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Key Points:
- Changes in Greenland centennial to millennial ice core isotope variability in the last glacial period can be attributed to noise levels
- The amount of noise systematically covaries with climate states and accumulation rates
- Most of it originates from local disturbances, likely related to the surface stratigraphy

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

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Greenland Ice Core Isotope Variability Strongly Influenced by Systematic Changes in Depositional Noise

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Abstract Stable water isotopes from ice cores are a unique proxy for reconstructing polar climate variability. Their interpretation is, however, challenging due to the impact of depositional noise. Here, we analyze the centennial- to millennial-scale isotope variability of the Greenland ice cores NGRIP, GRIP, and GISP2 to investigate how their coherent signal and local noise have evolved over the last 100,000 years. We show that the noise systematically depends on the climate state, with higher levels under colder temperatures and lower accumulation rates. Most of the noise originates from local stratigraphic disturbances, while additional noise variability only emerges in the Greenland stadials. The remaining climate signal variability is higher in the last glacial period compared to the Holocene, but does not systematically differ between stadials and interstadials. We show that, by considering systematic changes of noise, it is possible to achieve more accurate estimates of past climate variability.

Plain Language Summary The stable water isotope composition of snow, accumulating on the ice sheets of Greenland and Antarctica, records surface temperatures. Ice cores therefore provide valuable information on the past climate and its variability. However, the archival process of snow is disturbed and irregular, for example, due to winds and dune formations at the snow surface and patchy snowfall. This introduces noise, which increases the variability represented in this climate archive. Here, we analyze three ice core records from Greenland and how their variability changed during the Holocene and the last glacial period. We show that there is systematically more noise in climate states with lower temperatures and less snowfall. In the Holocene and the warmer phases of the last glacial period (interstadials) most of the noise seems to originate from local disturbances of the snow surface. The actual regional climate variability was much lower in the Holocene than in the last glacial period, whereas it does not systematically differ between the cold and warm phases of the last glacial period. We show that, by acknowledging that noise in the isotope compositions can change over time, it is possible to get more accurate estimates of the past climate variability.

1. Introduction

Stable water isotopes in ice cores are among the few proxies capable of assessing past climate variability on up to decadal timescales through the last glacial period. Greenland ice cores not only capture Dansgaard-Oeschger (D-O) events at a high temporal resolution (Rasmussen et al., 2014; Steffensen et al., 2008), but also record recent seasonal to annual climate variations, providing valuable insights into the North Atlantic region and its recent changes (e.g., Hörhold et al., 2023; Rimbu & Lohmann, 2011; Rimbu et al., 2021; Vinther et al., 2010). These records have the potential to reveal key aspects of climate variability, including its scaling properties (Shao & Ditlevsen, 2016), early warning signals for abrupt climate change (Hummel et al., 2024), and its relationship with the mean climate state (Hansen et al., 2012; Huntingford et al., 2013; Huybers & Curry, 2006).

Isotope variability in Greenland ice cores has been found to increase with cooler temperatures (Ditlevsen et al., 2002) and to exhibit exceptionally strong changes in variability between the Last Glacial Maximum and the Holocene compared to other climate proxies across the world (Rehfeld et al., 2018). However, directly interpreting isotope variability as temperature variability is challenging as it is also influenced by non-climatic processes. Analysis of isotope records of the last millennium in Antarctica (Münch & Laepple, 2018) and North Greenland (Hörhold et al., 2023) showed that a large fraction of the variability is independent between nearby records and must therefore be attributed to noise. In both studies, the noise variability was stronger than the variability of the common signal on up to centennial time scales. Two primary noise sources have been identified.

Stratigraphic noise describes any small-scale disturbances of the snow surface preventing an even layering of the isotopic signal of snow. The main reason is wind-driven erosion and accumulation of snow, continuously reshaping the snow surface by forming troughs and snow dunes (Fisher et al., 1985; Münch et al., 2016; Wolff et al., 2005). Typical spatial scales of stratigraphic noise are 5–10 m (Münch et al., 2016; Zuhr et al., 2021). The second most important noise is precipitation intermittency and includes any noise variance recorded in isotope records originating from irregular or patchy precipitation events (Helsen et al., 2005; Laepple et al., 2018; Persson et al., 2011; Sime et al., 2011). Other effects can be the influences of the local upstream topography (Dallmayr et al., 2025) and post depositional effects near the surface that may act on different spatial scales (Dietrich et al., 2023; Steen-Larsen et al., 2014).

