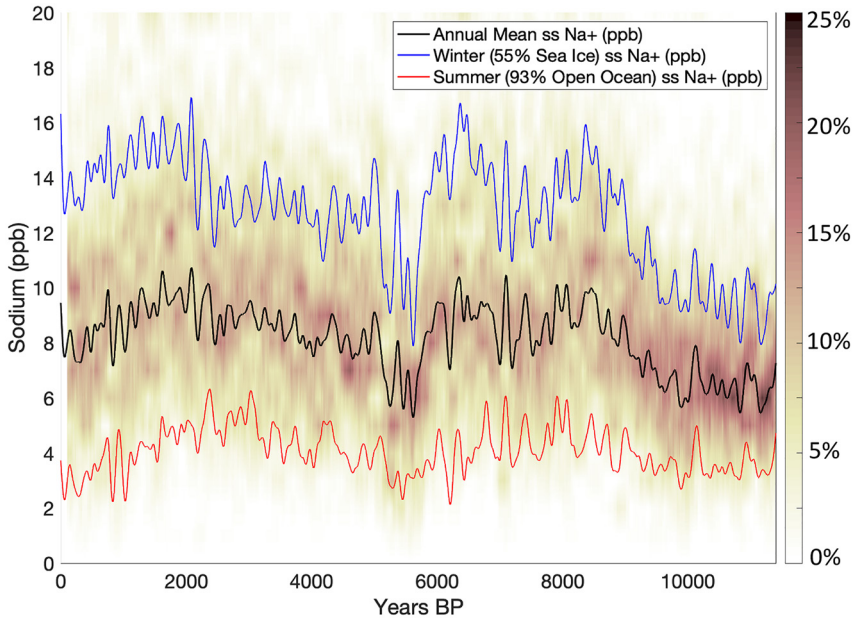

Figure 3. The Holocene sea salt sodium record in SPC14. Shading indicates a running histogram of mean annual ss-Na^+ concentrations. Units indicate the percentage of years within a 200-year window within each 1 ppb size bin. 200-year low pass filtered timeseries of annual mean (black), annual minimum (red) and annual maximum (blue) ss-Na^+ are overlaid, indicating mean, summer and winter ss-Na^+ concentrations.

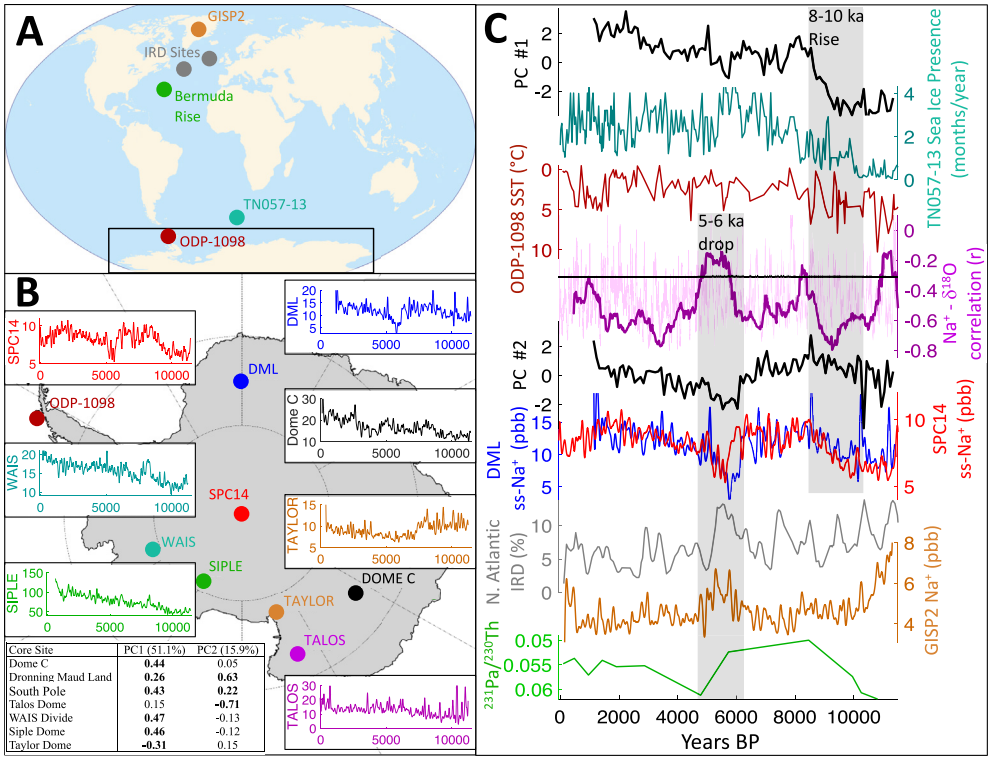

Figure 4. Comparison between Holocene Antarctic sodium records. Panels A and B show the locations of global (a) and Antarctic (b) sites. PCs 1 and 2 are from ice core sodium at Taylor Dome (Steig et al., 2000), Talos Dome (Mezgec et al., 2017), Siple Dome (Kreutz et al., 1997), Dome C (Rothlisberger et al., 2002), DML (Fischer et al., 2007), WAIS-Divide (Markle et al., 2018) and SPC14 (red). The first and second principal components of these seven sodium records are shown in the table (eigenvector components >0.20 in bold) and in Panel C (black). PC1 reflects increasing sea ice, especially during the early Holocene (gray shading) as supported by increasing sea ice presence (cyan, Divine et al., 2010), sea surface temperature (maroon, Shevenell et al., 2011), and negative ss-Na^+– $\delta^{18}O$ correlations (purple). PC2 primarily reflects the shared signal between DML and SPC14 (blue and red). Between 5 and 6 ka BP (gray shading), ss-Na^+ is decoupled from $\delta^{18}O$ (purple) but is consistent with GISP2 Na^+ (orange, Mayewski et al., 1994), North Atlantic IRD (gray, Bond et al., 2001) and Bermuda Rise ^{231} Pa/^{230}Th (green, McManus et al., 2004).

