Reviewer 1 (T. Cronin):

Thank you for this very helpful review. Following these suggestions, we are working on a much shorter manuscript, which includes pulling out a section to develop a separate publication. The most significant revisions that you will notice include streamlining the hypotheses (1. Orbital scale variability; 2. Millenial-scale variability; 3. Direction of Bering Strait throughflow) and better focusing the paper.

Below we have included specific responses to the general issues that Dr. Cronin raised. Please note that all minor, line-by-line suggestions will be completed in the final paper.

This paper reconstructs paleoceanography for an important glacial-interglacial cycle, MIS 12-11 in an important region in the Bering Sea using IODP cores. MIS 11 is an especially important interglacial due to pre industrial-level CO 2 concentrations but higher-than-present sea level and in many regions, significantly warmer air and sea temperatures. The study uses sediment, geochemical and micropaleo proxies (diatoms & calcareous nannofossils) for marine productivity, sea ice and land ice reconstruction. So I think a high-latitude marine record of the MIS12-11 period like this one is sorely needed to go with Lake E, Lake B and others.

Some general issues I think the authors should deal with in a revision:

1) the introduction tends to be unfocused and too long. Please shorten it giving the main hypotheses to be tested. I also think the methods and results sections tend to be long. In section 4.2.2, in the diatom ecology section, can the main taxa or assemblages used for productivity and sea ice be emphasized? Much of this section is taken care of in the table. In fact, it really constitutes a review of high latitude diatom ecology going back to Sancetta, Koizuma and other pioneers; this is useful but it merits its own paper in a micropaleo journal.

Thank you for this fabulous suggestion. The diatom ecology section has been removed from this paper and a separate manuscript is nearly ready to be submitted based on this (and other relevant) work. Additionally, the introduction, methods and results have all been shortened quite a bit.

2) The methods section is long and could be put in a supplement, in fact some of it is, but the Supplementary Materials is not cited until Page 28. Likewise, Section 5 is too descriptive and does not focus on the key patterns that address the hypothesis about suborbital variability.

Much of the methods section has been pulled out of the main text and put into a new methods supplement. This supplement also contains additional information requested by the second reviewer.

3) related to # 1, I sense some of the text and references are not quite up to date [interglacial sea level papers, Bering Sea sea-level section 2.2 [where is Keigwin 2006 paper?), modern Bering Sea oceanography, see section 2.3)

JULIE:
Section 2.2 intentionally left out the Keigwin paper because it was intended to be more general than the most recent deglaciation and also focused more on terrigenous input rather than timing of sea level rise, however, the Keigwin paper is important, so we've added it. We will of course also make reference to the sea level compilation of Kaufman and Brigham-Grette, 1993 in the context of the compilation by Rohling et al. 2014 in Nature. In addition, the following papers, particularly Bering Sea interglacial papers that were not yet in press when we first submitted this paper, have also been added: $\delta^{15}N$ studies (Schlung et al., 2013; Knudson and Ravelo, 2015); opal productivity (Kanematsu et al., 2013; Kim et al., 2013); clay mineralogy (Kim, 2015), and the diatom study from Teraishi (2015).

4) The NADW discussion does not belong under a section called Bering Sea hydrology. Later in the paper, Section 5, there is again NADW discussion in the context of late MIS 11 Bering Sea

reversed flow. In general, I don't think the Bering-N Atlantic links are well established mainly due to chronology/correlation issues, which I believe are discussed in a 2009 paper by L&R on Atlantic Pacific diachroneity of O18 records.

Discussion of NADW was included in this section because of its hypothesized influence on the direction of flow through Bering Strait, however we agree that this discussion is misplaced and you are correct that it should not be possible to determine millennial-scale synchronicity between the Atlantic and Pacific. The association with NADW has been removed from the paper and the issue of the direction of throughflow is included later in the paper when this hypothesis is tested.

5) I wonder if the suggested correlations of this study's IODP core records with emerged Quaternary marine deposits [this is mentioned in several places] are warranted given age uncertainty of the onshore deposits?

The chronology of the onshore deposits is certainly less accurate that a marine core will ever be. But we would like to argue that Kaufman and Brigham-Grette, 1993 and Pushkar et al., 1999 provide the most likely interglacial age for the Nome River Glaciation. The stratigraphy there places important constraints on early ice build up in local mountain ranges before global sea level drops. Kaufman et al., 2001 have the same advance in the Bristol Bay region. Our findings can add support to the onshore chronology.

6) The 404 ka ice-rafting event discussed on page 28 seems speculative and not up to date on ice-rafting processes in the Arctic and subarctic. This section evolves into a mechanistic explanation, covering the "snow gun" hypothesis and alternatives [turbidites, sea ice etc]. I think this section should be rethought and rewritten. As with the issue of Bering Sea flow reversal in an earlier section, are these central to the question of patterns and causes of variability within MIS11?

This section has been significantly updated and simplified to include the comments of Reviewer 2, who asked us to more fully explore the question of a turbidite during this interval. While we agree that the hypothesized glacial advance is likely not adequately tested, there are advances during MIS 11 and 5e/5d transition (the latter not important here), which do provide an important means of linking land and sea responses. This is something the Arctic Ocean records cannot do. We suggest that we reframe the discussion about this aspect into a speculative section that could drive new work to explore the sources of the IRD.

7) The paper uses both cores - U1345 & 1343 - although Kim published on U1343 using different proxies but the same O18 for tuning, is there any way to integrate results from both cores better to provide a more robust pattern of MIS paleoceanography?

This is an excellent point. Kim's 2013 and 2015 low resolution opal and clay mineralogy papers will be incorporated.

Is the main focus of the study on orbital glacial-interglacial timescales or millennial timescales (that is, stadials and interstadials within MIS 11, see section 2.1 on sea level, or abrupt reversals like DO events ? The 15-meter thick MIS 11 record [line 199] ought to allow millennial-scale events to be seen. I have concern with the authors statement, in their discussion of the age model and tuning to LR04 and the other site U1343: "we urge caution when interpreting millennial scale changes at the site or comparing our record to others that examine MIS 11 at millennial scale resolution or finer". I got the impression in the introduction there would be more definitive conclusions reached on within-interglacial climate variability. Plots in Figures 5-8 don't really show me DOlike or Heinrich-like variability, which could be an important new conclusion, given our ideas on what causes such events in at least the N Atlantic region.

There are 3 main hypotheses that this paper seeks to test:

1. **Productivity and sea ice extent are primarily controlled by orbital-scale forcing MIS 11**
2. **Millennial-scale changes in sea ice occur throughout MIS 11**
3. **Throughflow through Bering Strait temporarily reversed after Termination V**

> **Additionally, we speculate that continuous marine records in the Bering Sea include records of glacial advance that can be used to explore land-sea linkages, but this section is significantly shortened and not treated as equal to the above three hypotheses.**

We understand your concern about our caution about age model error, however we think it is important to recognize the limitations of the age model, especially in light of questions raised by Liesiecki and Raymo (2009) about synchronicity (or lack there of) of the isotope stack between the North Atlantic and Pacific. We think that the age model allows a reasonable estimate of sedimentation rates in the core, and the ages are likely fairly precise, however, the error in LR04 is 4 kyrs for sediments younger than 1 Ma. This means that it is not possible to say that an event that happened in U1345 at 412.4 corresponds with an event at 412.4 in a distal core. However, we can certainly resolve events at millennial scales within this core. Perhaps it makes the most sense to keep the caution about interpreting millennial-scale events BETWEEN cores, but remove the line about interpreting millennial scale changes within U1345.

In sum, I rated the paper as accept after minor revisions, some changes I am suggesting might take major text-shortening, but the science presented is sound, it is just not clearly packaged or presented.