When analyzing isotope variability, it is essential to account for the contribution from noise processes, for example, by averaging across multiple records. This allows for a more reliable interpretation of variations (Hörhold et al., 2023; Weißbach et al., 2016; White et al., 1997), especially on the fast timescales (Münch & Laepple, 2018). Nevertheless, some studies interpret isotope variability of single records without any correction (Brashear et al., 2024; Jones et al., 2023), while others correct for noise assuming a constant signal-to-noise ratio (SNR) across climate states (Rehfeld et al., 2018). However, since noise is related to depositional conditions such as accumulation rate and surface roughness (Fisher et al., 1985; Hirsch et al., 2023; Persson et al., 2011), which can systematically change over time and between different climate states, it might be necessary to account for changes in the level of noise over time.

In this study, we analyze three deep Greenland ice cores (GRIP, GISP2, and NGRIP) to assess how the common (signal) variability and the independent (noise) variability have evolved over the past 100,000 years and how they compare between different climate states. By comparing noise levels between nearby ice core records (∼30 km apart) and more distant ones (∼300 km apart), we further investigate hypotheses regarding the origins of this noise.

2. Timescale-Dependent Separation of Signal and Noise in Ice Core Isotope Records

We use δ^{18}O records covering the last 104,000 years at 20-year resolution on the GICC05 timescale (Rasmussen et al., 2014; Seierstad et al., 2014), from the ice cores NGRIP (North Greenland Ice Core Project, North Greenland Ice Core Project members, 2004), GRIP (Greenland Ice-Core Project, Greenland Ice-core Project (GRIP) Members, 1993), and GISP2 (Greenland Ice Sheet Project Two, Grootes et al., 1993). NGRIP is located ∼300 km north of GRIP and GISP2, while the latter two are in close proximity (∼30 km) at the summit of the Greenland ice sheet (Figure 1a). Missing values in the GISP2 δ^{18}O record (∼0.8%) are linearly interpolated. Additionally, we use the GRIP accumulation record (Hammer & Dahl-Jensen, 1999), which we align to the GICC05 timescale. We compare δ^{18}O variability across three climate states: the Holocene (up to 8,000 years before 2000 CE (b2k)) and the two distinct phases of the last glacial period: the Greenland stadials and interstadials. We use the timing of the transitions between interstadials and stadials as defined by Blockley et al. (2012) based on the steepest δ^{18}O gradients.

To analyze variability as a function of timescale, we estimate power spectral densities (PSDs) using the multitaper method (Percival & Walden, 1993; Thomson, 1982) with three tapers, applied to linearly detrended δ^{18}O records. The lowest frequency is removed to avoid biases associated with this method. Smoothing is performed for the visualization of the PSDs, using a Gaussian kernel with a constant width of 0.05 in logarithmic frequency space (Kirchner, 2005). Variances are derived by integrating the PSDs over the relevant frequency ranges. We assume that the total variance in ice core isotope records consists of both climate variability and additive noise. The climate signal is assumed to be shared among closely located proxy records, while the noise term—arising from processes like stratigraphic disturbances and precipitation intermittency—is assumed to be independent between the records. To separate these components, we follow the approach of Münch and Laepple (2018), which is implemented in the R package *proxysnr* (Münch, 2018): The power spectral density (PSD) of an individual ice core record at site i, $X_i(f)$, and for a given time period (Holocene, stadial or interstadial), where f represents frequency, is given by

