Orbitally paced shifts in the particle size of Antarctic continental shelf sediments in response to ice dynamics during the Miocene climatic optimum

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ABSTRACT

The AND-2A drill hole (ANDRILL [Antarctic Geological Drilling Program] Southern McMurdo Sound Project), ~10 km from the East Antarctica coastline, records nearly 6 m.y. of sedimentation across the Miocene climatic optimum at a high-latitude site. Sedimentological studies of bedforms and particle size distributions indicate that the paleoenvironment was strongly affected by waves and currents, consistent with deposition in a glacially influenced neritic environment. We document abrupt shifts in mud percent within glacial-interglacial cycles ca. 17.8 Ma and between ca. 16.7 and 15.7 Ma that we attribute to the hydrodynamic effects of wave stirring tied to episodes of ice growth and decay. Although wave climate and geodynamic forcing of the paleobathymetry simultaneously affect wave stirring on a high-latitude shelf, both are ultimately controlled by the size of the ice sheet. The mud percent record displays cyclicity at short-eccentricity time scales (94–99 k.y.) and, unexpectedly, ice retreat phases interpreted from the particle size record coincide with eccentricity minima. We attribute the eccentricity-paced ice retreat phases during the late Early Miocene polythermal glacial conditions and the cool orbital parameters to marine ice sheet instability in response to changes in ocean circulation and heat transport. The particle size record of the AND-2A core provides unique near-field evidence for orbitally paced changes in high-latitude climate and ice volume during the Miocene climatic optimum and important insights into the mechanisms of ice sheet growth and decay in a period of global warmth.

INTRODUCTION

Knowing how large ice masses and associated sea ice respond to external forcing is of vital importance because of their role in the Earth’s heat balance and global sea-level variations. The Miocene climatic optimum (ca. 17–14.7 Ma) is characterized by extensive faunal and floral turnovers, global sea-level changes, high concentrations of atmospheric CO₂, and the most depleted benthic δ¹³Cwater in the past 27 m.y. (Flower and Kennett, 1994; Billups and Shrag, 2002; John et al., 2011; Foster et al., 2012). During this time, the Antarctic ice sheet retreated from the continental shelf into the upland regions of the Transantarctic Mountains (Lewis et al., 2007; Passchier et al., 2011; Hauptvogel and Passchier, 2012).

Although it is known that the Antarctic ice sheet generally responded to orbital cyclicity with an oscillating margin in the marine environment (Naish et al., 2001), ice dynamics during warm periods have previously been poorly constrained. Due to the poor preservation of carbonate in sediments from high-latitude continental margins, other sedimentological proxies are traditionally investigated to extract high-resolution records of ice and climate variability. Here we present a laser particle size record for the Early to Middle Miocene portion of the AND-2A core, drilled ~10 km from the East Antarctica coast (Harwood et al., 2009), and discuss its implications for the reconstruction of ice dynamics through the Miocene climatic optimum.

The AND-2A drill core was collected in 2007 by the Antarctic Geological Drilling Program (ANDRILL, Southern McMurdo Sound Project) at 77°45.488′S, 165°16.605′E in Southern McMurdo Sound (SMS) in the western Ross Sea, which is connected to the Pacific Ocean (Fig. 1). Strata were recovered from the Victoria Land rift basin using a drill rig on a floating ice shelf platform (~8.5 m thick) in ~383 m of water. The lithostratigraphy for the AND-2A core is characterized as cyclical successions of diamictites, conglomerates, sandstones, and mudrocks; diamictites were deposited primarily from floating ice (Fielding et al., 2008–2009; Passchier et al., 2011; Fig. 2A). The sediments are sourced from the Transantarctic Mountains.

Figure 1. Location of the AND-2A drill site in Southern McMurdo Sound, Ross Embayment, Antarctica, and locations of nearby drill sites.
Orbitally paced AND-2A particle size

rift flank (Fielding et al., 2008; Miller et al., 2010), a mountain range with summit elevations higher than 4000 m.