Na^+ source (Figure 2), a winter Na^+ reduction at 5–6 ka (Figure 3) suggests that winter and early spring sea ice conditions may be associated with the millennial scale structure in the SPC14 sea salt record.

5. Discussion

5.1. Two Antarctic Holocene Sea-Salt Signals

In Figure 4b, we show Holocene sea salt records from SPC14, Dronning Maud Land (DML; Fischer et al., 2007), Dome C (Rothlisberger et al., 2002; Wolff et al., 2010), Taylor Dome (Mayewski et al., 1996; Steig et al., 2000), Talos Dome (Mezgec et al., 2017), WAIS-Divide (Markle et al., 2018) and Siple Dome (Kreutz et al., 1997). A principal component analysis reveals two dominant signals (PC1 and PC2) in Antarctic sea-salt variability over the Holocene. PC1 represents over 50% of the centennial-scale variability, showing a prevailing increase in Na^+ during the Holocene in all records except Taylor Dome (where Na^+ begins increasing at ~7 ka). This increase is particularly pronounced between 8-10 ka BP in all records but Talos Dome and Taylor Dome. Most of the Antarctic records have high correlations with PC1, especially Dome C ($r = 0.83$), Siple Dome ($r = 0.87$), SPC14 ($r = 0.82$), and WAIS-Divide ($r = 0.89$). This consistency on the broadest scale suggests an Antarctic-wide phenomenon occurring throughout the Holocene.

In contrast, PC2 is primarily weighed toward DML and SPC14. PC2 exhibits a drop between 5 and 6 ka, as seen exclusively in the DML (Fischer et al., 2007) and SPC14 records. At DML, ss-Na^+ drops approximately 50% at 6 ka, compared with a concomitant ~20% drop in ss-Na^+ at SPC14. DML represents an

overwhelmingly Atlantic source region with ~80% of 4-days trajectories originating in the Atlantic during winters (Reijmer et al., 2002). In contrast, only ~40% of July airmasses arrive at the South Pole from the Atlantic sector (Harris et al., 1992), with the majority of the remaining trajectories passing over W. Antarctica. Thus, we interpret the 5–6 ka anomaly as representing a regional phenomenon specific to the Atlantic sector sea salt source region common to DML and SPC14, with the more muted SPC14 signal representing dilution of the signal by contributions from the Pacific sector. Supporting this hypothesis are correlations between South Pole aerosol data (σ_{sp} – 550 nm; Bodhaine et al., 1986, 1987) and ERA5 (Hersbach et al., 2020) sea ice reanalysis fields showing that South Pole atmospheric sea salt is positively correlated with sea ice concentration within the southeast Atlantic Ocean ($r = 0.56$, $p < 0.05$; Figure S6).

5.2. Interpretation of the Holocene Secular ss-Na^+ Rise

Based on the combination of our seasonal SPC14 ss-Na^+ analysis and the GEOS-Chem results, we hypothesize that wintertime sea ice variability is the primary cause of the Antarctic-wide secular sodium rise during the Holocene (PC1), as well as the 5–6 ka sodium anomaly restricted to the Atlantic sector (PC2). This is consistent with the interpretation of the DML and Dome Fuji records as primarily sensitive to sea ice extent (Iizuka et al., 2008; Stenni et al., 2010). The large increase in SPC14 ss-Na^+ between 6-10 ka is consistent with sea ice presence records (Xiao et al., 2016), particularly from TN057-13 in the southeast Atlantic (C. Bianchi & Gersonde 2004; Divine et al., 2010, Figures 4a and 4c). Holocene cooling is also apparent in reconstructed sea surface temperature TN057-13 (Anderson et al., 2009) as well as from JPC-10 and ODP-1098, located west of the Antarctic Peninsula (Etourneau et al., 2013; Shevenell et al., 2011; Figures 4a and 4c). A long-term increase in Holocene sea ice indicates cooler late-Holocene conditions attributed to decreasing insolation amplified by internal mechanisms, as has been inferred by Antarctic-wide water isotope comparisons (Masson et al., 2000) and sea ice records (Divine et al., 2010; Etourneau et al., 2013; Hodell et al., 2001). A larger-than-modern Ross Ice Shelf during the early Holocene (Yokoyama et al., 2016) may have covered either some of the sea ice sodium sources or the polynyas that generate much of the sea ice in the Ross Sea (Comiso et al., 2011). This may account for the absence of steeply rising ssNa^+ between 8 and 10 ka at Taylor and Talos Domes.

In addition to changes in sea ice, ss-Na^+ variability on millennial timescales has been attributed to the distillation (e.g., rainout) of impurities under varying temperature (and therefore saturation vapor pressure) conditions (Markle et al., 2018; Yung et al., 1996). Analysis of the SPC14 $\delta^{18}O$ record (Steig et al., 2021) provides insight to this mechanism, as a major shift in atmospheric distillation would be apparent (Markle et al., 2018). We calculate running 41-years correlations between ss-Na^+ and $\delta^{18}O$ throughout the Holocene, finding a variable but typically significant relationship with r-values averaging −0.45 ($p < 0.01$), and with the strongest relationship between 8 and 10 ka ($r = -0.79$; Figure 4c). The magnitude of this relationship is approximately 1.7 ppb of ss-Na^+ for each permil $\delta^{18}O$. At WAIS-Divide the ss-Na^+ - $\delta^{18}O$ relationship developed for the last 68 ka is expectedly steeper (~4 ppb ss-Na^+ for each permil $\delta^{18}O$) and more exponential given the larger glacial-interglacial changes (Markle et al., 2018). In this interpretive framework, the secular Holocene increase in ss-Na^+ could indicate cooling Holocene conditions with less ss-Na^+ rainout enroute to the ice core sites. Thus, this is consistent with enhanced sea ice, and both increases in sea ice and decreases in rainout may have contributed to the secular Holocene sodium rise.