$$X_i(f) = C(f) + N_i(f), \tag{1}$$

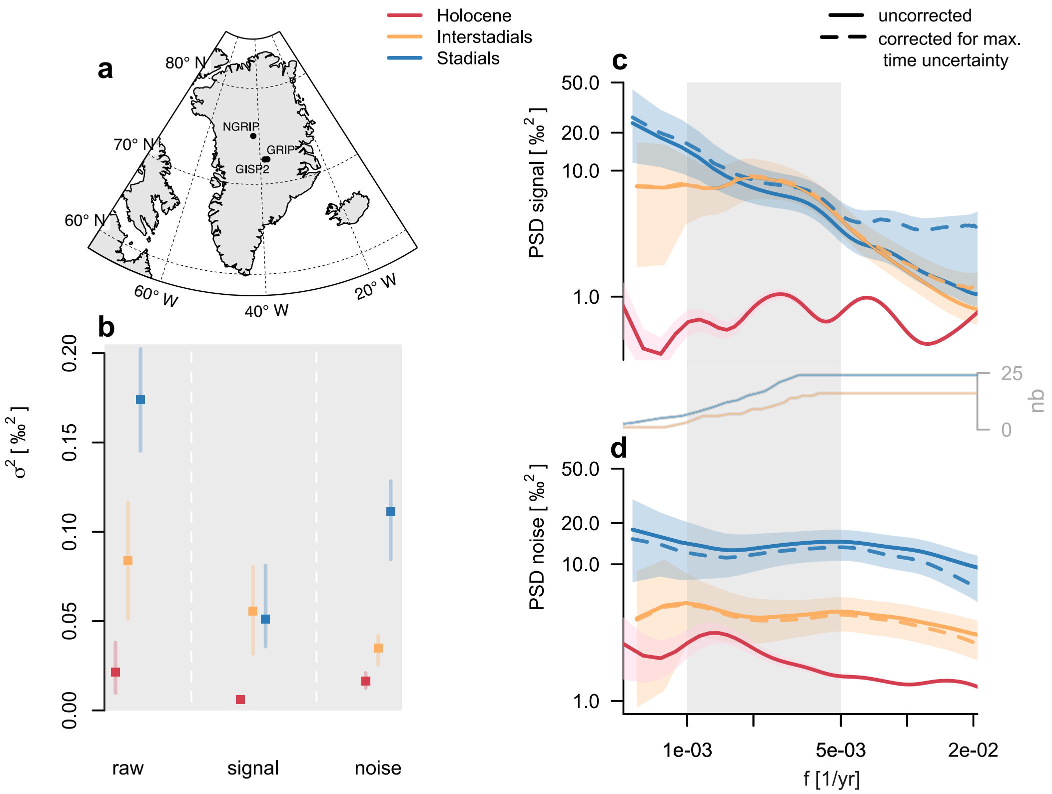

Figure 1. Signal and noise variability from the combined analysis of the NGRIP, GRIP, and GISP2 $\delta^{18}O$ records for the Holocene, the Greenland stadials, and the Greenland interstadials. (a) Locations of NGRIP, GRIP, and GISP2 ice core drilling sites on the Greenland ice sheet. (b) Raw, signal, and noise variance across the 1/1000–1/200 yr^{-1} frequency band. (c, d) Holocene and mean stadial and interstadial spectra of (c) the signal and (d) the noise on logarithmic axes. The number nb of interstadial and stadial intervals contributing to the spectra are shown on the inset plot between (c) and (d). Error bars and shadings represent the 90% confidence interval of the estimation error including time uncertainty.

where C(f) represents the common climate signal in that time period and N_i(f) the independent noise component. Stacking n records therefore reduces the noise variance by a factor of n, and the PSD of the stacked record $S(f)$ thus reads

$$S(f) = \Phi(f)C(f) + \frac{1}{n}N(f), \tag{2}$$

where $\Phi(f)$ is a linear transfer function accounting for time uncertainty and where we assume that the statistical properties of the noise terms are identical, $N_i(f) \equiv N(f)$. The common signal and noise spectra are then estimated as

$$C(f) = \frac{n}{n - \Phi(f)^{-1}} \cdot \Phi(f)^{-1}\left(S(f) - n^{-1}M(f)\right) \tag{3}$$

and

$$N(f) = M(f) - C(f), \tag{4}$$

where $M(f)$ is the mean spectrum of all individual spectra $X_i(f)$. Time uncertainty can cause signal misalignment in the time domain, leading to an underestimation of the climate spectrum and an overestimation of the noise spectrum at higher frequencies (Comboul et al., 2014; Münch & Laepple, 2018). We corrected for this with a transfer function, $\Phi(f)$. To quantify this uncertainty, we simulate a common climate signal using 1,000 different age-depth realizations and estimate the mean and stack spectra to derive $\Phi(f)$ (details in Appendix A). Based on this investigation, we exclude data beyond 90,140 years b2k (onset of interstadial 23.1) and limit our analysis to frequencies below 1/200 yr^{-1} to minimize the effect of time uncertainty onto our variability estimates. This also means that our variability estimates are not affected by isotopic diffusion, which impacts only high frequencies, for example, above 1/10 yr^{-1} in the recent Holocene (Hörhold et al., 2023). Finally, after interpolating all spectra to a common frequency axis, we average the individual stadial and interstadial spectra to obtain mean signal and noise estimates for each climate state.

3. Changing Isotope Variability in the Last Glacial Period can Be Explained by Changing Noise Levels

Comparing the variance of δ^{18}O, in the 1/200–1/1,000 yr^{-1} frequency band derived from the PSDs of the Holocene, stadials, and interstadials (Figure 1b), we find that the raw variability differs significantly (t-test, $p < 0.001$) between the mean climate states. The variability is lowest during the Holocene (0.02‰^{2}), higher during interstadials (0.08‰^{2}), and highest during stadials (0.17‰^{2}), confirming previous studies (Ditlevsen et al., 2002; Rehfeld et al., 2018). However, after decomposing the variability into common signal and independent noise components, we find that a substantial portion of the centennial- to millennial-scale variability is noise, with mean signal-to-noise variance ratios (SNRs) of 0.36 (Holocene), 1.70 (interstadials), and 0.46 (stadials).

