A low climate threshold for south Greenland Ice Sheet demise during the Late Pleistocene

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The Greenland Ice Sheet (GIS) has been losing mass at an accelerating rate over the recent decades. Models suggest a possible temperature threshold between 0.8 and 3.2 °C, beyond which GIS decline becomes irreversible. The duration of warming above a given threshold is also a critical determinant for GIS survival, underlining the role of ocean warming, as its inertia prolongs warmth and triggers longer-term feedbacks. The exact point at which these feedbacks are triggered remains equivocal. Late Pleistocene interglacials provide potential case examples for constraining the past response of the GIS to a range of climate states, including conditions warmer than present. However, little is known about the magnitude and duration of warming near Greenland during these periods. Using high-resolution multiproxy surface ocean climate records off southern Greenland, we show that the previous 4 interglacials over the last ∼450 ka all reached warmer than present climate conditions and exceeded the modeled temperature threshold for GIS collapse but by different magnitudes and durations. Complete deglaciation of the southern GIS in Marine Isotope Stage 11c (MIS 11c; 394.7 to 424.2 ka) occurred under climates only slightly warmer than present (∼0.5 ± 1.6 °C), placing the temperature threshold for major GIS retreat in the lower end of model estimates and within projections for this century.

Greenland Ice Sheet | Late Pleistocene interglacials | climate change | thresholds

Understanding the response of the Greenland Ice Sheet (GIS) to global warming is consequential, as the complete melting of the GIS can contribute up to 7 m of global sea-level rise (1). While the relative amounts of GIS retreat during recent interglacials remains somewhat equivocal, emerging results suggest that the size and discharge of GIS varied significantly both within and between recent interglacial periods. In Marine Isotope Stage 5e (MIS 5e) and MIS 11c, GIS retreat likely contributed 0.4 to 5.6 and 3.9 to 7.0 m, respectively, to sea-level rise above present (2–4). The latter implies that a substantial portion of the GIS was lost in MIS 11c, consistent with the presence of spruce forests and the cessation of Greenland silt discharge interpreted to reflect complete deglaciation of the southern GIS (5, 6). Bedrock data suggest that even central Greenland was ice free in one or more recent interglacials (7). Ice likely remained over southern Greenland in MIS 5e, MIS 7e, and MIS 9e, despite intervals of increased sediment discharge from Precambrian Greenland (PG) terranes, indicating elevated GIS activity and retreat, particularly in MIS 9e (8, 9). In the Holocene, by contrast, the GIS appears to have been relatively large and unusually stable (9). Thus, the response of the GIS to Late Pleistocene interglacial climate forcings varied substantially and included increased melting during 3 of the 4 recent interglacials compared with the Holocene (9) and near full retreat during MIS 11c.

Resolving the climate conditions associated with these different GIS responses is crucial for understanding the processes and thresholds determining past GIS retreat and survival. Yet, the climatic background associated with and driving these changes remains poorly constrained. Dinocyst-based sea surface temperature (SST) records suggest variable interglacial warmth during Late Pleistocene interglacials close to southern Greenland (5). However, there are no available SST records proximal to southern Greenland that span all recent interglacials, including MIS 9e, which is a particularly interesting interval given strong but incomplete GIS retreat (9).

Here, we provide high-resolution ocean climate (SST) reconstructions from Integrated Ocean Drilling Program (IODP) Site U1305 (57°28.5′ N, 48°31.8′ W; 3,459 m) from the Eirik Drift off southern Greenland, spanning MIS 7e (benthic δ18O plateau: 232.6 to 243.2 ka), MIS 9e (benthic δ18O plateau: 320.9 to 333.1 ka), and MIS 11c (benthic δ18O plateau: 394.7 to 424.2 ka), which we combine with existing MIS 5e (benthic δ18O plateau: 117.9 to 128.2 ka) records from this location (Core MD03-2664) (10). This site is sensitively situated to monitor subpolar climate near and partially over Greenland (SI Appendix, Fig. S1), fluctuations in GIS extent, and iceberg calving events (10, 11). We use benthic foraminifera δ18O to identify peak interglacial intervals and constrain our age model (SI Appendix, Fig. S2). Changes in climate are portrayed using planktonic foraminiferal (MAT)-derived SSTs, and Mg/Ca paleothermometry using Neogloboquadrina pachyderma