METHODS

The AND-2A core was sampled at ~1 m intervals for particle size analysis in 2007, immediately after drilling, in McMurdo Station. The samples were split between three lab groups for particle size analysis, and we received samples at irregular 2–3 m spacing. More than 300 samples were processed by wet mechanical and chemical disaggregation (Konert and Vandenberghe, 1997). Previous studies using dry and wet disaggregation through crushing between wooden blocks, soaking in water with chemicals, and sonication yielded incomplete disaggregation for clay-rich samples (Fielding et al., 2001). We improved the sample disaggregation by replacing the initial dry crushing step by wet disaggregation with a mortar and pestle (De Groot, 2004). With this technique it is important to apply only gentle vertical motion to the sample with the pestle to avoid breaking grains. In the case that disaggregation was incomplete, samples were first soaked in water.
for as long as several days before gentle wet dis-
aggregation via mortar and pestle was repeated.
The sediments were treated to remove organic
and inorganic carbon and carbonate with H₂O₂
and HCl, following the procedures recom-
mended in Konert and Vandenberghe (1997).

The grain size distribution of the gravel-
free fraction (<2 mm) was determined using a
dual light source Malvern Instruments Master-
sizer 2000 laser particle size analyzer in the
Sedimentology Laboratory at Montclair State
University (Montclair, New Jersey), capable of
measuring sediments with broad size ranges.
The analyzer measures the entire particle size
range from 0.02 to 2000 μm in one measure-
ment. The dual light source set-up and improved
software, including Mie theory, for the calcu-
lation of fine fraction distributions also avoids
spurious modes encountered with single lens
and single light source instruments, such as
the Mastersizer X (Fielding et al., 2001; Dun-
bar and Barrett, 2005). Instrument settings fol-
lowed the recommendations of Sperazza et al.
(2004). Quality control was performed through
repeat analysis of a fine-grained industrial stan-
dard QAS3002 and a natural fine sand standard
Sandy Hook Dune 4.

Two age models were previously proposed for
AND-2A, based on diatom biostratig-
aphy, magnetostatigraphy, ⁴⁰Ar/³⁹Ar dating,
⁸⁷Sr/⁸⁶Sr isotopic dating, fission track dat-
ing, and through correlation of compositional
and physical properties of regional and global
records (Acton et al., 2008–2009; Marcano
et al., 2009; Di Vincenzo et al., 2010). One age
model proposes a linear fit through the age tie
points (Table 1) for the interval below 296 m
below sea floor (mbsf), whereas an alternate age
model incorporates a significant hiatus at 646
mbsf (Acton et al., 2008–2009; Di Vincenzo
et al., 2010). Spectral analysis of the particle
size data between 646 and 296 mbsf was car-
rried out for the two proposed age models using
the REDFIT algorithms (Hammer et al., 2001;
Schulz and Mudelsee, 2002), with varying over-
lapping segments and with a variety of smooth-
ing windows (rectangular, Welch, triangle, and
Hanning). The REDFIT algorithms overcome
the problem of paleoclimate time series that
are unevenly spaced in time by fitting a first-
order autoregressive (AR1) process directly to
the paleoclimate time series without the need of
interpolation in the time domain. The program
can be used to fit peaks if peaks in the spectrum of a
time series are significant against the red-noise
background from an AR1 process (Schulz and
Mudelsee, 2002).

RESULTS

A total of 294 samples in the upper 855 m of
the AND-2A core yielded particle size distribu-
tions for fully disaggregated sediments. Below
855.12 mbsf, pyrite cementation inhibited complete
disaggregation. The sediments display
large fluctuations in mud percent (mud%) (Fig. 2B)
that correlate strongly to lithology (Fig. 2A), and for the interval below ~130 mbsf to the
detrended P-wave velocity record (Fig. 2B)
derived from multisensor track measurements
on whole round cores (Dunbar et al., 2008–
2009). Poor disaggregation of clay-rich samples
has been observed in previous studies (Fielding
et al., 2001), but our record does not display the
expected spurious low mud percentages, where
fine-grained lithologies are indicated (e.g., cf.
high mud% below ~800 mbsf in Fig. 2B to gray
mudstone in Fig. 2A). We conclude that our
preparation procedure worked sufficiently well
to disaggregate mud-rich samples. Downcore
variations of mud% in ice-distal facies (sand-
stones and mudstones with <1% clasts) show
a general trend toward lower mud% between
~855 and 426 mbsf, with a minimum between
~585 and 311 mbsf (Fig. 2C). However, high-
amplitude fluctuations are observed at ~650
mbsf and between ~426 and ~311 mbsf.