The comparison of absolute variances between interstadials and stadials is especially striking. While the noise variance in stadials (0.11‰^{2}) is around three times higher than in interstadials (0.03‰^{2}) (t-test, $p < 0.001$), the signal variance does not significantly differ between them ($p > 0.05$). These results suggest that the observed differences in isotope variability across the last glacial period can be attributed entirely to changes in noise levels.

Holocene noise levels (0.016‰^{2}) are nearly seven times lower than in stadials and about half those of interstadials. The Holocene signal variability, however, is much lower than that of interstadials and stadials (0.005‰^{2}, compared to 0.06‰^{2} in interstadials and 0.05‰^{2} in stadials), which means that signal differences mainly distinguish the Holocene from the last glacial period as a whole (interstadials and stadials). The Holocene climate variability in Greenland ice cores was found to be exceptionally low even compared to other Holocene climate proxies worldwide (Rehfeld et al., 2018) and may indicate a local climate decoupling from the broader Arctic (Hörhold et al., 2023). The increased climate signal variability within the last glacial period could be related to an extension of the sea ice, introducing more variability to the North Atlantic Sector (Li et al., 2005) and to a global increase in variability, potentially related to increased spatial temperature gradients (Rehfeld et al., 2018).

The spectral shape of the noise gives insight into its origins (Figures 1c and 1d). Across all climate states, the noise spectra exhibit a nearly uniform distribution of variance across the investigated frequency range, resembling white noise. This supports the hypothesis that the original isotope signal is aliased (Kirchner, 2005) by precipitation intermittency and stratigraphic disturbances (Casado et al., 2020; Kunz & Laepple, 2021; Laepple et al., 2018). If this hypothesis is correct, the same systematic noise changes should extend into higher frequencies and therefore must be considered when interpreting isotope variability on annual to multidecadal timescales.

4. Noise Co-Evolves With Temperature and Accumulation Rate

To explore how the noise levels have evolved over time alongside the mean climate state, we extract the noise variance on 1,000 year running windows (Figure 2a). The short time window requires that we restrict this analysis to the 1/200–1/500 yr^{-1} frequency range. We use the GRIP isotope and accumulation record as a comparison; however, similar results are obtained with the records of any of the three ice cores. The noise timeseries exhibits a very similar structure as the records of δ^{18}O and accumulation rate, with low levels of noise during the Holocene and high levels during glacial periods, further characterized by stadials (relatively high noise) and interstadials (relatively low noise). We compare values of noise variance from discrete time windows to ensure independence between data points (Figures 2b and 2c) and find strong negative correlations between the square-root of the total isotope variance of the three ice cores (hereafter SD, i.e., amplitudes) with mean isotope values (−0.81/−0.83/−0.81, $p < 0.001$, regression slope: 0.026‰) and accumulation rates (−0.82, $p < 0.001$). Isotope values and accumulation rates are however not independent as warmer air can hold more moisture (Clausius-Clapeyron