5.3. Interpretation of the Abrupt 5–6 ka ss-Na^+ Decline

Our interpretation of the 5–6 ka ss-Na^+ decline (PC2) as an abrupt reduction in Atlantic-sector wintertime sea ice extent is consistent with previous studies (Fischer et al., 2007; Stenni et al., 2010), interpreting the DML sodium record as reflecting sea ice changes. Records from marine cores TPC286 (62° S) and TPC078 (56° S) are near the inferred sodium source region for the South Pole during the instrumental period (Figure S6) and show reduced winter sea ice during the mid-Holocene relative to the early and late Holocene (Collins et al., 2012, 2013). A mid-Holocene sea ice reduction is not observed in marine records further to the north (C. Bianchi & Gersonde 2004; Divine et al., 2010; Nielsen et al., 2004; Xiao et al., 2016), from the southern Indian Ocean (Mashiotta et al., 1999; Orme et al., 2020), nor from the Antarctic Peninsula (Domack et al., 2001), further emphasizing the geographic specificity of the mid-Holocene ss-Na^+ anomaly. In contrast, a progressive sea ice increase and/or sea surface cooling is widely observed (Divine et al., 2010;

Etourneau et al., 2013; Hodell et al., 2001; Xiao et al., 2016), consistent with the secular Antarctic-wide Na^+ increase (PC1).

Importantly, we see no evidence in the SPC14 $\delta^{18}O$ for a change in rainout that could account for the 5–6 ka event. A plot of running correlations between ss-Na^+ and $\delta^{18}O$ reveals that this association disappears during the 5–6 ka event (Figure 4c). This is also apparent in Figure 1 wherein clear drops in Na^+ and Cl^- are visible while no major changes occur in $\delta^{18}O$ or accumulation rate. Given the transport of ss-Na^+ to the South Pole through the meridional flux of 'salt storms' (e.g., Shaw et al., 1988), and the prevalent association between ss-Na^+ and $\delta^{18}O$ (Figure 4c), it is difficult to explain the mid-Holocene ss-Na^+ drop through a rainout mechanism. Furthermore, if a reduction in meridional transport were responsible, it is probable that SPC14, being the more distal site, would see a larger ss-Na^+ drop compared with EDML; however, the opposite is observed.

5.4. A Global 5–6 ka Signal?

Sodium concentrations from the GISP2 and GRIP ice cores in central Greenland are elevated from 5-6 ka (Mayewski et al., 1994, 1997, Figures 4a and 4c), interpreted as reflecting very cold conditions in high northern latitudes (De Angelis et al., 1997; O'Brien et al., 1995). In Renland, $\delta^{18}O$ amplitudes were elevated at this time, reflecting variability in Atlantic Meridional Overturning Circulation (AMOC) and associated sea ice cover (Hughes et al., 2020). The Greenland and Antarctic records are consistent with the hypothesis of reduced North Atlantic Deep Water formation leading to a reduction in AMOC (Bond et al., 1997). This hypothesis invokes a shift in heat content from the North Atlantic to the South Atlantic near 6 ka BP, analogous to the bipolar see-saw observed in ice core records spanning the last glacial period (Blunier & Brook, 2001; Broecker, 1998). Marine studies (G. G. Bianchi & McCave 1999; Hansen & Østerhus, 2000; Thornalley et al., 2013) show more vigorous AMOC strength near Iceland and Scotland between 7 and 8 ka and then decreasing strength from 5 to 7 ka. At the Bermuda Rise, McManus et al. (2004) find that the only significant anomaly in Holocene AMOC strength was a weakening between approximately 5 and 6 ka. A hypothetical AMOC weakening between 5 and 6 ka may explain both the widespread cold anomalies in the Northern Hemisphere (Mayewski et al., 2004; Wanner et al., 2011, 2015) as well the inferred reduction in Weddell Sea ice inferred from ss-Na^+ in SPC14 and DML.

6. Conclusions

Results from the GEOS-Chem model (Huang & Jaeglé, 2017) indicate that the SPC14 sea salt record is primarily sensitive to changes in wintertime sea ice extent, consistent with the strong seasonality of the ice core chemistry and prior interpretations. Sea salt levels at the South Pole, and at most Antarctic ice core sites, increased throughout most of the Holocene and particularly between 8-10 ka (Figure 4), interpreted as an Antarctic-wide wintertime sea ice increase. Between 5 and 6 ka, an anomalous drop in sea salt is recorded at SPC14 and DML, but is not present in the $\delta^{18}O$ record (Steig et al., 2021) or other Antarctic sea salt records. We hypothesize that this drop reflects an abrupt decline in wintertime sea ice restricted to the South Atlantic/Weddell region. Evidence from Southern (e.g., Collins et al., 2012) and Northern Hemisphere (e.g., Bond et al., 2001; Mayewski et al., 1994; McManus et al., 2004) proxy records supports our hypothesis and indicates a possible bipolar influence of weakened AMOC at that time (Bond et al., 1997).

Data Availability Statement

The SPC14 major ion record is accessible at https://www.usap-dc.org/view/dataset/601399.

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References

Anderson, R. F., Ali, S., Bradtmiller, L. I., Nielsen, S. H. H., Fleisher, M. Q., Anderson, B. E., & Burckle, L. H. (2009). Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. *Science*, *323*(5920), 1443–1448. https://doi.org/10.1126/science.1167441

Arimoto, R., Zeng, T., Davis, D., Wang, Y., Khaing, H., Nesbit, C., & Huey, G. (2008). Concentrations and sources of aerosol ions and trace elements during ANTCI-2003. *Atmospheric Environment*, *42*(12), 2864–2876. https://doi.org/10.1016/j.atmosenv.2007.05.054

Bergin, M. H., Meyerson, E. A., Dibb, J. E., & Mayewski, P. A. (1998). Relationship between continuous aerosol measurements and firn core chemistry over a 10-year period at the South Pole. *Geophysical Research Letters*, *25*(8), 1189–1192. https://doi.org/10.1029/98gl00854