Spectral analysis of the mud% of the sedi-
ments in the well-dated interval 296–646 mbsf
yielded similar results for the two age models
(Acton et al., 2008–2009) and with different
smoothing procedures. In the depth domain,
cyclicity is found in the 16.7 m band using 3
overlapping segments and a Welch window
(Fig. 3A). However, we suspect that the average
2.7 m (16 k.y.) sample spacing in the 296–646
mbsf interval inhibits recognition of shorter
cycles; high power is also present in the 6.4 m
band, but it does not exceed the false alarm
level. The results for the linear age model pre-
dict cyclicity in the 99 k.y. band (Fig. 3B), while
shorter cycles (94 k.y.) were observed for the
piece-wise age model with hiatus at 646 mbsf
(Fig. 3C). These cycle lengths are near short-
eccentricity frequencies. High power in the
36–38 k.y. band (obliquity) is also observed, but
it does not exceed the false alarm level (Figs.
3B, 3C). While our average sample spacing
exceeds the Nyquist frequency for the obliquity
signal, it is not sufficient to detect precession.

We recognize that aliasing of short orbital
cyclicities (e.g., precession) can be a prob-
lem with low-resolution sampling of geologi-
cal records along evenly spaced time intervals
(Pisias and Mix, 1988). Our sampling, however,
was carried out along irregularly spaced depth
intervals, and samples are unevenly spaced in the
time domain. To assess aliasing of the preces-
sion signal we sampled the Laskar et al. (2004)
solution for precession at our sample depths in
the time domain and conducted a REDFIT spec-
tral analysis using both the linear and piece-wise
age models (Figs. 4A, 4B). The resulting aliased
precession frequencies are 83 k.y. for the linear
age model and 66 and 37 k.y. for the piece-wise
age model. These frequencies are significantly
different from the 99 k.y. and 94 k.y. frequencies
we find for the mud% data set. We conclude that
aliasing of the precession signal is an unlikely
contributor to the mud% cyclicity and that the
signal can be attributed to variability in the short
eccentricity band width.

SEDIMENTOLOGICAL
INTERPRETATION OF THE
PARTICLE SIZE DISTRIBUTIONS

Despite the glacial origin of the sediments in
AND-2A, there is no correlation between sand
percent and clast abundance or between sand and

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**Note:** The AND-2A drill hole is part of the ANDRILL (Antarctic Geological Drilling Program) Southern McMurdo Sound Project. Depth of top designates the shallowest sample position for the datum and Depth of bottom the deepest position. The Depth used is the average depth used as a tie point for the datum in the age model. *ChronC1N is Brunhes polarity chron (C—chronozones). Data from Acton et al. (2008–2009), Marcano et al. (2009) and Di Vincenzo et al. (2010).
silt percent, in contrast to most glacially sourced hemipelagic sediments deposited in deep-marine environments (Hass, 2002). Particle sizes of the dominant lithology, diamicite, show a wide spread of sand percentages (~10% to >80%; Fig. 5), similar to those of Late Oligocene to Early Miocene massive diamicits of the nearby CIROS-I and MSSTS-I drill holes (Barrett, 1989). Principle component analysis reveals that nearly half (49%) of the variance in the particle size data set is controlled by the presence of a fine silt mode, and the absence of a fine to medium sand mode, suggestive of wind-
and reflect the predominant influence of glaciomarine processes.

Figure 5. Ternary plot of sand-silt-clay percent of diamicts. Massive diamicts with shear fabrics are primary glacial tills. Laminated diamicts are generally more mud rich than primary tills, and most diamicts with crude stratification are more sand rich than primary tills and reflect the predominant influence of glaciomarine processes.

The interpretation of the bedforms implies that the downcore variations in mud% in the AND-2A core primarily record changes in the intensity of wave stirring on a wave-dominated coast. Similar conclusions were previously reached for Oligocene and Early Miocene sediments in nearby drill holes (Barrett, 1989; De Santis and Barrett, 1998; Dunbar et al., 2008). The intensity of wave stirring is controlled on the one hand by changes in the wave climate determined by surface wind strength, sea ice coverage, and iceberg density, and on the other hand by paleobathymetry. It is unlikely that the full amplitude of changes in mud% (6%-96%) can be attributed to any of these effects alone. However, these processes are all linked to ice dynamics through the ice sheets effect on the high-latitude climate system.