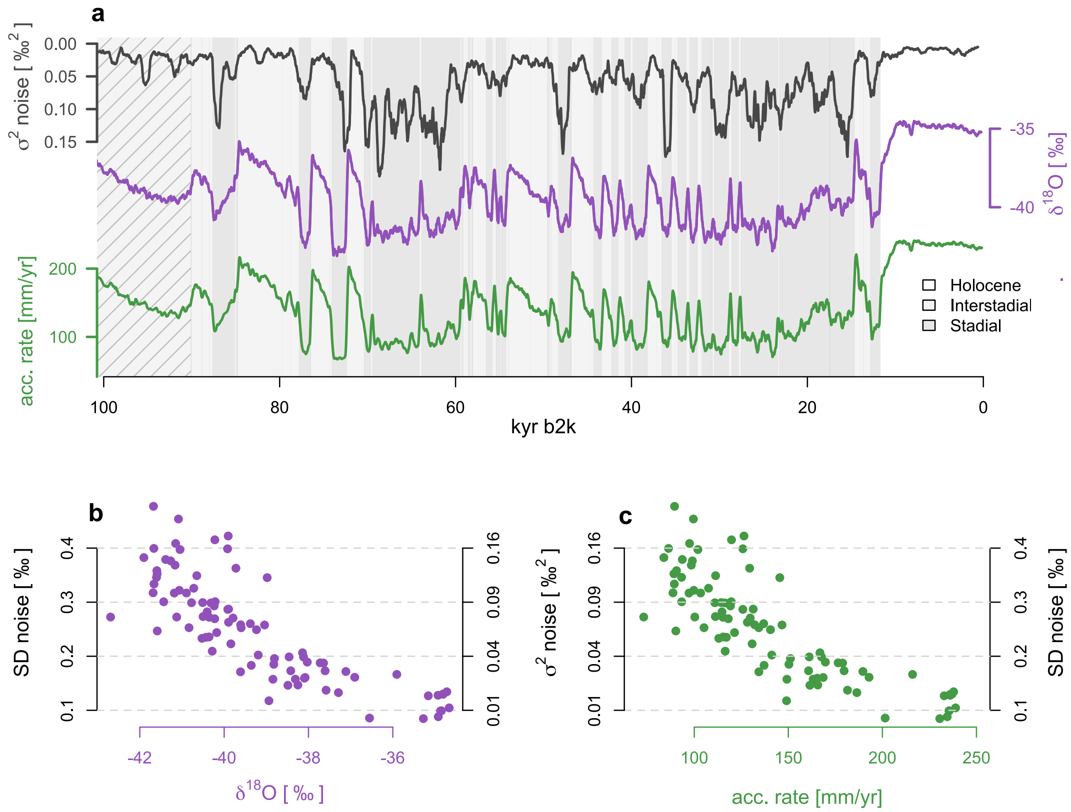

Figure 2. Relationship between noise strength, δ^{18}O, and accumulation rate over the last 100,000 years. (a) Noise variance (inverse axis) estimated from the three ice-core records, along with δ^{18}O and accumulation rate data from GRIP, all calculated on 1,000 year running windows. (b, c) Noise amplitude (standard deviation) versus (b) δ^{18}O and (c) versus accumulation rate. For (b, c), two *y*-axes are provided, displaying variance and standard deviation units. All noise variances are calculated within the 1/500–1/200 yr^{-1} frequency band. The striped time-interval is excluded for the analysis shown in panels (b, c) due to time-uncertainty.

equation) and accumulation rates change exponentially with isotopes (Dahl-Jensen et al., 1993). We can therefore not determine whether this relationship is driven primarily by temperature or accumulation changes, or by both.

The signal component (SD) is only weakly correlated to mean isotope values (−0.27, −0.27, −0.26, $p = 0.01$) as well as accumulation rates (−0.27, $p = 0.01$, Figure S3 in Supporting Information S1). The values are in the same range as the correlations of the overall (raw) isotope variability with isotopes (−0.29/−0.29/−0.31, $p < 0.007$) and accumulation rates (−0.29/−0.29/−0.32, $p < 0.007$).

5. Most Noise Is of Local Origin

The three ice cores allow us to estimate noise levels separately for different ice-core distances, providing insights into the origins of the noise (Figure 3). Even if this approach comes with higher uncertainty compared to our previous analyses, which aggregated all three cores together, we find that the noise during warmer phases (both the Holocene and interstadials) between 300 and 30 km distant ice cores identify similar levels over 1/200–1/1000 yr^{-1} frequencies. This suggests that during warm periods the main noise contribution is local (<30 km) stratigraphic noise, which has an horizontal spatial scale of less than 10 m (Münch et al., 2016), rather than precipitation intermittency, which would add an additional level of noise at the larger spatial scale (Münch et al., 2021; Sime et al., 2011). The small role of precipitation intermittency creating independent variations on the 300 km scale is consistent with the strong correlation between Summit (GISP2 and GRIP) and NGRIP temperatures and precipitation-weighted temperatures based on the ERA5 reanalysis (Hersbach et al., 2020, 2023, $r = 0.95, p < 0.05$, Figure S5 in Supporting Information S1). We conclude that the noise in the warmer phases must be mainly