Bertler, N., Mayewski, P. A., Aristarain, A., Barrett, P., Becagli, S., Bernardo, R., et al. (2005). Snow chemistry across Antarctica. *Annals of Glaciology*, *41*, 167–179. https://doi.org/10.3189/172756405781813320

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., et al. (2001). Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *Journal of Geophysical Research*, *106*(D19), 23073–23095. https://doi.org/10.1029/2001jd000807

Bianchi, C., & Gersonde, R. (2004). Climate evolution at the last deglaciation: The role of the Southern Ocean. *Earth and Planetary Science Letters*, *228*(3–4), 407–424. https://doi.org/10.1016/j.epsl.2004.10.003

Bianchi, G. G., & McCave, I. N. (1999). Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature*, *397*(6719), 515. https://doi.org/10.1038/17362

Blunier, T., & Brook, E. J. (2001). Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science*, *291*(5501), 109–112. https://doi.org/10.1126/science.291.5501.109

Bodhaine, B. A., Deluisi, J. J., Harris, J. M., Houmere, P., & Bauman, S. (1986). Aerosol measurements at the South Pole. *Tellus B: Chemical and Physical Meteorology*, *38*(3–4), 223–235. https://doi.org/10.3402/tellusb.v38i3-4.15131

Bodhaine, B. A., Deluisi, J. J., Harris, J. M., Houmere, P., & Bauman, S. (1987). PIXE analysis of South Pole aerosol. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *22*(1–3), 241–247. https://doi.org/10.1016/0168-583x(87)90336-3

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., et al. (2001). Persistent solar influence on North Atlantic climate during the Holocene. *Science*, *294*(5549), 2130–2136. https://doi.org/10.1126/science.1065680

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., Priore, P., et al. (1997). A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science*, *278*(5341), 1257–1266. https://doi.org/10.1126/science.278.5341.1257

Broecker, W. S. (1998). Paleocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography*, *13*(2), 119–121. https://doi.org/10.1029/97pa03707

Casey, K. A., Fudge, T. J., Neumann, T. A., Steig, E. J., Cavitte, M. G. P., & Blankenship, D. D. (2014). The 1500 m South Pole ice core: recovering a 40 ka environmental record. *Annals of Glaciology*, *55*(68), 137–146. https://doi.org/10.3189/2014aog68a016

Clem, K. R., Fogt, R. L., Turner, J., Lintner, B. R., Marshall, G. J., Miller, J. R., & Renwick, J. A. (2020). Record warming at the South Pole during the past three decades. *Nature Climate Change*, *10*(8), 762–770. https://doi.org/10.1038/s41558-020-0815-z

Cole-Dai, J., & Mosley-Thompson, E. (1999). The Pinatubo eruption in South Pole snow and its potential value to ice-core paleovolcanic records. *Annals of Glaciology*, *29*, 99–105. https://doi.org/10.3189/172756499781821319

Collins, L. G., Allen, C. S., Pike, J., Hodgson, D. A., Weckström, K., & Massé, G. (2013). Evaluating highly branched isoprenoid (HBI) biomarkers as a novel Antarctic sea-ice proxy in deep ocean glacial age sediments. *Quaternary Science Reviews*, *79*, 87–98. https://doi.org/10.1016/j.quascirev.2013.02.004

Collins, L. G., Pike, J., Allen, C. S., & Hodgson, D. A. (2012). High-resolution reconstruction of southwest Atlantic sea-ice and its role in the carbon cycle during marine isotope stages 3 and 2. *Paleoceanography and Paleoclimatology*, *27*(3) 3217. https://doi.org/10.1029/2011pa002264

Comiso, J. C., Kwok, R., Martin, S., & Gordon, A. L. (2011). Variability and trends in sea ice extent and ice production in the Ross Sea. *Journal of Geophysical Research: Oceans*, *116*(C4). https://doi.org/10.1029/2010jc006391

De Angelis, M., Steffensen, J. P., Legrand, M., Clausen, H., & Hammer, C. (1997). Primary aerosol (sea salt and soil dust) deposited in Greenland ice during the last climatic cycle: Comparison with east Antarctic records. *Journal of Geophysical Research*, *102*(C12), 26681–26698. https://doi.org/10.1029/97jc01298

Divine, D. V., Koç, N., Isaksson, E., Nielsen, S., Crosta, X., & Godtliebsen, F. (2010). Holocene Antarctic climate variability from ice and marine sediment cores: insights on ocean–atmosphere interaction. *Quaternary Science Reviews*, *29*(1–2), 303–312. https://doi.org/10.1016/j.quascirev.2009.11.012

Domack, E., Leventer, A., Dunbar, R., Taylor, F., Brachfeld, S., & Sjunneskog, C. (2001). Chronology of the Palmer Deep site, Antarctic Peninsula: A Holocene palaeoenvironmental reference for the circum-Antarctic. *The Holocene*, *11*(1), 1–9. https://doi.org/10.1191/095968301673881493

Etourneau, J., Collins, L. G., Willmott, V., Kim, J. H., Barbara, L., Leventer, A., et al. (2013). *Holocene climate variations in the western Antarctic Peninsula: Evidence for Sea ice extent predominantly controlled by changes in insolation and ENSO variability*.