Specific Comments

Line 27 comma before however
Line 28: This confuses me as the paper is in the Bering Sea, not the N Atlantic: led to "lowered productivity in both the northern Atlantic and the northern Pacific. "
Line 48 proper citation of IPCC 2013
Lines 55-56. Fix grammar in second part of sentence. **This sentence was cut.**
Line 58 – which coastal region were these glaciers? **This sentence was cut.**
Line 70 – do you mean little is known from North Pacific Ocean region incl. Bering Sea?
Line 74. Is this marginal zone sea ice?
Line 114 E Antarctic ice was stable. . .
Line 196 "and" no italics

Section 4.2.1. Authors begin to use "ka" in discussions of diatoms but absolute years were not discussed in the age model-tuning section. So please tell readers earlier in the paper, at Table 2 reference, which should be in age model section, about the ages of MIS12, MIS 11 per the tuning to LR04. See line 586- the section title should say how old oldest sediments are, not "beginning of record"

We agree with these changes.

Section 5.1 includes early deglaciation but section 5.2 is on Termination V, which is the deglaciation. Line 625, the debate about the duration of MIS 11 should be mentioned, embodied in papers by Masson-Delmotte, Ruddiman and others. See line 710 on this topic. I became confused about the MIS11 duration and the number of substages. Many authors do NOT use the substage terminology and the LR04 and the Antarctic ice core records show only two MIS 11 peak warm periods. One reason this is critical is this study of MIS 11 in the Bering Sea is one of the most detailed available. So it should shed light on the issue.

We will address this issue in the revisions and appreciate this important point.

Figure 1 in the caption, mention both U-cores plotted in the map.

Figure 3 is a little complicated but it is critical. Consider dividing into 2 figures. The U1345 curve, red line, certainly looks different from that for U1343 – why so? Cook and Kim age model papers might be summarized in the text, in fact it would be useful to reproduce the O18, tie points data for the entire period covered by their tuning study.

A table will be added.

Figures 5-8 are fine and do show what the study sought to accomplish: variability in diversity, lithology and microfossil assemblages. A more succinct treatment of these data in the text and better summary in the conclusions would help readers not familiar with these proxies. Why is MIS 11 split on the left in Fig 7 but not in others? Label horizontal colored panels in the figures for clarity. Figure 7 what is the source of N Atlantic stadials? Are they really relevant to this study?

We will correct the figures.

Reviewer 2: J. Addison

The paper presented by Caissie and her colleagues details the development of oceanographic conditions in the Bering Sea prior, during, and immediately following Marine Isotope Stage 11. The focus on MIS 11 is timely due to its environmental similarities to predicted near-future climate change, and the Bering Sea geography provides an environment that is of broad interest across many disciplines. This study is also one of only a handful that documents marine environmental change in the high-latitudes during MIS 11, which adds to this study's timeliness. The authors use a combination of diatom and calcareous nannofossil micropaleontology, bulk sediment geochemistry, and grain-size analyses to show the evolution of this interesting period though changes in the marine ecosystem, sea ice conditions, and water column nutrient cycling. There are several elements of this study that are great, including detailed environmental changes associated with the various phases of the MIS 12-10 transition, and an honest assessment of the age control. I also particularly liked seeing the application of modern species richness indices to the diatom data in this paper.

Some issues the authors need to address include:

> 1) Better integration of these new Exp. 323 results with the other recent papers that have resulted from the cruise [e.g., d15N studies of Schlung et al. (2013) and Knudson & Ravelo (2015); opal productivity studies of Kanematsu et al. (2013) and Kim et al. (2014)]. While these studies do not provide as detailed an analysis of MIS 11 as the current paper, they do provide a good background for assessing glacial/interglacial background changes in the Bering Sea that are relevant to the current study.

These records will be assessed and integrated into this manuscript. Thank you for pointing out their omission.

> 2) To better assess the relative contributions of terrigenous versus marine organic matter to the dataset, cross-plots of the organic matter d13C, sedimentary d15N, and molar N/C ratios (see Perdue and Koprivnjak (2007) for explanation of N/C instead of C/N for % terrestrial calculations) need to be presented. See Walinsky et al. (2009)'s Figure 9 for a good example. It might also be worth considering breaking the data into groups based on the time intervals introduced in the discussion.

Thank you for this suggestion. This will help frame the discussion about contribution of terrigenous matter and organic matter as well as help us interpret sub-millennial scale variability.

> 3) During the time periods associated with low sea-level stands in this paper, the mouths of the Yukon and Kuskokwim Rivers (and other smaller rivers that currently drain into the Bering Sea) would have been greatly advanced across the exposed shallow continental shelf. Are these the "glacial meltwater rivers" that are suggested in Section 5.1? It is difficult to dismiss them as potential sources of terrigenous material, especially given the evidence that they contributed an enormous sediment load to the glacial Bering Sea [as evinced at the Meiji Drift, see VanLaningham et al., (2009)], as well as cut some of the largest submarine canyons in the world during these low stands (e.g., Scholl et al. 1970 and subsequent work). Additional explanation for why Site U1345 appears to be devoid of this terrigenous material seems warranted.

This is an excellent point, we did not intend to dismiss the sedimentation from these rivers. In light of the new clay mineralogy data (see below), this interpretation has been revisited. Pelto et al, in revision, shows a decrease in the input of sediment to a nearby site from the Yukon as sea level rose during the Deglaciation. Our work on this older time period (MIS 11) can reference Pelto (in revision) for additional context.

4) As written, the entire Discussion section is tough to follow. There are quite a few time overlaps between the various subsections that are confusing, plus the added details from the contemporaneous North Atlantic and Antarctic regions add further complexities. I recommend re-organizing the Discussion into 2 major sections – (1) the MIS 12-10 transitions as seen at U1345 [subsections for each time interval (without time overlaps), which is similar to what has already been written], and relating the U1345 variability to other regional/global records.

This suggestion, combined with the suggestions of reviewer 1 should make the discussion shorter and much more readable.

5) Since the original premise of this study was intended to present the Bering Sea MIS 11 paleoceanographic variability as an analogue for future conditions, perhaps a small section at the end of the discussion should address this?

This will be added to the final paper in addition to a short summary of the question about the length of MIS 11.

6) I'm skeptical about the nature of the deposit that is attributed to being evidence of the Bering Strait Current Reversal (Subsection 5.3.1). When I first saw the grain-size data, I thought turbidite, and the enrichment in P. sulcata [a common diatom marker of redeposition and/or downslope transport due to its highly silicified morphology; see Sancetta (1982)] seems to support that idea. However, the authors discount the turbidite mechanism on account of no visible sedimentary structures that are normally associated with turbidites. However, the authors make a good point about illite being an additional potential Arctic Ocean flow marker (Lines 767-771), as well as being a potential way to explain the anomalous N data. I highly recommend the authors do a little XRD analysis on the sediments in this interval (and immediately preceeding/succeeding) to determine presence/absence of illite in this interval. It is pretty easy, and the lead author's institute has an appropriate instrument (housed in ISU's Office of Biotechnology; www.marl.iastate.edu/xrd.html). This will serve as both an additional line of evidence to support the idea of an Arctic Ocean inflow, as well as help to explain the N data (since the low d15N values suggest an increase in the relative proportion of terrigenous organic matter, not necessarily inorganic N hosted in clays).

Thank you for asking us to take a closer look at this interval. The nature of this anomalous deposit remains unknown, though a turbidite is certainly possible. However, the site's position was chosen on an interfluve to avoid turbidites as much as possible. Moreover, the typical graded layers, from coarse sand and microconglomerates in the bottom to silt and clay in the top (Bouma sequence) are missing from this site. Instead we see very poorly sorted terrigenous fragments mixed together. It's unusual to get just one layer like this. We would expect a turbidite to work in the same place for a prolonged period. If the low δ^{15}N suggested an increase in terrigenous organic matter, we would expect to see a change in C/N and/or δ^{13}C as well. There is nothing remarkable about either marker during these low δ^{15}N excursions.

In addition, as suggested, we have analyzed the clay mineralogy in 10 samples across MIS 11, including several in the proposed glacial advance/throughflow reversal interval and found no evidence of illite in the core, so an Arctic Ocean influence is unlikely at U1345. This is in direct contrast to the results of Kim et al., 2015 who saw large amounts of illite nearby in U1343. It may be that the currents were such that the same events are not recorded everywhere, though this seems unlikely. Our revision examines these two interpretations and addresses possible spatial variability of the Bering Strait current.