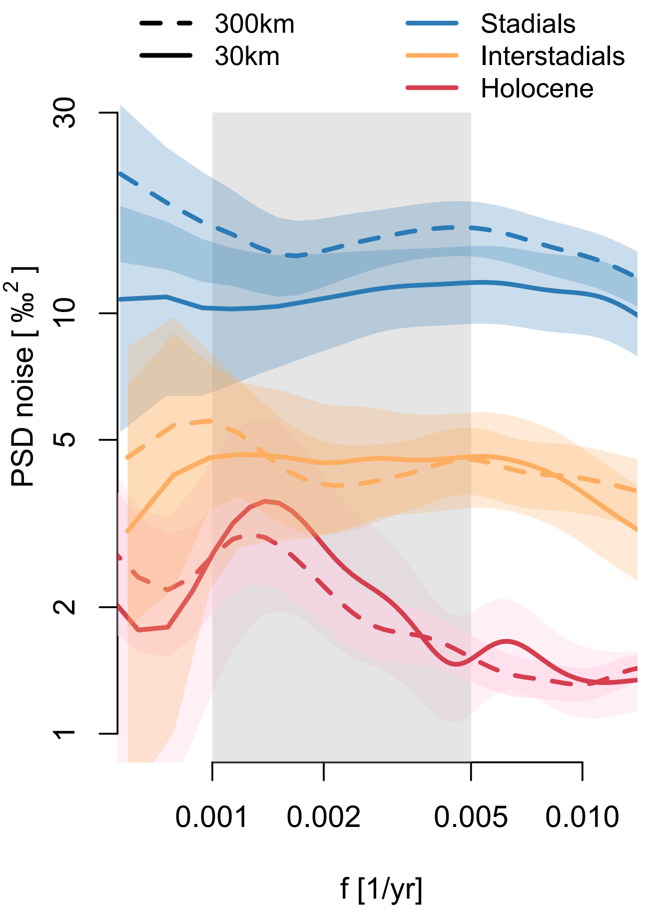

Figure 3. Noise power spectral density depending on the distance between the ice core records. The three cores are arranged into pairs representing two spatial scales: 300 km (NGRIP–GISP2 and NGRIP–GRIP) and 30 km (GISP2–GRIP). Shown are the resulting Holocene and mean stadial and interstadial noise spectra, including 90% confidence intervals (shading). Results on the 300 km scale are the averaged results from the two ice core pairs. Gray shading is the analyzed frequency range.

stratigraphic noise, which is ninefold higher during the interstadials compared to the Holocene. Stratigraphic noise is furthermore three times higher in the stadials compared to the interstadials. Such changes of stratigraphic noise could directly result from the changes in precipitation amounts as higher accumulation rates were shown to enhance signal preservation in isotope records (e.g., Hirsch et al., 2023). But also other changing depositional conditions, for example, increasing wind speeds (McGee et al., 2010; Werner et al., 2002) or changes in the surface roughness could drive stratigraphic noise in the cold periods (Birnbaum et al., 2010; Hirsch et al., 2023).

During the cold interstadial periods, we observe an additional noise level at the 300 km scale which is 1.5 times larger than at the 30 km scale (*t*-test, $p < 0.002$). Stadials are marked by a reorganization of the climate system, including expanded sea-ice cover due to reduced marine deep convection (Hoff et al., 2016; Sadatzki et al., 2019, 2020), along with shifts in atmospheric circulation, moisture transport, and precipitation patterns (Ludwig et al., 2016; Újvári et al., 2017, 2022). These changes may increase the decoupling between Summit and NGRIP conditions. A changing temperature to isotope relationship or a stronger spatial temperature gradient across Greenland was previously hypothesized to explain the increased mean isotopic differences between the two sites during stadial periods (Cauquoin et al., 2023; Seierstad et al., 2014). Similarly, greater independence of local temperatures or moisture source regions and more patchy precipitation could account for the higher uncorrelated variability at the 300 km scale.

6. Conclusions and Implications

It has previously been shown that isotope variability in Greenland ice cores differs between the Holocene, stadials, and interstadials, with cooler periods exhibiting more variability (e.g., Ditlevsen et al., 2002). However, the origin of these differences has remained unclear. By separating the centennial- to millennial-scale isotope variability into a common signal and an independent noise component, based on comparisons of three nearby ice cores, we show that isotopic variability is systematically influenced by noise. In fact, the entire difference in the centennial- to millennial-scale isotopic variance between stadials and interstadials can be explained by changes in noise, while the climate signal variability does not systematically change. In contrast, the Holocene exhibits 10 times less climate signal variability than the glacial period overall.

Because the PSD of the noise is similar across all analyzed frequencies (white noise), we argue that these systematic differences likely also apply to faster timescales such as interannual to decadal variations. Our findings therefore contrast with earlier studies like Ditlevsen et al. (2002), who attribute the different isotopic variability between stadials and interstadials to climate variability. Climate state dependent noise could also provide an alternative explanation for the maxima in interannual variability that precede Dansgaard-Oeschger events (Brashear et al., 2024) and might also affect the changes in annual amplitudes observed in the WAIS isotope record during the Holocene (Jones et al., 2023; Laepple et al., 2025). Since additive white noise influences both overall variance and autocorrelation structures, it could also affect the detection of early warning signals for abrupt climate shifts in ice core isotope timeseries, such as those sought during the last glacial period in the raw isotope variability of the Greenland cores (Hummel et al., 2024).