Significance

Understanding how warmer climates affected Greenland in the past helps in determining how future warming will impact it. The Greenland Ice Sheet (GIS) has retreated during recent interglacials, suggesting a critical survival threshold within a few degrees of modern temperatures. Defining this temperature threshold requires records of the past climates responsible for GIS demise. Using microfossil temperature reconstructions, we show that the current interglacial is unusually moderate and that all 4 previous interglacials were warmer than present near Greenland. Both magnitude and duration of past warmth were important influences on the ice sheet. Notably, the critical temperature threshold for past GIS decay will likely be surpassed this century. The duration for which this threshold is exceeded will determine Greenland’s fate.

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Results and Discussion

Our SST records (Figs. 1 and 3) show that all 4 previous interglacials were at least as warm as present south of Greenland, albeit with varying degrees of excess warmth. The mean MAT summer SSTs through the interglacial plateaus indicate that MIS 9e was the warmest (~11 °C) of the previous 4 interglacials followed by MIS 5e (~9.3 °C), MIS 11c (~8.1 °C), and MIS 7e (~7 °C). For reference, modern MAT summer SSTs at the site are 7.7 °C (SI Appendix). Peak temperatures during each of the 4 most recent interglacials intermittently exceeded the modern (core top MAT SST) (Fig. 3). The duration of warmer than present conditions also varied widely between the interglacial δ18O plateaus, with temperatures above present levels for 20.7 ka in MIS 11c, 12.2 ka in MIS 9e, 9.7 ka in MIS 5e, and 4.4 ka in MIS 7e. The distinct changes in relative abundance of foraminifer fauna further highlight the environmental (habitat) differences experienced between interglacials. In particular, MIS 9e stands out in terms of warm planktonic foraminifer fauna (SI Appendix, Fig. S3). The relative abundance of subpolar N. incompta reached a maximum of ~88% during late MIS 9e, and N. pachyderma (s) coiling ratio dropped to 0% for the only time in the last ~450 ka. Reduced N. pachyderma (s) coiling ratio is also observed during the peak warm periods of MIS 5e (~11%), MIS 7e (~48%), and MIS 11c (~42%). For context, the modern planktonic foraminiferal assemblage at Eirik Drift is dominated by the polar N. pachyderma (s) with core top coiling ratios reaching as high as 100% (SI Appendix, Fig. S4), similar to the last 2 ka (94%) and Holocene average (95%) (SI Appendix), revealing anomalously cold and stable conditions in the current interglacial that are not particularly representative of interglacials in general.

Comparing our climate records with previous reconstructions of GIS sediment discharge and retreat (6, 8, 9) reveals a clear pattern of high southern GIS melt (PG percentage and silt provenance records) when SSTs were high and polar fauna [N. pachyderma (s) coiling ratio] were low (Fig. 2), indicating that GIS activity was closely coupled to nearby ocean temperatures on centennial–millennial timescales. Thus, strong GIS melt and retreat occurred when subpolar temperatures exceeded current levels. However, the different magnitude and duration of interglacial warmth off of southern Greenland provide additional information for delineating the sensitivity of the GIS to climates warmer than today. The recent increase in GIS melting coincided with the onset of industrial era Arctic warming, but the magnitude of GIS melting has only recently emerged beyond the range of natural variability (13) and quadrupled over the past decade (14). Due to the nonlinear response of surface melting to increasing summer air temperatures, continued atmospheric warming will