Ferris, D. G., Cole-Dai, J., Reyes, A. R., & Budner, D. M. (2011). South Pole ice core record of explosive volcanic eruptions in the first and second millennia AD and evidence of a large eruption in the tropics around 535 AD. *Journal of Geophysical Research: Atmospheres*, *116*(D17). https://doi.org/10.1029/2011jd015916

Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Wegner, A., Udisti, R., et al. (2007). Reconstruction of millennial changes in dust emission, transport and regional sea ice coverage using the deep EPICA ice cores from the Atlantic and Indian Ocean sector of Antarctica. *Earth and Planetary Science Letters*, *260*(1), 340–354. https://doi.org/10.1016/j.epsl.2007.06.014

Hansen, B., & Østerhus, S. (2000). North Atlantic-Nordic Seas exchanges. *Progress in Oceanography*, *45*(2), 109–208. https://doi.org/10.1016/s0079-6611(99)00052-x

Harris, J. M. (1992). An analysis of 5-day midtropospheric flow patterns for the South Pole: 1985-1989. *Tellus B: Chemical and Physical Meteorology*, *44*(4), 409–421. https://doi.org/10.3402/tellusb.v44i4.15466

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hodell, D. A., Kanfoush, S. L., Shemesh, A., Crosta, X., Charles, C. D., & Guilderson, T. P. (2001). Abrupt Cooling of Antarctic Surface Waters and Sea Ice Expansion in the South Atlantic Sector of the Southern Ocean at 5000 cal yr B.P. *Quaternary Research*, *56*(2), 191–198. https://doi.org/10.1006/qres.2001.2252

Hogan, A. (1997). A synthesis of warm air advection to the South Polar Plateau. *Journal of Geophysical Research*, *102*(D12), 14009–14020. https://doi.org/10.1029/97jd00282

Huang, J., & Jaeglé, L. (2017). Wintertime enhancements of sea salt aerosol in polar regions consistent with a sea ice source from blowing snow. *Atmospheric Chemistry and Physics*, *17*(5), 3699–3712. https://doi.org/10.5194/acp-17-3699-2017

Huang, J., Jaeglé, L., Chen, Q., Alexander, B., Sherwen, T., Evans, M. J., et al. (2020). Evaluating the impact of blowing-snow sea salt aerosol on springtime BrO and O3 in the Arctic. *Atmospheric Chemistry and Physics*, *20*(12), 7335–7358. https://doi.org/10.5194/acp-20-7335-2020

Hughes, A. G., Jones, T. R., Vinther, B. M., Gkinis, V., Stevens, C. M., Morris, V., et al. (2020). High-frequency climate variability in the Holocene from a coastal-dome ice core in east-central Greenland. *Climate of the Past*, *16*(4), 1369–1386. https://doi.org/10.5194/cp-16-1369-2020

Iizuka, Y., Hondoh, T., & Fujii, Y. (2008). Antarctic sea ice extent during the Holocene reconstructed from inland ice core evidence. *Journal of Geophysical Research: Atmospheres*, *113*(D15). https://doi.org/10.1029/2007jd009326

Jaeglé, L., Quinn, P. K., Bates, T. S., Alexander, B., & Lin, J.-T. (2011). Global distribution of sea salt aerosols: New constraints from in situ and remote sensing observations. *Atmospheric Chemistry and Physics*, *11*(7), 3137. https://doi.org/10.5194/acp-11-3137-2011

Jones, J. M., Gille, S. T., Goosse, H., Abram, N. J., Canziani, P. O., Charman, D. J., et al. (2016). Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nature Climate Change*, *6*(10), 917–926. https://doi.org/10.1038/nclimate3103

Kreutz, K. J., Mayewski, P. A., Meeker, L. D., Twickler, M. S., & Whitlow, S. I. (2000). The effect of spatial and temporal accumulation rate variability in West Antarctica on soluble ion deposition. *Geophysical Research Letters*, *27*(16), 2517–2520. https://doi.org/10.1029/2000gl011499

Kreutz, K. J., Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S. I., & Pittalwala, I. I. (1997). Bipolar changes in atmospheric circulation during the Little Ice Age. *Science*, *277*(5330), 1294–1296. https://doi.org/10.1126/science.277.5330.1294

Lazzara, M. A., Keller, L. M., Markle, T., & Gallagher, J. (2012). Fifty-year Amundsen-Scott South Pole station surface climatology. *Atmospheric Research*, *118*, 240–259. https://doi.org/10.1016/j.atmosres.2012.06.027

Legrand, M., & Delmas, R. J. (1987). A 220-year continuous record of volcanic H2SO4 in the Antarctic ice sheet. *Nature*, *327*(6124), 671–676. https://doi.org/10.1038/327671a0

Legrand, M., & Kirchner, S. (1988). Polar atmospheric circulation and chemistry of recent (1957-1983) south polar precipitation. *Geophysical Research Letters*, *15*(8), 879–882. https://doi.org/10.1029/gl015i008p00879

Legrand, M. R., & Delmas, R. J. (1984). The ionic balance of Antarctic snow: A 10-year detailed record. *Atmospheric Environment*, *18*(9), 1867–1874. https://doi.org/10.1016/0004-6981(84)90363-9

Legrand, M. R., & Delmas, R. J. (1988). Formation of HCl in the Antarctic atmosphere. *Journal of Geophysical Research*, *93*(D6), 7153–7168.

Levine, J. G., Yang, X., Jones, A. E., & Wolff, E. W. (2014). Sea salt as an ice core proxy for past sea ice extent: A process-based model study. *Journal of Geophysical Research - D: Atmospheres*, *119*(9), 5737–5756. https://doi.org/10.1002/2013jd020925

Lilien, D. A., Fudge, T. J., Koutnik, M. R., Conway, H., Osterberg, E. C., Ferris, D. G., et al. (2018). Holocene Ice-Flow Speedup in the Vicinity of the South Pole. *Geophysical Research Letters*, *45*(13), 6557–6565. https://doi.org/10.1029/2018gl078253

Markle, B. R., Steig, E. J., Roe, G. H., Winckler, G., & McConnell, J. R. (2018). Concomitant variability in high-latitude aerosols, water isotopes and the hydrologic cycle. *Nature Geoscience*, *1*.