7) The idea that the Nome River Glaciation started during peak warmth in MIS 11 is a bit counter-intuitive; I think a better treatment of the extant Nome River Glaciation sites (and in particular, their respective age controls) is required to support this idea. Also, while the authors do introduce the "snow-gun" hypothesis near the end of Subsection 5.3.2, I think re-organization to increase clarity and introduce the snow-gun idea sooner will greatly improve the readability here.

We agree that it is counter-intuitive to find that the Nome River Glaciation began during peak warmth, however, we believe that there is significant terrestrial evidence that supports this not only occurred during MIS 11, but also during MIS 5e (Kaufman and Brigham-Grette, 1993; Kaufman et al., 2001; Pushkar et al., 1999). What these terrestrial studies lack is an accurate chronology. We think that our findings can add support to the onshore chronology and provide an important means of linking land and sea responses. We will rewrite this section to make this more clear. Additionally, we recognize that this hypothesis is not adequately tested yet but rather it provides an opportunity for future work.

There are a few minor issues as well:

1) Overall, the mean d15N = 6.4‰ for the full dataset, and from looking at Fig. 7, it looks like there might be values that exceed 8 or 9‰These high values are suggestive of denitrification, yet this process isn't considered ˙ in the N cycle discussions spread throughout the paper.

Yes, thank you for pointing out this omission. You are likely correct that denitrification is happening thoughout much of the record. This will be expanded upon and the new analyses you suggested above should clarify the isotope results.

2) Because many of the figures are very data-rich, in many cases axes have been truncated, which makes it difficult to assess extreme data points (which are often very important, such as the extremely low d15N values associated with the 406-402 ka event). I would recommend that, instead of cutting axes ranges, they should instead be offset so that the full axis range can be indicated. I'm specifically thinking of Figure 7, but this could apply to many other figures, too. There are also several instances where it is difficult to determine which line goes with which axis; perhaps color coding or additional labels are necessary.

We tried hard to make the figures as readable as possible. Thank you for these very specific suggestions to help us improve.

3) I am also providing a PDF copy of the manuscript that I have made several grammatical corrections to; please review in detail.

In conclusion, I would like to recommend this article for acceptance, pending the minor revisions I've indicated here, as well as the editorial revisions on the attached manuscript. If any of my notes are not clear (or legible), I recommend the authors contact me directly with any questions they may have.

Please also note the supplement to this comment:

Noted, thank you for the detailed comments.

Bering Sea surface water conditions during Marine Isotope Stages 12 to 10 at Navarin Canyon (IODP Site U1345)

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Abstract

Records of past warm periods are essential for understanding interglacial climate system dynamics. Marine Isotope Stage 11 occurred 425-394 ka when global ice volume was the lowest, sea level was the highest and terrestrial temperatures were the warmest of the last 500 kyrs. Because of its extreme character, this interval has been considered an analog for the next century of climate change. The Bering Sea is ideally situated to record how opening or closing of the Pacific-Arctic Ocean gateway (Bering Strait) impacted primary productivity, sea ice, and sediment transport in the past; however, little is known about this region prior to 125 ka. IODP Expedition 323 to the Bering Sea offered the unparalleled opportunity to look in detail at time periods older than had been previously retrieved using gravity and piston cores. Here we present a multi-proxy record for Marine Isotope Stages 12-10 from Site U1345 located near the continental shelf-slope break. MIS 11 is bracketed by highly productive laminated intervals that may have been triggered by flooding of the Beringian shelf. Although sea ice is reduced during the early MIS 11 laminations, it remains present at the site throughout both glacials and MIS 11.

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High summer insolation is associated with higher productivity, but colder SSTs, which implies that productivity was likely driven by increased upwelling. Multiple examples of Pacific-Atlantic teleconnections are presented including laminations deposited at the end of MIS 11 in sync with brief expansions in sea ice in the Bering Sea and stadial events seen in the North Atlantic. When global eustatic sea level was at its peak, an series of anomalous conditions are seen at U1345. We examine whether this is evidence for a reversal of Bering Strait Through Flow, an advance of Beringian tidewater glaciers, or a turbidite.

1 Introduction

Predictions and modeling of future climate change require a detailed understanding of how the climate system works. Reconstructions of previous warm intervals shed light on interhemispheric teleconnections. The most recent interglacial period with orbital conditions similar to today was approximately 400 ka, during the extremely long interglacial known as Marine Isotope Stage (MIS) 11. CO_2 concentration averaged approximately 275 ppm, which is similar to pre-industrial levels (EPICA Community Members, 2004). The transition from MIS 12 into MIS 11 has been compared to the last deglaciation (Dickson et al., 2009) and extreme warmth during MIS 11 has been considered an analog for future warmth (Droxler et al., 2003; Loutre and Berger, 2003), although the natural course of interglacial warmth today has been disrupted by anthropogenic forcing (IPCC, 2013).

Despite the work done to characterize the warmth of MIS 11 in the terrestrial realm (Candy et al., 2014; Melles et al., 2012; Prokopenko et al., 2010), as well as the North Atlantic (Bauch et al., 2000; Chaisson et al., 2002; Dickson et al., 2009; Milker et al., 2013; Poli et al., 2010), little is known about this interval from the North Pacific and Bering Sea region (Candy et al., 2014). Modeling studies describe several mechanisms for linking the Atlantic and Pacific through oceanic heat transport on glacial-interglacial time scales (DeBoer and Nof, 2004; Hu et al., 2010), however, there have been no tests of these modeling studies using proxy data older than 30 ka. Furthermore, the location of the Bering Sea marginal sea ice zone advanced and retreated hundreds of kilometers during

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the past three glacial-interglacial cycles (Caissie et al., 2010; Katsuki and Takahashi, 2005; Sancetta and Robinson, 1983); however, sea surface and intermediate water variability before MIS 5 is unknown.

This investigation of terrestrial-marine coupling at the shelf-slope break from MIS 12 to 10 is the first study of this interval in the subarctic Pacific (Fig. 1). We use a multi-proxy approach to examine orbital- and millennial-scale changes in productivity and sea ice extent. We demonstrate that insolation plays a major role in these changes, but that sea ice also shows rapid, millennial-scale variability. Finally, we test the hypotheses that 1) in Beringia, tidewater glaciers advanced while sea level was high and 2) Bering Strait Through Flow reversed shortly after the MIS 12 glacial termination (Termination V). We find inconclusive evidence of a glacial advance, but no evidence of Bering Strait reversal.

2 Background

2.1 Global and Beringian Sea Level during MIS 11

The maximum height of sea level during MIS 11 is an open question with estimates ranging from 6 to 13 m above present sea level (apsl) (Dutton et al., 2015) to 0 m apsl (Rohling et al., 2010; Rohling et al., 2014). The discrepancy may stem from large differences between global eustatic (Bowen, 2010) or ice-volume averages (McManus et al., 2003) and regional geomorphological or micropaleontological evidence (van Hengstum et al., 2009). Regional isostatic adjustment due to glacial loading and unloading are now known to be significant and regional highstands may record higher than expected sea levels if glacial isostasy and dynamic topography have not been accounted for, even in places that were never glaciated (PAGES et al., 2016; Raymo and Mitrovica, 2012; Raymo et al., 2011). For example, Raymo and Mitrovica (2012) suggest eustatic sea level during MIS 11 was 6-13 m apsl globally and near 5 m apsl locally in Beringia, yet MIS 11 shorelines are at +22 m today in northwest Alaska (Kaufman and Brigham-Grette, 1993) due to this complex geophysics.