![Fig. 1. SST records from Sites MD03-2664 (MIS 5e) and U1305 (MIS 7e, MIS 9e, and MIS 11c) spanning the last 450 ka. (A) MAT summer (pink) and winter (blue) SSTs. (B) Mg/Ca SSTs from N. pachyderma (s) (light green) and N. incompta (dark green). (C) N. pachyderma (s) coiling ratio (percentage). (D) N. pachyderma (s) δ18O record. Core top MAT summer (pink diamonds), MAT winter (blue diamonds), and N. pachyderma (s) Mg/Ca (green diamonds) SSTs from the Eirik Drift Multicore GS06-144-03 MC A (18) are shown for comparison with modern SSTs at core site. In A, dashed light pink lines and SST values mark the mean MAT summer SSTs through the interglacial plateaus. The dashed light blue line in C marks the mean Holocene (last 9.5 ka) N. pachyderma (s) coiling ratio from the Eirik Drift Core MD03-2663 (SI Appendix). Open circles mark samples with low (~150) total number of planktonic foraminifera. Yellow shading marks the interglacial benthic δ18O plateaus. Data points only within the interglacial benthic δ18O plateaus (yellow shaded intervals) are included in the mean SST calculations (Materials and Methods). Gray (cross-hatched) shading marks deglacial IRD peaks (Heinrich events) (SI Appendix). VPDB, Vienna Pee Dee Belemnite.](www.pnas.org/cgi/doi/10.1073/pnas.1911902116)
further accelerate the melting (13). Models suggest that GIS demise is inevitable after a certain temperature threshold is passed (15, 16). Robinson et al. (16) estimate a warming threshold for an ice-free Greenland to be in the range of 0.8 to 3.2 °C, with a best estimate of 1.6 °C warming relative to preindustrial climate. However, crossing the temperature threshold does not necessarily lead to a rapid GIS collapse, and the time needed to melt a significant portion of the GIS may be strongly dependent on the level
of warming (3, 15, 17). In order to further explore GIS thresholds, we apply the 1.6 °C (0.8 to 3.2 °C) warming threshold of Robinson et al. (16) to our SST records (Fig. 3). According to our MAT summer SSTs, all of the previous 4 interglacials over the last ~450 ka intermittently exceeded the modeled temperature threshold of 1.6 °C suggested for GIS collapse. Within the interglacial δ18O plateaus, SSTs stayed above the 1.6 °C threshold for 11.7 ka in MIS 9e, 8.7 ka in MIS 11c, 5.8 ka in MIS 5e, and 3.0 ka in MIS 7e. MAT summer SSTs at the Eirik Drift never reached the 1.6 °C warming threshold during the last 2 ka or any other time during the Holocene (SI Appendix, Fig. S5).

Comparison of MIS 5e, MIS 9e, and MIS 11c is particularly interesting, since ice persisted on southern Greenland during both MIS 5e and MIS 9e, whereas it was nearly completely deglaciated during MIS 11c (6, 8, 9). Yet, our MAT summer SST records suggest that MIS 9e was the warmest of the previous 4 interglacials and that SSTs stayed above the 1.6 °C threshold the longest throughout the interglacial plateau (Fig. 3). Elevated southern GIS sediment discharge during the MIS 9e warmth (Fig. 2) may suggest that the ice sheet responded, but retreat was limited compared with MIS 11c (9). The contrast between the near-complete deglaciation of southern GIS during the moderate warming of MIS 11c and a persistent southern GIS during the warmer MIS 9e has implications for the critical factors determining GIS size. An ice-free southern GIS during MIS 11c suggests that southern GIS survival was strongly dependent on the duration of warmer than present conditions rather than crossing the modeled (1.6 °C) temperature threshold for the GIS collapse. For example, taking a lower temperature threshold of 0.8 °C, the lower limit of the estimate of Robinson et al. (16), could help explain strong retreat during MIS 11c. MIS 11c was over 0.8 °C, the lower limit of the estimate of Robinson et al. (16), and warming during the last 2 ka or any other time during the Holocene (SI Appendix, Fig. S5).