Mashiotta, T. A., Lea, D. W., & Spero, H. J. (1999). Glacial-interglacial changes in Subantarctic sea surface temperature and δ18O-water using foraminiferal Mg. *Earth and Planetary Science Letters*, *170*(4), 417–432. https://doi.org/10.1016/s0012-821x(99)00116-8

Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P., et al. (2000). Holocene climate variability in Antarctica based on 11 ice-core isotopic records. *Quaternary Research*, *54*(3), 348–358. https://doi.org/10.1006/qres.2000.2172

Mayewski, P. A., Meeker, L. D., Twickler, M. S., Whitlow, S., Yang, Q., Lyons, W. B., & Prentice, M. (1997). Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research*, *102*(C12), 26345–26366. https://doi.org/10.1029/96jc03365

Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Morrison, M. C., Bloomfield, P., et al. (1994). Changes in atmospheric circulation and ocean ice cover over the North Atlantic during the last 41,000 years. *Science*, *263*(5154), 1747–1751. https://doi.org/10.1126/science.263.5154.1747

Mayewski, P. A., Rohling, E. E., Curt Stager, J., Karlén, W., Maasch, K. A., Meeker, L. D., et al. (2004). Holocene climate variability. *Quaternary Research*, *62*(3), 243–255. https://doi.org/10.1016/j.yqres.2004.07.001

Mayewski, P. A., Twickler, M. S., Whitlow, S. I., Meeker, L. D., Yang, Q., Thomas, J., et al. (1996). Climate change during the last deglaciation in Antarctica. *Science*, *272*(5268), 1636–1638. https://doi.org/10.1126/science.272.5268.1636

McManus, J. F., Francois, R., Gherardi, J.-M., Keigwin, L. D., & Brown-Leger, S. (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, *428*(6985), 834. https://doi.org/10.1038/nature02494

Mezgec, K., Stenni, B., Crosta, X., Masson-Delmotte, V., Baroni, C., Braida, M., et al. (2017). Holocene sea ice variability driven by wind and polynya efficiency in the Ross Sea. *Nature Communications*, *8*(1), 1334. https://doi.org/10.1038/s41467-017-01455-x

Mosley-Thompson, E., Paskievitch, J. F., Gow, A. J., & Thompson, L. G. (1999). Late 20th Century increase in South Pole snow accumulation. *Journal of Geophysical Research*, *104*(D4), 3877–3886. https://doi.org/10.1029/1998jd200092

Nielsen, S. H. H., Koç, N., & Crosta, X. (2004). Holocene climate in the Atlantic sector of the Southern Ocean: Controlled by insolation or oceanic circulation?. *Geology*, *32*(4), 317–320. https://doi.org/10.1130/g20334.1

O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S., & Whitlow, S. I. (1995). *Complexity of Holocene climate as reconstructed from a Greenland ice core*.

Orme, L. C., Crosta, X., Miettinen, A., Divine, D. V., Husum, K., Isaksson, E., et al. (2020). Sea surface temperature in the Indian sector of the Southern Ocean over the Late Glacial and Holocene. *Climate of the Past* .

Parkinson, C. L. (2014). Global sea ice coverage from satellite data: Annual cycle and 35-yr trends. *Journal of Climate*, *27*(24), 9377–9382. https://doi.org/10.1175/jcli-d-14-00605.1

Parkinson, C. L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(29), 14414–14423. https://doi.org/10.1073/pnas.1906556116

Parungo, F., Bodhaine, B., & Bortniak, J. (1981). Seasonal variation in Antarctic aerosol. *Journal of Aerosol Science*, *12*(6), 491–504. https://doi.org/10.1016/0021-8502(81)90052-5

Reijmer, C. H., Van den Broeke, M. R., & Scheele, M. P. (2002). Air Parcel Trajectories and Snowfall Related to Five Deep Drilling Locations in Antarctica Based on the ERA-15 Dataset*. *Journal of Climate*, *15*(14), 1957–1968. https://doi.org/10.1175/1520-0442(2002)015<1957:aptasr>2.0.co;2

Röthlisberger, R., Mulvaney, R., Wolff, E. W., Hutterli, M. A., Bigler, M., Sommer, S., & Jouzel, J. (2002). Dust and sea salt variability in central East Antarctica (Dome C) over the last 45 kyrs and its implications for southern high-latitude climate. *Geophysical Research Letters*, *29*(20). https://doi.org/10.1029/2002gl015186

Shaw, G. E. (1988). Antarctic aerosols: A review. *Reviews of Geophysics*, *26*(1), 89–112. https://doi.org/10.1029/rg026i001p00089

Shepherd, A., Fricker, H. A., & Farrell, S. L. (2018). Trends and connections across the Antarctic cryosphere. *Nature*, *558*(7709), 223–232. https://doi.org/10.1038/s41586-018-0171-6