**WAVE CLIMATE**

The geographic setting for southern McMurdo Sound in the Miocene was different from today, as the younger volcanic islands (visible in Fig. 1) did not yet exist (Di Vincenzo et al., 2010). Based on the paleotopographic evidence and the sedimentary facies in the AND-2A core, we envision a relatively sediment-starved straight coastline along a wave-graded inner shelf with a moderate- to high-intensity wave climate. Paleoclimate modeling suggests that during the warmer than present Miocene climatic optimum, mid-latitude austral summer storm tracks were displaced poleward (Herold et al., 2011). However, in the Southern Hemisphere the intensity of the storms was diminished, according to the model, and the net effects on the wind fields around coastal East Antarctica translate into only small increases in wind speeds during the Miocene climatic optimum relative to today. The main control on the pressure gradients that drive the wind fields is the size of the ice sheet, and the wave stirring through a more intensive wind-driven wave climate increases in intensity as the ice sheet decreases in size.

Sea ice and floating glacial ice absorb wave energy and influence wave climate. Evidence for floating glacial ice comes from the gravel component of the diamicite-dominated succession of the AND-2A site (Passchier et al., 2011); episodic intensification of sea ice coverage is indicated by the presence of sea ice diatoms (Taviani et al., 2008–2009). A modeling study suggests that the formation of sea ice requires ice to be grounded in the Ross Sea (DeConto et al., 2007), a condition that would coincide with the production of floating glacial ice. Iceberg and sea ice production and survival is greatest for a large marine-based ice sheet. Therefore, the influence of floating ice on wave stirring is also controlled by the size of the ice sheet.

In summary, wave climate is controlled by the size of the ice sheet. A larger ice sheet decreases wave energy and wave stirring, resulting in high mud% in marine sediments, whereas a smaller ice sheet increases wave stirring, because of an increase in the pressure gradients and wind strength, coincident with a decrease in the effects of floating ice.

**PALEOBATHYMETRY**

Empirical relations between water depth and mud% with seaward fining have been found for low-latitude coasts under a variety of wave climates and are predicted by linear wave theory (Dunbar and Barrett, 2005; Ferré et al., 2005; Dunbar et al., 2008). The long-term trends in the intensity of wave stirring may be controlled by bathymetric changes related to tectonic or volcanic processes. Seismic data, however, suggest that the Victoria Land Basin was characterized by relatively constant and slow passive thermal subsidence in the late Early and Middle Miocene, with renewed rifting commencing later, ca. 13 Ma (Fielding et al., 2008). Extensive surface uplift and increased denudation of the
Transantarctic Mountains took place prior to the Miocene (Miller et al., 2010). Sediment accumulation rates were relatively constant and were not a major control on the paleobathymetry (Acton et al., 2008–2009). The expanded Miocene interval at the AND-2A site coincides with volcanic activity at the Mount Morning volcanic center, directly south of the drill site (Fig. 1), from ca. 19 Ma (Di Vincenzo et al., 2010) with possible crustal loading or flexure.

On time scales shorter than 1 m.y., the paleobathymetry of the AND-2A site was potentially affected by ice dynamics as a consequence of the exponential increase in the self-gravitation effect in the direction of the center of an ice mass, which at this latitude could be larger than the eustatic signal (Gomez et al., 2010). Through geodynamic modeling, Gomez et al. (2010) demonstrated that ice mass loss in the Wilkes subglacial basin area of East Antarctica would result in sea-level fall in the vicinity of the AND-2A drill site due to the combined effects of eustasy, glacioisostasy, and self-gravitation. The imprint of the evolution of local sea level near the margin of a continental-scale ice sheet was hypothesized as a regressive sequence (Fig. 6, postglacial stage). The lithostratigraphy of the AND-2A site is dominated by glaciomarine diamict, mud, and stratified coastal sandstones (Passchier et al., 2011), in agreement with the sedimentation model presented by Boulton (1990).