Regardless of the ultimate height of sea level, the transition from MIS 12 to MIS 11 records the greatest change in sea level of the last 500 ka (Rohling et al., 2014); sea level

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rose from perhaps -140 m to its present level or higher (Bowen, 2010)(Dutton et al., 2015). Sea level during MIS 11 may have been complex (Kindler and Hearty, 2000), but most records agree that sea level during this exceptionally long interglacial (30 kyrs) was highest from 410 to 401 ka, coincident with a second peak in June insolation at 65°N. This long highstand most likely requires partial or complete collapse of the Greenland ice sheet (up to 6 m) (de Vernal and Hillaire-Marcel, 2008; Reyes et al., 2014) and/or the West Antarctic Ice Sheet (Scherer et al., 1998), but not the East Antarctic Ice Sheet (Berger et al., 2015; Dutton et al., 2015; Raymo and Mitrovica, 2012). It has frequently been hypothesized that the West Antarctic Ice Sheet collapsed during MIS 11 and modeling studies confirm this (Pollard and DeConto, 2009), however unconformities in the record prevent confirmation of a collapse (McKay et al., 2012). Yet, Teitler (2015) show that IRD during MIS 11 dropped as low as it was during MIS 31, when it is clear that the West Antarctic Ice Sheet had collapsed (Naish et al., 2009). With uncertainties, East Antarctica ice was stable; however, small changes in either sector of the Antarctic ice sheet may have contributed up to 5 m of sea level rise (Berger et al., 2015; EPICA Community Members, 2004).

The sea level history of Beringia defines Arctic communication between the Pacific and the Atlantic oceans during the Plio-Pleistocene. As a region, Beringia consists of both the terrestrial and marine regions north of the Aleutian Islands that stretch to the shelf-slope break in the Bering, East Siberian, Chukchi, and Beaufort seas (Fig. 1). On land, Beringia extends from the Lena River in Siberia to the Mackenzie River in Canada. Large portions of the Beringian shelf were exposed when sea level dropped below -50 m (Hopkins, 1959) and this subaerial expanse stretches more than 1000 km from north to south during most glacial periods (Fig. 2). In contrast, as sea level rises at glacial terminations the expansive continental shelf is flooded, rapidly once sea level reaches -60 mapsl (Keigwin et al., 2006). This introduces fresh organic matter and nutrients into the southern Bering Sea (i.e. Bertrand et al., 2000; Shiga and Koizumi, 2000; Ternois et al., 2001), re-establishing at -50 mapsl the connection between the Pacific and Atlantic oceans through Bering Strait (Keigwin et al., 2006). The late Cenozoic history of the depth of the Bering Strait sill is poorly known, hence current oceanographic reconstructions (e.g., Knudson and Ravelo, 2015) assume that a sill depth of -50 mapsl was temporally stable, which is

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probably not the case and requires future study. However, in this study, we also assume that a sill depth of -50 mapsl controls oceanographic communication between the Atlantic and Pacific Oceans.

2.2 Site Location and Oceanographic Setting

The Integrated Ocean Drilling Program's (IODP) Expedition 323, Site U1345, is located on an interfluve ridge near the shelf-slope break in the Bering Sea (Fig. 1). Navarin Canyon, one of the largest submarine canyons in the world (Normack and Carlson, 2003) is located just to the northwest of the site. Sediments were retrieved from ~1008 m of water, placing the site within the center of the modern day oxygen minimum zone (Takahashi et al., 2011). We focus on this site because of its proximity to the modern marginal ice zone in the Bering Sea and observed high sedimentation rates. Its siting on top of an interfluve was chosen to reduce the influence of turbidites moving through Navarin Canyon.

Today, water circulates cyclonically in the deep basins of the Bering Sea (Fig. 1). Site U1345 is influenced by the northwest flowing Bering Slope Current (BSC), which is derived from the Alaskan Stream (AS). South of the Aleutians Islands, the Alaskan Stream flows westward and enters the Bering Sea through deep channels in the western Aleutian Islands. Once north of the Aleutian Islands, this water mass becomes the Aleutian North Slope Current (ANS), and flows eastward until it reaches the Bering Sea shelf. Interactions with the shelf turn this current to the northwest where it becomes the Bering Slope Current (Stabeno et al., 1999). Tidal forces and eddies in the Bering Slope Current drive upwelling through Navarin Canyon and other interfluves along the shelf-slope break (Kowalik, 1999). The resulting cold water and nutrients brought to the sea surface, coupled with the presence of seasonal sea ice, drive the high productivity found today in the so called "Green Belt" (Springer et al., 1996) along the shelf-slope break. North of the site, low salinity, high nutrient shelf waters (Cooper et al., 1997) primarily flow north through the Bering Strait to the Arctic Basin (Schumacher and Stabeno, 1998).

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3 Methods

3.1 Age Model

The age model (Fig. 3) is derived from the shipboard age model, which was developed using magnetostratigraphy and biostratigraphy. First and last appearance datums for diatoms and radiolarians make up the majority of the biostratigraphic markers used to place the record in the correct general stratigraphic position (Takahashi et al., 2011). Oxygen isotope measurements taken on the benthic foraminifera, *Uvigerina peregrina, Nonionella labradorica,* and *Globobulimina affinis* (Cook et al., 2016) were then used to tune site U1345 to the global marine benthic foraminiferal isotope stack (LR04) (Lisiecki and Raymo, 2005) (Fig. 3; Table 1). Based on this combined age model, MIS 11 spans from 115.3 to 130.6 mbsf (Cook et al., 2016); however, the characteristic interglacial isotopic depletion was not found in U1345 which means that the exact timing of peak interglacial conditions is unknown.

The nearby core, IODP Exp 323, Site U1343 (Fig. 1) has an excellent oxygen isotopic record during MIS 11 {Asahi, 2016}. We compared the two isotopic records and their magnetic susceptibilities (Fig. 3) and found that even with only two tie points, there was good correlation between the timing of the onset of laminated intervals and also the interglacial increase in magnetic susceptibility (Fig. 3b). We added one additional tie point to connect the inflection points in magnetic susceptibility (Table 1). In U1343, this point occurred at 398.50 ka. U1345 was shifted 1.5 ka younger in order to align with U1343. The addition of this point allows us to have more confidence in the timing of peak interglacial conditions in U1345. However, given the oxygen isotope sampling resolution, as well as the stated error in the LR04 dataset (4 kyr), we estimate the error of the age model could be up to 5 kyr. Therefore, we urge caution when comparing millennial scale changes at this site with other sites that examine MIS 11 at millennial scale resolution or finer.

Sedimentation rates during the study interval range from 29 cm/kyrs to 45 cm/kyr with the highest sedimentation rates occurring during glacial periods. Depths and ages of major climate intervals referred to in the text are found in Table 2.

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3.2 Sediment Analyses

Details about sediment sampling can be found in the Supplementary Materials. Quantative diatom slides were prepared {Scherer, 1994 #107} and counted {Schrader and Gersonde, 1978 #592} using published taxonomic descriptions and images (Hasle and Heimdal, 1968; Koizumi, 1973; Lundholm and Hasle, 2008, 2010; Medlin and Hasle, 1990; Medlin and Priddle, 1990; Onodera and Takahashi, 2007; Sancetta, 1982, 1987; Syvertsen, 1979; Tomas, 1996; Witkowski et al., 2000). Diatom taxa were then grouped according to ecological niche (Table 3) based on biological observations (Aizawa et al., 2005; Fryxell and Hasle, 1972; Håkansson, 2002; Horner, 1985; Saito and Taniguchi, 1978; Schandelmeier and Alexander, 1981; von Quillfeldt, 2001; von Quillfeldt et al., 2003) and statistical associations (Barron et al., 2009; Caissie et al., 2010; Hay et al., 2007; Katsuki and Takahashi, 2005; Lopes et al., 2006; McQuoid and Hobson, 2001; Sancetta, 1982, 1981; Sancetta and Robinson, 1983; Sancetta and Silvestri, 1986; Shiga and Koizumi, 2000). In cases where a diatom species was reported to fit into more than one environmental niche, it was grouped into the niche where it was most commonly recognized in the literature.

Eighteen quantitative calcareous nannofossil slides were prepared {Flores and Sierro, 1997 #4572} and counted using a Zeiss polarized light microscope at 1000x magnification. Samples were considered barren if no coccoliths were found in at least 165 randomly selected fields of view. All taxa were identified to the species or variety level {Flores et al., 1999 #4573}{Young et al., 2003 #4574}.