Sheridan, P., Andrews, E., Schmeisser, L., Vasel, B., & Ogren, J. (2016). *Aerosol measurements at South Pole: Climatology and impact of local contamination*.
Shevenell, A. E., Ingalls, A. E., Domack, E. W., & Kelly, C. (2011). Holocene Southern Ocean surface temperature variability west of the Antarctic Peninsula. *Nature*, *470*(7333), 250–254. https://doi.org/10.1038/nature09751
Steig, E. J., Jones, T. R., Schauer, A. J., Kahle, E. C., Morris, V. A., Vaughn, B. H., et al. (2021). Continuous-Flow Analysis of $\delta^{17}O$, $\delta^{18}O$, and δD of H_2O on an Ice Core from the South Pole. *Frontiers of Earth Science*, *9*. https://doi.org/10.3389/feart.2021.640292
Steig, E. J., Morse, D. L., Waddington, E. D., Stuiver, M., Grootes, P. M., Mayewski, P. A., et al. (2000). Wisconsinan and Holocene climate history from an ice core at Taylor Dome, western Ross Embayment, Antarctica. *Geografiska Annaler - Series A: Physical Geography*, *82*(2-3), 213–235. https://doi.org/10.1111/j.0435-3676.2000.00122.x
Stenni, B., Masson-Delmotte, V., Selmo, E., Oerter, H., Meyer, H., Röthlisberger, R., et al. (2010). The deuterium excess records of EPICA Dome C and Dronning Maud Land ice cores (East Antarctica). *Quaternary Science Reviews*, *29*(1–2), 146–159. https://doi.org/10.1016/j.quascirev.2009.10.009
Thornalley, D. J. R., Blaschek, M., Davies, F. J., Praetorius, S., Oppo, D. W., McManus, J. F., et al. (2013). Long-term variations in Iceland-Scotland overflow strength during the Holocene. *Climate of the Past*, *9*(5), 2073–2084. https://doi.org/10.5194/cp-9-2073-2013
Tuncel, G., Aras, N. K., & Zoller, W. H. (1989). Temporal variations and sources of elements in the South Pole atmosphere: 1. Nonenriched and moderately enriched elements. *Journal of Geophysical Research*, *94*(D10), 13025–13038. https://doi.org/10.1029/jd094id10p13025
Turner, J., & Comiso, J. (2017). Solve Antarctica's sea-ice puzzle. *Nature*, *547*(7663), 275. https://doi.org/10.1038/547275a
Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., & Phillips, T. (2015). Recent changes in Antarctic sea ice. *Philosophical Transactions of the Royal Society A*, *373*, 20140163. https://doi.org/10.1098/rsta.2014.0163
Turner, J., Marshall, G. J., Clem, K., Colwell, S., Phillips, T., & Lu, H. (2020). Antarctic temperature variability and change from station data. *International Journal of Climatology*, *40*(6), 2986–3007. https://doi.org/10.1002/joc.6378
Wanner, H., Mercolli, L., Grosjean, M., & Ritz, S. P. (2015). Holocene climate variability and change; a data-based review. *Journal of the Geological Society*, *172*(2), 254–263. https://doi.org/10.1144/jgs2013-101
Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P., & Jetel, M. (2011). Structure and origin of Holocene cold events. *Quaternary Science Reviews*, *30*(21–22), 3109–3123. https://doi.org/10.1016/j.quascirev.2011.07.010
Whitlow, S., Mayewski, P. A., & Dibb, J. E. (1992). A comparison of major chemical species seasonal concentration and accumulation at the South Pole and summit, Greenland. *Atmospheric Environment A. General Topics*, *26*(11), 2045–2054. https://doi.org/10.1016/0960-1686(92)90089-4
Winski, D. A., Fudge, T. J., Ferris, D. G., Osterberg, E. C., Fegyveresi, J. M., Cole-Dai, J., et al. (2019). The SP19 chronology for the South Pole Ice Core–Part 1: volcanic matching and annual layer counting. *Climate of the Past*, *15*(5). https://doi.org/10.5194/cp-15-1793-2019
Wolff, E. W., Barbante, C., Becagli, S., Bigler, M., Boutron, C. F., Castellano, E., et al. (2010). Changes in environment over the last 800,000 years from chemical analysis of the EPICA Dome C ice core. *Quaternary Science Reviews*, *29*(1–2), 285–295. https://doi.org/10.1016/j.quascirev.2009.06.013
Wolff, E. W., Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Littot, G. C., et al. (2006). Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles. *Nature*, *440*(7083), 491. https://doi.org/10.1038/nature04614
Xiao, W., Esper, O., & Gersonde, R. (2016). Last Glacial - Holocene climate variability in the Atlantic sector of the Southern Ocean. *Quaternary Science Reviews*, *135*, 115–137. https://doi.org/10.1016/j.quascirev.2016.01.023
Yokoyama, Y., Anderson, J. B., Yamane, M., Simkins, L. M., Miyairi, Y., Yamazaki, T., et al. (2016). Widespread collapse of the Ross Ice Shelf during the late Holocene. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(9), 2354–2359. https://doi.org/10.1073/pnas.1516908113
Yung, Y. L., Lee, T., Wang, C.-H., & Shieh, Y.-T. (1996). Dust: A diagnostic of the hydrologic cycle during the Last Glacial Maximum. *Science*, *271*(5251), 962–963. https://doi.org/10.1126/science.271.5251.962

References From the Supporting Information

Bowen, H. J. M. (1979). *Environmental chemistry of the elements*. Academic Press.
Breton, D. J., Koffman, B. G., Kurbatov, A. V., Kreutz, K. J., & Hamilton, G. S. (2012). Quantifying signal dispersion in a hybrid ice core melting system. *Environmental Science & Technology*, *46*(21), 11922–11928. https://doi.org/10.1021/es302041k
Cosme, E., Hourdin, F., Genthon, C., & Martinerie, P. (2005). Origin of dimethylsulfide, non-sea-salt sulphate, and methanesulfonic acid in eastern Antarctica. *Journal of Geophysical Research: Atmospheres*, *110*(D3). https://doi.org/10.1029/2004jd004881
Curran, M. A. J., Van Ommen, T. D., & Morgan, V. (1998). Seasonal characteristics of the major ions in the high-accumulation Dome Summit South ice core, Law Dome, Antarctica. *Annals of Glaciology*, *27*, 385–390. https://doi.org/10.1017/s0260305500017778
Dansgaard, W., & Johnsen, S. J. (1969). A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology*, *8*, 215–223. https://doi.org/10.1017/s0022143000031208
Eisen, O., Rack, W., Nixdorf, U., & Wilhelms, F. (2005). Characteristics of accumulation around the EPICA deep-drilling site in Dronning Maud Land, Antarctica. *Annals of Glaciology*, *41*, 41–46. https://doi.org/10.3189/172756405781813276
Ekaykin, A. A., Lipenkov, V. Y., Kuzmina, I. N., Petit, J. R., Masson-Delmotte, V., & Johnsen, S. J. (2004). The changes in isotope composition and accumulation of snow at Vostok station, East Antarctica, over the past 200 years. *Annals of Glaciology*, *39*, 569–575. https://doi.org/10.3189/172756404781814348
Epifanio, J. A., Brook, E. J., Buizert, C., Edwards, J. S., Sowers, T. A., Kahle, E. C., et al. (2020). The SP19 chronology for the South Pole Ice Core - Part 2: gas chronology, Δage, and smoothing of atmospheric records. *Climate of the Past*, *16*(6), 2431–2444. https://doi.org/10.5194/cp-16-2431-2020. .
Fudge, T. J., Lilien, D. A., Koutnik, M., Conway, H., Stevens, C. M., Waddington, E. D., et al. (2020). Advection and non-climate impacts on the South Pole Ice Core. *Climate of the Past*, *16*(3), 819–832. https://doi.org/10.5194/cp-16-819-2020
Goodwin, I. D., Van Ommen, T. D., Curran, M. A. J., & Mayewski, P. A. (2004). Mid latitude winter climate variability in the South Indian and southwest Pacific regions since 1300 AD. *Climate Dynamics*, *22*(8), 783–794. https://doi.org/10.1007/s00382-004-0403-3
Grannas, A. M., Jones, A. E., Dibb, J., Ammann, M., Anastasio, C., Beine, H. J., et al. (2007). An overview of snow photochemistry: evidence, mechanisms and impacts. *Atmospheric Chemistry and Physics*, *7*(16), 4329–4373. https://doi.org/10.5194/acp-7-4329-2007
Hogan, A. W., & Gow, A. J. (1997). Occurrence frequency of thickness of annual snow accumulation layers at South Pole. *Journal of Geophysical Research*, *102*(D12), 14021–14027. https://doi.org/10.1029/97jd00280