We find that both temperature and accumulation rate co-evolve with noise levels, with colder and drier conditions associated with more noise. This relationship is consistent with findings of higher levels of stratigraphic noise at lower accumulation rates across Antarctic sites (Hirsch et al., 2023). Increased seasonality during cold periods could also enhance both stratigraphic noise and precipitation intermittency related noise. These can be conceptualized as aliasing of the seasonal cycle due to intermittent snowfall (Laepple et al., 2018; Persson et al., 2011), or as the redistribution of snow (Fisher et al., 1985; Laepple et al., 2018). Our comparison of noise levels between ice core pairs spaced 30 and 300 km apart reveals a consistent local (<30 km) noise level across all climate states, whereas an additional noise component at the 300 km scale appears only during the coldest phases of the last glacial period. We therefore speculate that stratigraphic noise is the primary source of additive noise in all climate states, with an added decoupling of the more distant sites during the coldest phases. Further studies using replicate ice cores will enable the testing of our hypotheses regarding the origin of the noise and its dependence on climate and accumulation conditions. We propose two complementary approaches: first, to exploit spatial variations in climate by analyzing large-scale core arrays from a single climate state; and second, to compare long replicated ice cores, such as the newly drilled core at Little Dome C (Beyond EPICA Oldest Ice Core project) with the nearby EPICA Dome C core (EPICA community members, 2004), located approximately 30 km away.

We conclude that, despite the high resolution and rich information preserved in ice cores isotope records, interpreting their variability requires particular caution. However, systematic changes in depositional noise can be addressed by using replicate ice cores to separate signal and noise components, as demonstrated in this study. This approach enables a more accurate estimation of signal variance across timescales and, ultimately, leads to more robust reconstructions of past climate variability.

Appendix A: Time Uncertainty

Our method to estimate signal and noise spectra is influenced by relative time uncertainty between the different records. Time uncertainty impacts the coherence between records, leading to an overestimation of noise variance and an underestimation of signal variance. We briefly discuss the time uncertainty of the GICC05 chronology and quantify its effect on our results.

For the GICC05 timescale used here, the ice cores GRIP and GISP2 were matched to the NGRIP ice core by common peak signals like volcanic ash layers (tiepoints) (Rasmussen et al., 2014; Seierstad et al., 2014). In between these tiepoints the NGRIP depths were converted to GRIP and GISP2 depths using linear interpolation. In the Holocene, NGRIP, GRIP (Rasmussen et al., 2005; Vinther et al., 2005), and GISP2 (Alley et al., 1997; Meese et al., 1997) records were annually layer counted and the matching was done using a large number of tiepoints (∼170 in the last 8,000 years) with a mean gap of only ∼30 years. In contrast, in the last glacial period, there are large tiepoint gaps, with an average gap size of 139 years in the interstadials and 501 years in the stadials. There are fewer tiepoints in the stadials (Figure S1 in Supporting Information S1) due to its ice being more alkaline and thus muting volcanic signals (Seierstad et al., 2014). We therefore assess the effect of time uncertainty on the estimated signal and noise variances for the last glacial period, using realizations of chronologies consistent with the GICC05 and its uncertainty. To generate these realizations, we use the Bayesian age-depth model *hamstr* (Dolman, 2025). *Hamstr* models the accumulation of sediment/ice as a discrete first order autoregressive process with gamma distributed innovations. It is similar to Bacon (Blaauw & Christen, 2011), but more robust to down-core changes in accumulation rates. We ran sets of 1,000 age-depth model realizations for each of the three ice cores and used them to distort a common signal timeseries. Because the NGRIP ice core is annually layer counted until around 60.2 k years b2k (Seierstad et al., 2014), we use an undisturbed signal for this part of the core. We then estimate time uncertainty transfer functions by combining the distorted timeseries from each core, and estimating the ratio of the spectrum of the stack S(f) and the mean spectrum M(f), repeating this 1,000 times (Figure A1).

The *hamstr* models were fitted with four independent MCMC chains (Figure S2 in Supporting Information S1) using settings as listed in Table A1. The three resulting *hamstr* models have mean Rhat values of 1.01, 1.05, and 1.02, indicating that the four chains have mixed sufficiently well (Figure S2 in Supporting Information S1). The delta_t/delta_d (named "accumulation rate" in the *hamstr* model) was on average at 32.11 (NGRIP), 28.4 (GRIP), and 31.1 (GISP2) yr/m. The AR1 coefficient was on average at 0.67 (SD 0.2, NGRIP), 0.54 (SD 0.25, GRIP), and 0.16 (SD 0.14, GISP2).