Grain size of both biogenic and terrigenous sediment was measured using a Malvern Mastersizer 3000 with the Hydro MV automated wet dispersion unit. The mineralogy of ten samples was analyzed using a Siemens D-5000 X-Ray Diffractometer (Eberl, 2003)

The carbon and nitrogen isotopic and elemental composition of organic matter was determined by Dumas combustion using a Carlo Erba 1108 elemental analyzer coupled to a Thermo-Finnigan Delta Plus XP isotope ratio mass spectrometer at the University of California Santa Cruz Stable Isotope Laboratory. The 1-sigma precision of stable isotope measurements and elemental composition of carbon are 0.2‰ and 0.03%, respectively,

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and for nitrogen are 0.2‰ and 0.002%, respectively. $\delta^{13}C$ values are reported relative to the Vienna Pee Dee Belemnite (VPDB) and $\delta^{15}N$ values are reported relative to atmospheric N_2. Percent $CaCO_3$ was calculated according to Schubert and Calvert (2001). More detailed methodology can be found in the Supplemental Materials.

4 Results

4.1 Sedimentology

The sediments at Site U1345 are massive with centimeter–scale dark or coarse-grained mottles. They are mainly composed of clay and silt with varying amounts of diatoms, sand, and tephra throughout. Laminated intervals bracket MIS 11 (Fig. 4). The proportion of diatoms relative to terrigenous or volcanogenic grains is highest during laminated intervals and lowest immediately preceding Termination V (~425 ka). Vesiculated tephra shards were seen in every diatom slide analyzed. Several thin (< 1 cm) sand layers and shell fragments were visible on the split cores, especially during MIS 12. However, high-resolution grain size analyses show that the median grain size was lowest during MIS 12, increasing from approximately 14 µm to 21 µm at the start of Termination V at 424.5 ka (130.92 mbsf). Median grain size peaks at 84 µm between 401 and 407 ka (125.42-123.62 mbsf). This interval is also the location of an obvious sandy layer in the core. After this "anomalous interval," median grain size remains steady at about 17 µm. Subrounded to rounded clasts (granule to pebble) commonly occur on the split surface of the cores. We combined clast and sand layer data from all Holes at Site U1345 when examining their distribution (Fig. 4).

A 3.5 m thick laminated interval, estimated to span 12 kyrs (see Table 4 for depths and ages) is deposited beginning during Termination V. Although the termination is short-lived and the laminated interval quite long, we refer to it as the Termination V Laminations for the sake of clarity throughout this manuscript. The next laminated interval occurs at about 394 ka and lasts approximately 1.1 kyrs. During the transition from late MIS 11 to MIS 10, a series of four thin laminated intervals are observed. Each interval lasts between 0.34 and 1.25 ka (Table 4). In general, the upper and lower boundaries of laminated intervals are gradational; however the boundaries between

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individual lamina are sharp (Takahashi et al., 2011). There are two types of laminations. The Termination V Laminations are Type I laminations: millimeter-scale alternations of black, olive gray, and light brown triplets. In addition to containing a high proportion of diatoms, this type of laminated interval also contains high relative proportions of calcareous nannofossils and foraminifera (Takahashi et al., 2011). The majority of laminations are parallel; however, a 7 cm interval during the Termination V Laminations is highly disturbed in Hole A, showing recumbent folds in the laminations (Takahashi et al., 2011). This interval was not sampled. Type II laminations occur throughout the remainder of MIS 11. These laminations have fewer diatoms and tend to be couplets of siliciclastic sediments with <40% diatoms (Takahashi et al., 2011). Percent $CaCO_3$ also increases during these laminations though foraminifera and calcareous nannofossils are very rarely seen. None of these later laminated intervals contain any evidence of disturbance.

4.2 Mineralogy

We determined the weight percent of 23 common minerals in ten samples across the study interval. Samples are primarily composed of quartz, plagioclase, tephra, illite and chlorite with minor amounts of other clay and non-clay minerals (Table 5). Downcore, the largest variability occurs in the weight percent of quartz, chlorite, and illite. In general, chlorite comprises nearly 35% of the minerals present in the sediments until 408 ka, and then declines ~ 5% for the remainder of MIS 11. Conversely, quartz increases from 425 to 406 ka and then comprises ~15% of the minerals for the remainder of MIS 11. Illite is lower than 2% of the mineral assemblage at 424 ka, and then increases rapidly to nearly 10% at 422 ka. It remains near 10% for the remainder of MIS 11 except for a brief negative excursion at 406 ka.

4.3 Diatoms

4.3.1 Diatom Assemblages

A total of 97 different diatom taxa were identified. Individual samples include between 26 and 46 taxa each with an average of 37 taxa. Both types of laminated intervals contain

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fewer taxa than bioturbated intervals do. This decrease in diversity is confirmed using the Margalef, Simpson, and Shannon indices (Maurer and McGill, 2011) which all show similar down-core profiles (Fig. 5). The Margalef index is a measure of species richness. It shows a decrease in the number of taxa during four out of five laminated intervals that are sufficiently well sampled. Between laminated intervals, there is also a noted decrease in taxa at 388 ka. The Simpson index measures the evenness of the sample. Values close to 1 indicate that all taxa contain an equal number of individuals, while values close to 0 indicate that one species dominates the assemblage. In general, the Simpson index is close to 1 throughout the core; however, during the Termination V Laminations and the most recent two laminations, the Simpson index decreases reflecting the dominance by *Chaetoceros* RS during these intervals (Fig. 5). The Simpson index never approaches 0, which would likely indicate a strong dissolution signal. The Shannon diversity index measures both species richness and evenness. Correspondingly, it is low during three of the laminated intervals, high during MIS 12 and peaks at 397 ka (Fig. 5).

Absolute diatom abundances vary between 10^6 and 10^8 diatoms deposited per gram of sediment with values an order of magnitude higher during most laminated intervals than during massive intervals (Fig. 5). The diatom assemblage is dominated by *Chaetoceros* and *Thalassiosira antarctica* resting spores (RS), with lesser contributions from *Fragilariopsis oceanica, Fragilariopsis cylindrus, Fossula arctica, Shionodiscus trifultus* (=*Thalassiosira trifulta), Thalassiosira binata,* small (<10 µm in diameter) *Thalassiosira* species, *Paralia sulcata, Lindavia* cf. *ocellata*, *Neodenticula seminae,* and *Thalassionema nitzschioides* (Fig. 6).

4.3.2 Qualitative Diatom Proxies

Diatoms, like many organisms, thrive m

under a specific range of environmental conditions or optima and these optima are different for each species. For this reason, diatom assemblages are excellent paleoceanographic indicators (Smol, 2002). We grouped diatoms with similar environmental niches together (Table 3) to interpret the paleoceanographic sea surface conditions at the Bering Sea shelf-slope break during MIS 12 to 10 (Caissie, 2012;

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Katsuki and Takahashi, 2005; Sancetta, 1982){Caissie and Nesterovich, In Prep} (Fig. 7). Grouping diverse species together may result in a loss of information when two different species in the same niche show differing abundance patterns over time. On the other hand, changes in abundances may simply reflect different species filling the same niche at different times.

Chaetoceros resting spores are the dominant taxa included in the high productivity group (Table 3). Relative percent abundances of *Chaetoceros* RS are highest (up to 69%) during the Termination V Laminations and follow the pattern of both diatom accumulation rate and insolation at 65° N (Berger and Loutre, 1991). The lowest relative abundances (15-20%) of *Chaetoceros*/high productivity species occur between 403 and 390 ka (124.21 to 120.07 mbsf) when both obliquity and insolation are low (Fig. 7h).

Epontic diatoms are those that bloom attached to the underside of sea ice or within brine channels in the ice (Alexander and Chapman, 1981). This initial bloom occurs below the ice as soon as enough light penetrates to initiate photosynthesis in the Bering Sea, which can occur as early as March (Alexander and Chapman, 1981). A second ice-associated bloom occurs as sea ice begins to break up on the Bering Sea shelf. This bloom is referred to as the marginal ice zone bloom and many of its members are common species in the sediment assemblage. Several diatom species are present in both types of sea ice blooms, and so while they are indicators of ice presence, they cannot be used to distinguish between types of sea ice. These species are grouped under "both ice types" (Table 3).