Kaspari, S., Hooke, R. L., Mayewski, P. A., Kang, S., Hou, S., & Qin, D. (2008). Snow accumulation rate on Qomolangma (Mount Everest), Himalaya: synchroneity with sites across the Tibetan Plateau on 50-100 year timescales. *Journal of Glaciology*, *54*(185), 343–352. https://doi.org/10.3189/002214308784886126

Koutnik, M. R., Fudge, T. J., Conway, H., Waddington, E. D., Neumann, T. A., Cuffey, K. M., et al. (2016). Holocene accumulation and ice flow near the West Antarctic Ice Sheet Divide ice core site. *Journal of Geophysical Research: Earth Surface*, *121*(5), 907–924. https://doi.org/10.1002/2015jf003668

Kreutz, K. J., Mayewski, P. A., Twickler, M. S., Whitlow, S. I., White, J. W. C., Shuman, C. A., et al. (1999). Seasonal variations of glaciochemical, isotopic and stratigraphic properties in Siple Dome (Antarctica) surface snow. *Annals of Glaciology*, *29*, 38–44. https://doi.org/10.3189/172756499781821193

Kuivinen, K. C., Koci, B. R., Holdsworth, G. W., & Gow, A. J. (1982). South Pole ice core drilling, 1981–1982. *Antarctic Journal of the United States*, *17*(5), 89–91.

Lefebvre, W., Goosse, H., Timmermann, R., & Fichefet, T. (2004). Influence of the Southern Annular Mode on the sea ice–ocean system. *Journal of Geophysical Research: Oceans*, *109*(C9). https://doi.org/10.1029/2004jc002403

Meeker, L. D., Mayewski, P. A., & Bloomfield, P. (1995). A new approach to glaciochemical time series analysis. *Ice core studies of global biogeochemical cycles* (pp. 383–400). Springer.

Osterberg, E. C., Handley, M. J., Sneed, S. B., Mayewski, P. A., & Kreutz, K. J. (2006). Continuous ice core melter system with discrete sampling for major ion, trace element, and stable isotope analyses. *Environmental Science & Technology*, *40*(10), 3355–3361. https://doi.org/10.1021/es052536w

Osterberg, E. C., Winski, D. A., Kreutz, K. J., Wake, C. P., Ferris, D. G., Campbell, S., et al. (2017). 1200-Year Composite Ice Core Record of Aleutian Low Intensification. *Geophysical Research Letters*.

Rankin, A. M., Wolff, E. W., & Mulvaney, R. (2004). A reinterpretation of sea-salt records in Greenland and Antarctic ice cores? *Annals of Glaciology*, *39*, 276–282. https://doi.org/10.3189/172756404781814681

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., et al. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, *24*(14), 3624–3648. https://doi.org/10.1175/jcli-d-11-00015.1

Röthlisberger, R., Hutterli, M. A., Sommer, S., Wolff, E. W., & Mulvaney, R. (2000). Factors controlling nitrate in ice cores: Evidence from the Dome C deep ice core. *Journal of Geophysical Research*, *105*(D16), 20565–20572. https://doi.org/10.1029/2000jd900264

Schwander, J., Jouzel, J., Hammer, C. U., Petit, J.-R., Udisti, R., & Wolff, E. (2001). A tentative chronology for the EPICA Dome Concordia ice core. *Geophysical Research Letters*, *28*(22), 4243–4246. https://doi.org/10.1029/2000gl011981

Sigl, M., Fudge, T. J., Winstrup, M., Cole-Dai, J., Ferris, D., McConnell, J. R., et al. (2016). The WAIS Divide deep ice core WD2014 chronology - Part 2: Annual-layer counting (0-31 ka BP). *Climate of the Past*, *12*(3), 769–786. https://doi.org/10.5194/cp-12-769-2016

Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Sowers, T. A., Henderson, K. A., Zagorodnov, V. S., et al. (1998). A 25,000-year tropical climate history from Bolivian ice cores. *Science*, *282*(5395), 1858–1864. https://doi.org/10.1126/science.282.5395.1858

Udisti, R., Dayan, U., Becagli, S., Busetto, M., Frosini, D., Legrand, M., et al. (2012). Sea spray aerosol in central Antarctica. Present atmospheric behavior and implications for paleoclimatic reconstructions. *Atmospheric Environment*, *52*, 109–120. https://doi.org/10.1016/j.atmosenv.2011.10.018

Wagenbach, D., Ducroz, F., Mulvaney, R., Keck, L., Minikin, A., Legrand, M., et al. (1998). Sea-salt aerosol in coastal Antarctic regions. *Journal of Geophysical Research*, *103*(D9), 10961–10974. https://doi.org/10.1029/97jd01804

Winski, D., Osterberg, E. F., Kreutz, D., K.C. C. Wake, S. Hawley, et al., M. (2017), Industrial-age doubling of snow accumulation in the Alaska Range linked to tropical ocean warming, *Nature Scientific Reports*.