**CALCULATED APPARENT PALEOBATHYMETRY FOR ICE-DISTAL FACIES**

The wave climate for ice-distal facies with <1% gravel clasts was less likely affected by floating ice absorbing wave energy. The increase in wind strength for the Miocene climatic optimum is quite small (Herold et al., 2011). Although we recognize the uncertainties introduced by these variables, we believe that it is possible to estimate the paleobathymetry for the ice-distal facies (Fig. 2C) using empirical relations between water depth and mud% derived from modern low-latitude coasts (Dunbar and Barrett, 2005). Attributing all changes in mud% to variable wave stirring controlled by water depth, we calculated paleobathymetry and analyzed its downcore pattern for ice-distal facies only (Fig. 2C). As suggested in Dunbar et al. (2008), we calculated the average paleobathymetry using equations based on low-latitude circum-Pacific coasts with moderate and

![Figure 6. Sedimentation model in response to ice growth and decay and associated relative sea-level variations near the center of a large continental ice sheet (modified after Boulton, 1990). From bottom to top, the figure illustrates ice extent and relative sea level (RSL) changes through a glacial cycle. The left panel illustrates the more or less opposite behavior of global (eustatic) versus high-latitude relative sea-level variations due to the combined effects of self-gravitation and glacioisostasy near the margin of an ice sheet. The right panel is a schematic model of the resulting paleobathymetric changes and sedimentation patterns through a glacial cycle. The dark blue line marks RSL within each stage of the glacial cycle. ML is marine limit, the maximum RSL reached during glacial advance.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/9/1/54/3345129/54.pdf)
The interval with mud% minima (ice decay) between ~585 and 311 mbsf (ca. 17–15.7 Ma; Fig. 2C) in the AND-2A core anticorrelates to abundances of heavy minerals sourced from the Ferrar Group (Fig. 2E) that were interpreted as indicating ice sheet retreat into the upland regions of the Transantarctic Mountains (Hauptvogel and Passchier, 2012). We interpret that the high-amplitude changes in mud% in ice-distal facies (Fig. 2C) between 426 and 311 mbsf (ca. 16.3 and ca. 15.7 Ma) can be attributed to increased wave stirring (low mud%) reflecting a combination of shoaling of the inner shelf due to geodynamic effects of ice decay coincident with a slight increase in wave climate during interglacials, followed by decreased wave stirring (high mud%) reflecting the effects of deepening and intermittent sea ice formation during episodes of ice growth. It is interesting that the intensity of wave stirring minima reflected in the mud% of ice-distal facies decreases from the height of the Miocene climatic optimum ca. 16.3 Ma into the Middle Miocene (Fig. 2C).

The dominant lithofacies in the AND-2A core is diamictite (Passchier et al., 2011). However, the lack of a glacial signature in the particle size distributions and the presence of bedforms in diamictites suggest that currents and waves were significantly modifying grain size distributions for these facies as well. The complete record of mud% for all samples including diamictites reflects a pattern broadly similar to that of the ice-distal facies alone. Applying both age models (Acton et al., 2008–2009), episodes of low mud% coincide with eccentricity lows ca. 17.8 Ma and between 16.7 and 15.7 Ma (Fig. 8). Although we cannot quantify the relative contributions of changes in wave climate and paleobathymetry to the intensity of wave stirring reflected in the mud%, as discussed herein, both variables are ultimately forced by the size of the ice sheet. The cyclicity in the 99 or 94 k.y. band can therefore be interpreted as a reflection of high-latitude climate and ice volume, which are intimately linked.

**PALEOClimATIC IMPLICATIONS**

The orbitally paced changes in mud% in the AND-2A core represent the first near-field evidence for a dynamic ice sheet coinciding with the late Early Miocene climatic optimum (Flower and Kennett, 1994). The interpretations of the mud% in the AND-2A core reflecting wave stirring of decreasing intensity at ice sheet minima between ca. 16.3 and 15.7 Ma are in agreement with regional and global records of ice growth and decay. From ca. 17 Ma onward the Antarctic ice sheet retreated from the continental shelf into the upland regions of the Transantarctic Mountains, and the process of considerable thickening of the East Antarctic ice sheet for it to overtop some of the mountains and to become grounded on the shelf in the Ross Sea did not begin until after ca. 15 Ma (Lewis et al., 2007; Passchier et al., 2011; Hauptvogel and Passchier, 2012). The data are also in partial agreement with combined backstripping and oxygen isotope records of the Antarctic Marion Plateau and other low-latitude continental margins (Kominz et al., 2008; John et al., 2011) that document a 54–69 m eustatic change between 16.5 and 13.9 Ma over 4 separate events reflecting a stepwise and increasing amplitude of ice growth, separated by episodes of eustatic rise indicating ice decay. However, as discussed herein, geodynamic modeling suggests that eustasy is not likely a major driver of wave energy in our record (Gomez et al., 2010), and the link between the records is an ice volume signal expressed differently at low- and high-latitude margins.