Epontic species are present in low relative percent abundances (< 5%) throughout much of the record, but there is a marked absence of them during the laminated interval from 423 to 410 ka (129.96-126.45 mbsf) (Fig. 7i). Marginal ice zone species fluctuate between 4% and 14% throughout the record and do not show any trends in abundance changes (Fig. 7j). The grouping of species found both within the ice and in the water surrounding ice, however, is also somewhat reduced during laminated intervals (Fig. 7k).

A cold layer of water found between seasonally warmer surface and warmer deep water characterizes dicothermal water. It is stable because of its very low salinity. In the Sea of Okhotsk and the Bering Sea today, the dicothermal layer is associated with melting sea ice. Genera present in the Bering Sea during late summer tend to co-vary with the dicothermal water indicators, so the two groups were merged for comparison with other diatom groups. *S. trifultus* is the dominant species in the dicothermal group (Table 3). It is relatively high (~4%) during MIS 12, is virtually absent from the sediments during the Termination V Laminations, and then increases again until it peaks at 10% relative abundance at 400 ka (123.22 mbsf) (Fig. 6).

Neritic species maintain ~10% relative abundance throughout the core (Fig. 7m). The dominant species in the neritic group is *Paralia sulcata* (Table 3), sometimes considered an indicator of shallow, moving water (Sancetta, 1982). Neritic species are lowest during the Termination V Laminations and increase dramatically around 404 ka (124.61 mbsf) to almost 50% of the assemblage (Fig. 7n). *L.* cf. *ocellata* is the dominant taxa in the fresh water group. This group is notably absent from much of the core, but prevalent between 401 and 392 ka (123.70 mbsf and 121.20 mbsf); it reaches its highest relative percent abundance (12%) at 401 ka (123.62 mbsf) (Fig. 7n).

Neodenticula seminae is used here as a tracer of Pacific water (Caissie et al., 2010; Katsuki and Takahashi, 2005). Absolute abundances begin to increase at 422 ka as global eustatic sea level rises above -50 mapsl. Abundance then decreases slowly over the course of the Termination V Laminations and peaks again at 392 ka and 382 ka. As sea level drops below -50 mapsl, *N. seminae* is no longer present at U1345. Relative percent abundances remain stable at ~2% relative percent abundance between 422 and 400 ka (129.62-123.62 mbsf), then peak at 13% at 392 ka (121.22 mbsf) (Fig. 6 and 7o).

Diatoms associated with warmer water or classified as members of temperate to subtropical assemblages (Table 3) are quite low throughout the record (<5%), and are highest (3-4%) during mid to late MIS 11 approximately ~410 to 391 ka (126.74 to 116.50 mbsf) (Fig. 7p).

4.4 Calcareous Nannofossils

Calcareous nannofossils were examined between 432-405 ka (133.4 to 125.0 mbsf); one third of the samples were barren (Fig. 7g, open purple circles) and only one sample (418

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ka; 128.8 mbsf) had sufficient individuals to estimate relative percent abundances (Fig. 7g). This sample is located midway through the Termination V Laminations when the diatom assemblage is overwhelmingly dominated by *Chaetoceros* RS. Small *Gephyrocapsa* dominates (>50%) the calcareous nannofossil assemblage. There are 35% medium *Gephyrocapsa,* 9% *Coccolithus pelagicus*, and 1% *Gephyrocapsa oceanica*.

4.5 Geochemistry

4.5.1 Organic and Inorganic Carbon Content

Total organic carbon (TOC) roughly follows the trend of relative percent abundances of *Chaetoceros* RS, with higher values during the Termination V Laminations (Fig. 7b, 7h). Mean TOC value during MIS 12 is 0.76%, and during the Termination V Laminations, it is 1.11%. TOC decreases between 408 (125.82 mbsf) and 404 ka (124.77 mbsf) coeval with a decrease in $\delta^{15}N$ values. After 404 ka, it increases linearly to 374 ka (115.39 mbsf). TOC is again high during the late MIS 11/MIS 10 laminations.

In contrast, inorganic carbon, calculated as % $CaCO_3$ is less than 1% for most of the record (Fig. 7g). However, it increases up to 3.5% during the laminated intervals and also at 382 ka (117.87 mbsf), 392 ka (110.00 mbsf), and 408 ka (125.82 mbsf).

4.5.2 Terrigenous vs. Marine Input Indicators

Nitrogen, carbon and their isotopes can be used to determine relative amounts of terrigenous vs. marine organic mater input. Total nitrogen (TN) is significantly correlated with total organic carbon (TOC) (Fig. 8a); however, the y-intercept of a regression line through the data is 0.03 (Fig. 8a), indicating that there is a significant fraction of inorganic nitrogen in the sediments (Schubert and Calvert, 2001). Inorganic nitrogen can be adsorbed onto clay particles or incorporated into the crystal lattice of potassium-rich clays such as illite. This complicates interpretations of elemental nitrogen and its isotopes because the presence of inorganic nitrogen will lower C_{org}/N ratios and $\delta^{15}N$ values (Muller, 1977; Schubert and Calvert, 2001).

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Bearing this bias in mind, the relative terrigenous contribution to the sediments can be estimated by examining where U1345 samples plot in relation to typical C_{org}/N, $\delta^{15}N$, and $\delta^{13}C$ values for marine phytoplankton, refractory soil organic matter, and C3 vascular plants (Fig. 8). **Note that we use N/C_{org}, the inverse of C_{org}/N, because we seek to derive the terrigenous carbon fraction** rather than the fraction of terrigenous nitrogen **(Perdue and Koprivnjak, 2007)**.

Throughout MIS 12-10, organic matter is comprised of a mixture of marine and terrigenous organic matter. There is a higher contribution of marine organic matter during MIS 12, 10, and between 394 and 405 ka and a higher contribution of terrigenous organic matter during peak MIS 11 (Fig. 8). The N/C_{org} ratio indicates that during peak MIS 11, this terrigenous organic matter is likely refractory soil organic matter, rather than fresh vascular plant organic matter (Fig. 8b).

During MIS 12, C_{org}/N is highly variable, when sea level is below -50 m apsl (Fig. 7). As sea level rises during Termination V, C_{org}/N values increase from 6 to more than 9. The highest C_{org}/N value occurs at the start of the Termination V Laminations. C_{org}/N decreases as sea level rises until at 400 ka (123.62 mbsf) it stabilizes near 7 for the remainder of the record (Fig. 7).

Carbon isotopic values range between -22 ‰ and -26 ‰. No sample has low enough $\delta^{13}C$ values to be comprised fully of typical Arctic Ocean marine phytoplankton (-22 to -19‰) or ice-related plankton (-18.3‰) (Schubert and Calvert, 2001); however samples from MIS 10, MIS 12, and the "anomalous interval" all plot close to marine phytoplankton values (Fig. 8b). At the onset of the Termination V Laminations, $\delta^{13}C$ becomes more negative and then gradually increases to a maximum of -22.33 at 404 ka (124.62). After 400 ka (123.5 mbsf), $\delta^{13}C$ is relatively stable around -23.5‰ (Fig 7).

4.5.3 Nitrogen Isotopes

The nitrogen isotopic composition of bulk marine sediments can be thought of as a combination of the $\delta^{15}N$ of the source nitrate and the amount of nitrogen utilization by phytoplankton (Brunelle et al., 2007). Denitrification is common in the low oxygen

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waters of the eastern tropical North Pacific (Liu et al., 2005) and in the Bering Sea during the Bølling-Allerød (Schlung et al., 2013), leading to enriched core top $\delta^{15}N$ values between 8 and 9‰. When diatoms utilize nitrogen, they preferentially assimilate the lighter isotope, ^{14}N, which enriches surface waters with respect to ^{15}N {Sigman, 1999}. Complete nitrogen utilization would result in $\delta^{15}N$ values identical to that of the source nitrate (Sigman et al., 1999). Sponge spicules (very low $\delta^{15}N$ values) and radiolarians (highly variable $\delta^{15}N$ values) may contaminate the $\delta^{15}N$ of bulk organic matter; therefore, we looked for and found no correlation between spicule abundance and $\delta^{15}N$ in our samples.