Of course, there may not be a single uniformly applicable temperature threshold for GIS survival. GIS mass balance also depends on other factors, such as geometry, accumulation, and moisture supply, which in turn, are related to SSTs and sea ice extent (19). Thus, a number of mechanisms could explain why the degree, or even the sign, of the mass balance response to warming is time sensitive. For example, warming may initially increase accumulation locally and in particular, in southeast Greenland (20) but also, decrease ice viscosity (via liquid water and warming), resulting in slow dynamic feedbacks eventually driving mass loss (21). In addition to dynamics, the apparent long response time for removal of the southern and eastern central GIS might simply reflect the inherent stability of this region due to its high mass turnover (accumulation–ablation). In this region, surplus melting due to a warmer climate does not represent a large relative imbalance to natural fluxes (22, 23). Using the temperature dependence of the surface mass balance from idealized simulations with a comprehensive model (20), we estimate the resilience of different regions of the GIS (SI Appendix, Fig. S5). The accelerating surface warming due to the ice-elevation feedback reaches a tipping point where a reversal of the initial warming is not enough to stop further ice loss. Large regions in northern and western Greenland destabilize quickly, whereas large parts of the ice margin along the eastern coast are less vulnerable, requiring up to 10 ka to reach a tipping point.

Conclusions

The current interglacial seems to have been notably stable and mild off southern Greenland, perhaps explaining the relative stability and large size of the GIS during the Holocene, while also skewing our concept of the “natural” interglacial size and stability of this ice sheet (9, 24). By corollary, each of the previous 4 interglacials was warmer than the Holocene by varying degrees. We suggest that these conditions can explain both the interglacial size and the evolution of the southern GIS, where the duration of warming relative to the modern climate seems to have been as important as the magnitude, at least beyond a critical threshold value. Our reconstructions suggest that temperatures in the lower range of the modeled warming threshold (~0.8 °C) (3), within the range of projections for this century, were enough to cause southern GIS disintegration during MIS 11c. A low GIS threshold increases the plausibility that one of the most economically impactful (25) long-term consequences of warming could be passed well below the 2 °C threshold and may already be unavoidable if even modestly warmer conditions were to persist long enough (26).

Materials and Methods

Sample Preparation. Site U1305 was recovered during IODP Expedition 303 off southern Greenland. The core was sampled continuously with 2-cm sample spacing over the interglacial periods MIS 7e (43.85 to 49.75 meters composite depth [mcd]), MIS 9e (54.99 to 63 mcd), and MIS 11c (63.8 to 80.03 mcd). Samples were soaked in distilled water and left overnight on a shaker to disperse the sediment. All samples were wet sieved using a 63-μm-sized sieve.

Table 1. GIS thresholds summary

| Age range (ka) of MIS plateaus* (based on LR04) | MIS 5e | MIS 7e | MIS 9e | MIS 11c |
|----------------|--------|--------|--------|--------|
| Rough amplitude of southern GIS retreat† | Medium (8) | Small (9) | Medium (9) | Large (5, 6, 9) |
| Mean summer SSTs through MIS plateaus, °C | 9.3 | 7.0 | 6.0 | 8.1 |
| Mean measure of GIS discharge‡ | High§ | Low | High | Low |
| Duration (ka) of warming above modern SSTs | 10.2 [11.5]§ | 5.5 | 12.0 [15.6]§ | 20.2 |
| Duration (ka) of warming above 0.8 °C threshold | 9.4 [10.4]§ | 4.8 | 11.9 [14.7]§ | 14.9 |
| Duration (ka) of warming above 1.6 °C threshold | 5.8 [6.5]§ | 3.0 | 11.7 [14.2]§ | 8.7 |