The described method results in the time uncertainty transfer functions shown in Figure A1. They are used to correct for the time uncertainty while separating signal and noise components as described in Equations 2 and 3. However, the here proposed combination of independent age-depth realizations between cores is the most conservative approach. More probable is, that age-depth deviations of the three cores are similar to each other as large-scale accumulation patterns are similar across the Greenland ice sheet. We therefore consider the signal and

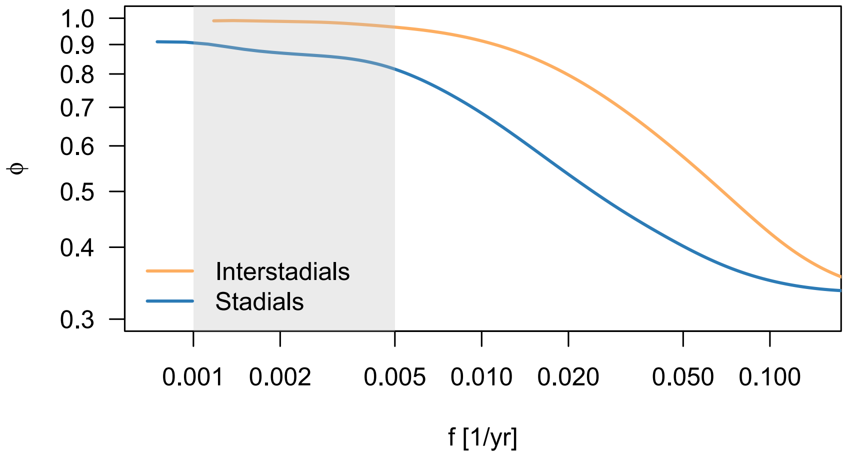

Figure A1. Time uncertainty transfer functions Φ(f) for the signal spectra of interstadials and stadials. The transfer function is averaged across all interstadials and stadials occurring after 90,140 years b2k. The gray shading represents the frequency range which the variance analysis is focussed on.

Table A1
Parameters and Settings Used in the Hamstr Model

Parameter	Description	Value
K_fine	Number of discrete modeled core sections	4,419
acc_shape	Shape parameter of the gamma prior distribution on accumulation rates. It influences how much the single realizations deviate from the mean age model	24
mem_mean, mem_strength	Parameters of the beta prior distribution on the memory between accumulation rates in neighboring modeled core sections	0.5 and 2
obs_err	Uncertainty in the age of the tiepoints	3 years
R_scaled	AR1 coefficient can be scaled by the thickness of the modeled sections	False

Note. The resolution of the age models (K_fine) was set so that there were on average five modeled sections between neighboring tiepoints. The value for "acc_shape," was determined by fitting a gamma distribution to the distribution of accumulation rates between tiepoints. The tiepoints were first interpolated to a regular spacing of 2 times the median depth interval. To obtain a robust estimate we split the complete sequence of tie-points into multiple sections and fit a gamma distribution each. We repeated this using from 7 to 15 sections. Sections which contained large gaps between the real tiepoints showed strongly elevated shape values as a result of the interpolation, however the median shape value of 24 was insensitive to the number of sections used. The memory parameter (AR1 coefficient) was given a flat beta prior distribution (mem_mean and mem_strength). Obs_err was set to 3 years to account for uncertainty in the age of detected tiepoints, for example, ash layers. Furthermore, R_scaled was set to False, such that AR1 coefficient is not scaled by the thickness of the modeled sections.

noise spectra based on this transfer function Φ (Figure A1) and $\Phi = 1$ as an uncertainty range. The transfer functions show a deviation of 2% (interstadials) and 14.5% (stadials) from the $\Phi = 1$ baseline in the 1/1000–1/200 yr^{-1} frequencies, which translates to a maximum of 3% (interstadials) and 22% (stadials) underestimation of the signal variance and a maximum of 5% (interstadials) and 10% (stadials) overestimation of the noise variance.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The GICC05 isotope records were downloaded from www.iceandclimate.nbi.ku.dk/data (Rasmussen et al., 2014; Seierstad et al., 2014). ERA5 data (Hersbach et al., 2020) are available from the Copernicus Climate Change Service (Hersbach et al., 2023). R packages and code are archived by Dolman (2025), Münch (2018), and Hirsch (2025).

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