$\delta^{15}N$ is relatively stable, but quite high throughout the study interval, fluctuating around an average value of 6.4‰ and reaching values greater than 7‰ and up to 8‰ several times (Fig. 7). There are several notable excursions from these high values. Coeval with sea level rise and increased relative percent *Chaetoceros* RS, $\delta^{15}N$ decreased 2.7‰ to 4.4‰ before recovering to average values during the Termination V Laminations. Two other depletions occur at 405 ka (124.77 mbsf) and 393 ka (121.62 mbsf), the first is the most extreme and reaches 2.9‰.

5 Discussion

5.1 Orbital-Scale Changes in Productivity and Sea Ice

The observed changes in diatom assemblages and lithology (Fig. 7) allow us to break the sedimentary record into five zones: MIS 12, Termination V, Peak MIS 11, Beringian Glacial Initiation, and Late MIS 11 (Table 2). These zones reflect changing sea ice, glacial ice, sea level, and SST and correspond to events recognized elsewhere in ice cores and marine and lake sediments.

5.1.1 Marine Isotope Stage 12 and Early Deglaciation (431-425 ka)

From 431 to 425 ka, the record chronicles conditions at the end of MIS 12. Although diatom accumulation rate is quite low, a relatively diverse assemblage characterizes this period (Fig. 5) with moderate amounts of sea ice, high productivity, and dicothermal

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species (Fig. 7), indicating seasonal sea ice with highly stratified waters during the ice-melt season. Nitrogen isotopes indicate high nutrient utilization (Fig. 7) consistent with nitrogen-limited productivity in stratified waters as well as localized denitrification.

Numerous shell fragments, two sand layers and the highest percentages of clay-sized sediments in the record were deposited during MIS 12 (Figs 4 and 8) indicating input of terrigenous material, however, crossplots of elemental (C_{org}/N or N/C_{org}) and isotopic ($\delta^{13}C$, $\delta^{15}N$) indicators of terrigenous and marine carbon pools indicate that the organic matter during MIS 12 is a diverse mix of marine phytoplankton and soil detritus (Fig. 8) likely derived from in-situ, but low, productivity and transport by several methods including large, oligotrophic rivers and downslope transport. Glacial ice was likely restricted to mountain-valley glaciers, similar to the last glacial maximum (e.g. Glushkova, 2001). These small, distant glaciers would not have produced large amounts of ice bergs though occasional glacial ice rafted debris (IRD) may have come from the Koryak Mountains, the Aleutians or Beringia. Consistent with this, sediments typical of glacial IRD, such as dropstones, are sparse, but present. In addition, sea ice rafting tends to preferentially entrain clay and silt (Reimnitz et al., 1998) and is likely to be an important contributor of terrigenous sediments.

5.1.2 Termination V (425-423 ka)

Termination V is the transition from MIS 12 to MIS 11. Worldwide, it is a rapid deglaciation that is followed by a long (up to 30 kyrs) climate optimum (Milker et al., 2013). At U1345, gradually increasing productivity coupled with decreasing nutrient utilization and sea ice occurs between 425 and 423 ka. This is seen as an increase in absolute diatom abundances and relative percent abundance of *Chaetoceros* RS and a decrease in sea ice diatoms and $\delta^{15}N$ values (Fig. 7). It is plausible that increased nitrogen availability drove higher primary productivity as floods scoured fresh organic matter from the submerging continental shelf (Bertrand et al., 2000). Rapid input of bioavailable nitrogen as the shelf was inundated has been suggested to explain increasing productivity during the last deglaciation in the Sea of Okhotsk (Shiga and Koizumi, 2000) and during MIS 11 in the North Atlantic (Poli et al., 2010) and also may have contributed to dysoxia

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by ramping up nutrient recycling, bacterial respiration, and decomposition of organic matter in the Bering Sea.

5.1.3 Peak MIS 11 (423-394 ka)

Globally, peak interglacial conditions (often referred to as MIS 11.3 or 11c) are centered around 400 to 410 ka (Dutton et al., 2015; Raymo and Mitrovica, 2012), though the exact interval of the temperature optimum varies globally and lasted anywhere from 10 to 30 kyrs (Kandiano et al., 2012; Kariya et al., 2010; Milker et al., 2013). At U1345, peak interglacial conditions begin during the Termination V Laminations at 423 ka and continue until 394 ka, lasting nearly 30 kyrs consistent with the synthesis of the PAGES Past Interglacials working group (2016).

5.1.3.1 Laminations (423-410 ka)

A 3.5 m thick laminated interval is deposited during early MIS 11 beginning at 423 ka (Fig. 7) when insolation was high at 65°N (Berger and Loutre, 1991). Its presence indicates that the bottom water at 1,000 m in the Bering Sea was dysoxic for more than 11 kyrs. These laminations are characterized as Type I laminations with a high diatom content (Fig. 4). Several lines of evidence point towards high productivity among multiple phytoplankton groups as opposed to simply a change in preservation. First, we see an increase in diatom abundances by two orders of magnitude increase since MIS 12, second, a low-diversity diatom assemblage dominated by *Chaetoceros* RS, third, an abrupt increase in percent organic carbon, and fourth, high percent $CaCO_3$ and abundant calcareous nannofossils dominated by small *Gephyrocapsa*. Furthermore, enriched $\delta^{15}N$ values indicate either increased nitrogen utilization that likely led to this increased productivity or localized denitrification in low oxygen waters (Fig. 7).

Sea ice extent is reduced during this interval with almost no epontic diatoms present and reduced amounts of other sea ice diatoms (Fig. 7). Geochemical crossplots indicate a high contribution from soil detritus and C3 plant organic matter (Fig. 8). At the onset of the

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laminated interval (423 ka), $\delta^{13}C$ decreases and C_{org}/N increases rapidly (Fig. 7) as the tundra-covered Bering Sea shelf is flooded.

However, the diatom record during the laminated interval has the lowest contribution of neritic diatoms and virtually no fresh water diatoms (Fig. 7), suggesting that although terrigenous organic matter was an important input at the site, coastal, river, or swamp/tundra diatoms were not carried out to U1345 with this terrigenous organic matter.

5.1.3.2 Post Laminations (410-394 ka)

Both high N/C_{org} and $\delta^{13}C$ indicate that input of terrigenous organic matter is highest at the onset of the Termination V Laminations and then declines until mid MIS 11 (400 ka) at which time the organic matter is largely derived from marine phytoplankton (Fig. 7; red to grey dots in Fig. 8). This may be related to rising eustatic sea level causing the migration of the paleoshoreline farther northward and away from U1345.

Throughout MIS 11, *Chaetoceros* RS, a species indicative of high productivity, is generally higher when insolation is higher and lower when isolation is lower (404-390 ka; Fig. 7). However, although their fluctuations are small, warm water species show the opposite trend, with higher proportions of warm water diatoms when insolation is low (Fig. 7). If higher proportions of warm water diatoms indicate warmer water, then this suggests that productivity is highest in colder waters but when insolation is high, and lowest in warmer waters when insolation is low. This may reveal a relationship between upwelling of colder waters and high productivity.

5.1.4 Late MIS 11 to MIS 10 (younger than 394 ka)

After 394 ka, diatom productivity indicators are the lowest in the record but linearly increase to the top of the record. This is in contrast to a slight increase in diatom abundance, which increases at 393 ka and then remains relatively stable into MIS 10. Sea ice indicators also remain relatively high from 392 to the top of the record and dicothermal species reflect moderately stratified waters. Warm water species decrease

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from 390 ka to the top of the record (Fig. 7). The sum of this evidence indicates that at the end of MIS 11, summers were warm and sea ice occurred seasonally, perhaps lasting a bit longer than at other times in the record.