In the late Early Miocene, the thermal isolation of Antarctica was well on its way; most tectonic and sedimentary evidence indicates opening and deep flow through the Drake Passage since ca. 23–16 Ma (Barker et al., 2007; Lyle et al., 2007) and a transition to polythermal glaciers with some freezing in the marginal areas by ca. 18 Ma (Passchier et al., 2011). It is interesting that in the Southern Ocean, Early and Middle Miocene decreases in δ¹⁸Oseawater interpreted as episodic ice decay, coincided with surface- and bottom-water cooling events (Shevenell et al., 2008), which Holbourn et al. (2005) attributed to melting pulses of the Antarctic ice sheet under severe summer melt as orbital eccentricity increased (Fig. 8). The facies in the AND-2A core, however, do not provide evidence of higher surface melt rates in the late Early and Middle Miocene (Passchier et al. 2011).
et al., 2011), and we show that pronounced ice retreat–induced wave stirring is observed during short-eccentricity minima between ca. 16.7 and 15.7 Ma (Fig. 8).

During eccentricity minima the seasonality in the Southern Hemisphere is diminished, with relatively cool summers promoting a positive surface mass balance for the Antarctic ice sheet. To explain the depleted oxygen isotope values in late Early Miocene deep-sea cores of the Southern Ocean, some have proposed a role for injection of relatively warm waters, such as the Tethyan Indian Saline Water, at intermediate depth into the Antarctic circumpolar circulation (Woodruff and Savin, 1989; Flower and Kennett, 1994; Shevenell et al., 2008). Another important factor for the Miocene scenario may have been the opening of Fram Strait in the North Atlantic ca. 17.5 Ma (Jakobsson et al., 2007) that significantly enhanced the oceanic meridional heat transport. The entrainment of corrosive North Atlantic bottom waters within the Antarctic circumpolar circulation is supported by the presence of eccentricity-paced deep-ocean carbonate dissolution events in the Miocene record of the southeastern Pacific (Ocean Drilling Program Site 1237; Holbourn et al., 2007). Driven by the southward migration of atmospheric frontal systems during the Miocene climatic optimum (Herold et al., 2011), incursions of relatively warm Circumpolar Deep Water onto the overdeepened Antarctic shelf may have been capable of destabilizing marine-grounded ice margins in West Antarctica (Jacobs et al., 2011) or in the Wilkes and Aurora subglacial basins (Gomez et al., 2010; Young et al., 2011). Today, the presence of a thermocline between fresh, cold, Antarctic surface waters and relatively warm, salty, Circumpolar Deep Water 600–700 m beneath the surface near marine-grounded ice allows for a scenario of sub–ice shelf melt without significant surface melt (Jacobs et al., 2011). We therefore conclude that a possible explanation for the Antarctic ice retreat phases during eccentricity minima of the Miocene climatic optimum is a Northern Hemisphere forcing of the temperature of the Circumpolar Deep Water and its effect on marine-grounded ice margins.

CONCLUSIONS

We discuss a laser particle size record of the AND-2A core on the Antarctic continental shelf and its implications for Miocene ice development from a high-altitude site. Abrupt shifts in mud% within glacial-interglacial cycles mark the record between ca. 16.7 and 15.7 Ma. We attribute these to the combined effects of episodic changes in ice coverage of surface waters, storm activity, and paleobathymetry associated with ice sheet instability in Antarctica during the Miocene climatic optimum. Changes in mud% are orbitally paced with significant power in the short-eccentricity band. In addition, ice sheet minima coincide with eccentricity minima indicative of far-field forcing. In the absence of strong evidence for extensive early Late and Middle Miocene surface melt in the lithofacies of the AND-2A core (Pascich et al., 2011), we attribute the cycles of ice growth and decay to fluctuations in marine ice sheet instability in response to changes in ocean circulation and heat transport.

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