*GIS plateaus (i.e., the periods of low and relatively constant ice volume) are defined based on our epibenthic foraminifera Cibicidoides wuellerstorfi δ18O records (SI Appendix, Fig. S2).
†Small indicates minimal southern GIS retreat (southern GIS did not retreat from the shelf) (9). Medium indicates extensive southern GIS retreat, but ice remained on each south Greenland PG terrane (8, 9). Large indicates near-complete deglaciation of southern GIS (5, 6, 9).
‡Based on PG silt percentage and duration of quadrant 1 (Q1) signatures (high PG percentage and high silt content) in Eirik Drift Core MD99-2227 after Hatfield et al. (9).
§The duration of warming was estimated based on MAT-derived summer SSTs using only data within the MIS plateaus (e.g., yellow shaded intervals in Fig. 3). However, SSTs were intermittently high prior to the beginning of the MIS 5e plateau (at ~129.5 ka) and the MIS 9e plateau (at ~336.7 ka). If these intermittent warmings are included (and the duration is extended to 117.9 to 129.5 ka for MIS 5e and 320.9 to 336.7 ka for MIS 9e to include part of the deglacial), the MIS 5e and MIS 9e interval of warmth is longer (shown in brackets). Note, however, that this does not influence the ranking of interglacials according to the duration of warming.
The coarse fraction (≥63 μm) was dry sieved and further used for stable isotope analysis, foraminiferal assemblages, IRD counts, and Mg/Ca analysis.

Stable Isotopes. Stable isotope analyses (δ18O and δ13C) were performed on the planktonic foraminifer species *N. pachyderma* (sinistral) in order to reconstruct surface ocean physical and chemical properties. *N. pachyderma* (s) tests were picked every 4 cm (with notable gaps due to absence, particularly in MIS 9e) from the 150- to 212-μm-sized fraction (7 to 12 specimens per analysis) and measured twice per sample when the abundance allowed (≈92% of the total 616 samples measured).

A Finngian MAT253 mass spectrometer, located at the Facility for Advanced Isotopic Research and Monitoring of Weather, Climate and Bio-geochemical Cycling, Department of Earth Science, University of Bergen, was used for the stable isotope analysis. Averages of the replicate measurements are shown in the results, and values are reported relative to Vienna Pee Dee Belemnite, calibrated using National Bureau of Standards (NBS)-19 and compared with NBS-18. During the analysis period, the long-term reproducibility (1σ) values of in-house standards for samples between 10 and 100 μg were better than 0.08 and 0.004% for δ18O and δ13C, respectively.

Foraminiferal Assemblages and IRD Counts. Foraminiferal assemblage and IRD counts for Site U1305 were performed at every 16-cm resolution through MIS 9e and every 32 cm through MIS 7e and MIS 11c. The >150-μm fraction was used for foraminiferal assemblages and IRD counts. After additional dry sieving, samples were split, and at least 300 planktonic foraminifera were counted. The total number of foraminifera was too low (<150) for 2 samples from MIS 5e, MIS 7e, and MIS 11c and 7 samples from MIS 9e. For completeness, these samples are shown but denoted with open circles in Figs. 1–3 and SI Appendix, Figs. 53, 56, and 57. However, they are not included when estimating mean summer MAT SSTs (Fig. 1 and Table 1) or when following the equation Mg/Ca = 0.09(T) after correcting the Mg/Ca for the (CO3)−2 and calcite effect. The latter correction was done using BGC data obtained for these samples following the approach proposed by Morley et al. (37). Morley et al. (37) report a large calibration error on the order of ±0.28 °C, which they attribute to the limited data available to estimate the relationship between Mg/Ca and CO3-ion concentration for values <200 μmol kg−2. However, based on the comparison of downcore data between the 2 foraminifera species and the MAT results, we estimate our error in these records to be on the order of ±0.5 °C.

To convert our *N. incompta*-derived Mg/Ca data to temperature estimates, we further use the calibration developed by Morley et al. (37), and we use the equation Mg/Ca = 0.40 × (0.0077 − T) after correcting the Mg/Ca for the (CO3)−2 effect. The latter correction was done using BGC data obtained for these samples following the approach proposed by Morley et al. (37). Morley et al. (37) report a large calibration error on the order of ±0.28 °C, which they attribute to the limited data available to estimate the relationship between Mg/Ca and CO3-ion concentration for values <200 μmol kg−2. However, based on the comparison of downcore data between the 2 foraminifera species and the MAT results, we estimate our error in these records to be on the order of ±0.5 °C.

**Data Availability.** Proxy data are available in Dataset S1.

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