Eustatic sea level decreased beginning about 402 ka (Rohling et al., 2010), but sea level remained high enough to allow *N. seminae* to reach the shelf slope break until about 380 ka (Fig. 7).

5.2 The Bering Sea in the Context of Regional and Global Variability

Across the Bering Sea, sediments at sites near Bowers Ridge (Fig. 1) are dominated by opal during MIS 11 (Kanematsu et al., 2013); whereas, biogenic sediments at sites along the Bering Slope, including U1345, are diluted by sea ice transport of lithogenic sediments as well as down-slope sediment transport (Kanematsu et al., 2013). However, the rate of biogenic opal accumulation is comparable for all sites in the Bering Sea, despite differences in sedimentation rates (Kanematsu et al., 2013; Stroynowski et al., 2015). Opal content in the sediments varies on glacial/interglacial time scales with high productivity during interglacials. Indeed, the highest percent opal concentration of the past 1 Ma occurs during MIS 11 at the two slope sites, U1345 and U1343 (Kanematsu et al., 2013).

Biogenic opal increases during early MIS 11 at Sites U1343 and U1345 (Kanematsu et al., 2013). At U1345, it mimics the pattern of relative percent abundance of *Chaetoceros* RS, the most abundant productivity indicator (Fig. 9). Although diatom data from other cored sites is low resolution (1-4 samples during MIS 11) (Kato et al., 2016; Onodera et al., 2016; Stroynowski et al., 2015; Teraishi et al., 2016), it provides a snapshot of diatom assemblages during MIS 11. Sea ice diatoms contribute approximately 30% of the diatom assemblages at the two slope sites, U1345 (this study) and U1343 (Teraishi et al., 2016), between 10 and 20% of the assemblage at the eastern Bowers Ridge site (U1340) (Stroynowski et al., 2015), but less than 2% of the assemblage on the western flanks of Bowers Ridge (U1341) (Onodera et al., 2016). In the North Pacific (ODP Site 884), no sea ice diatoms are present during MIS 11 (Kato et al., 2016). Site U1341 contained an assemblage high in dicothermal indicators such as *Shionodiscus trifultus*, and

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Actinocyclus curvatulus, oceanic front indicators such as *Rhizosolenia hebetata,* and *N. seminae* (Onodera et al., 2016), while the North Pacific (Site 884) assemblage is dominated by dicothermal indicators during MIS 11(Kato et al., 2016). Percent opal declines at Bowers Ridge during early MIS 11 at the same time as it increases at the slope sites (Iwasaki et al., 2016) (Fig. 9) when sea ice is reduced and upwelling along the shelf-slope break is increased. This implies that the relationship between productivity and sea ice in the Bering Sea is perhaps more complex than the simple idea that sea ice inhibits productivity (Iwasaki et al., 2016; Kim et al., 2016). The region is strongly influenced by winter sea ice throughout MIS 11 with seasonal sea ice present farther south along the slope than today and also in the eastern Bering Sea. Highly stratified waters, perhaps due to the seasonal expansion and retreat of sea ice, extended across the entire basin and even into the North Pacific.

Local ventilation of North Pacific Intermediate Water decreased as Bering Strait opened during Termination V with the weakest ventilation occurring around 400 ka (Knudson and Ravelo, 2015). This is coeval with the highest relative percent abundances of dicothermal diatoms indicating highly stratified water (Fig. 9).

5.2.1 Temperature and Aridity during MIS 11

When sea level was low during glacial periods such as MIS 12 (Rohling et al., 2010), U1345 was proximal to the Beringian coast (Fig. 2). With the Bering land bridge exposed, the continent was relatively cold and arid (Gualtieri et al., 2000). In western Beringia, Lake El'gygytgyn was perennially covered with ice, summer air temperatures were warming in sync with increasing insolation from 4 to 12° C, but annual precipitation was low (200-400 mm) (Vogel et al., 2013).

As sea level rose, and global ice volume reached the lowest amount for the past 500 kyrs (Lisiecki and Raymo, 2005), the generally continental temperatures in the Northern Hemisphere increased (D'Anjou et al., 2013; de Vernal and Hillaire-Marcel, 2008; Lozhkin and Anderson, 2013; Lyle et al., 2001; Melles et al., 2012; Pol, 2011; Prokopenko et al., 2010; Raynaud et al., 2005; Tarasov et al., 2011; Tzedakis, 2010; Vogel et al., 2013) with a northward expansion of boreal forests in Beringia (Kleinen et

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al., 2014). However, the marine realm does not reflect this warming as strongly. At U1345, the relative percent warm water species suggest that SSTs during peak MIS 11 were only slightly warmer than during MIS 12. Indeed, MIS 11 is not the warmest interglacial in most marine records (Candy et al., 2014), rather MIS 5e is the warmest many places (PAGES et al., 2016). This is especially evident in the Nordic Seas where MIS 11 SSTs were lower than Holocene values (Bauch et al., 2000). However, MIS 11 is unique because it was much longer than MIS 5e in all records (PAGES et al., 2016). One exception to this is the Arctic Ocean, which was warm enough during MIS 11 to imply increased Pacific water input through Bering Strait (Cronin et al., 2013).

With elevated sea level, peak MIS 11c was very humid in many places. In the Bering Sea, modeling studies estimate up to 50 mm more precipitation than today at 410 ka (Kleinen et al., 2014). The most humid, least continental period recorded in the sediments at Lake Baikal occurs from 420-405 ka (Prokopenko et al., 2010), and extremely high precipitation is recorded at Lake El'gygytgyn on the nearby Chukotka Peninsula from 420-400 ka (Melles et al., 2012).

5.2.2 Millennial-Scale Laminations and Changes in Sea Ice

Globally, late MIS 11 is characterized as a series of warm and cold cycles (Candy et al., 2014; Voelker et al., 2010), though there is no agreement on the timing of these cycles. At Site U1345, laminations are deposited intermittently between 394 and 392 ka and again after 375 ka (Fig. 4) as the climate transitioned into MIS 10. These laminations are quite different from the Termination V Laminations due to their shorter duration and lack of obvious shift in terrigenous vs. marine carbon source. In addition, these Type II laminations have higher diatom abundances and $CaCO_3$, but lack increased upwelling indicators. Primary production during these laminations is likely not driven by nutrient upwelling along the shelf-slope break. Instead, most of these laminations show an increase in sea ice diatoms and roughly correspond with millennial scale stadial events that occurred during late MIS 11 in the North Atlantic (Fig. 9) (Voelker et al., 2010) as well as carbonate peaks at Blake Ridge (Chaisson et al., 2002). This suggests

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teleconnections between the Bering Sea and the North Atlantic at this time and places an indirect constraint on the depth of the Bering Strait sill.

It is tantalizing to note that the laminations occur at a time when global sea level was fluctuating near the sill depth of Bering Strait (-50 m apsl) (Rohling et al., 2010) (see grey line at -50 m on Fig. 9). When sea level fluctuates near this level, Bering Strait modulates widespread climate changes that see-saw between the Atlantic and Pacific regions on millennial-scale time frames (Hu et al., 2010). And when Bering Strait is closed, North Pacific Intermediate Water formation increases (Knudson and Ravelo, 2015). Further study will elucidate these connections.

A "Younger Dryas-like" temperature reversal is seen midway through Termination V in the North Atlantic (Voelker et al., 2010), Antarctica (EPICA Community Members, 2004) and at Lake El'gygytgyn (Vogel et al., 2013), however there is no evidence for such an event in the Bering Sea.

5.2.3 Anomalous Interval (405-394 ka)

The interval between 405 and 394 ka contains a number of unusual characteristics. Diatom assemblages are similar to those found in nearshore sediments from the Anvillian Transgression 800 km northeast of U1345 in Kotzebue Sound (Fig. 1) (Pushkar et al., 1999). A large peak in neritic species occurs at 404 ka followed by the highest relative percentages of fresh water species at the site and a slight increase in sea ice diatoms from 400 to 394 ka (Fig. 7, grey bar). Primary productivity was low during this interval with the highest $\delta^{15}N$ values of MIS 11, likely indicating denitrification. However, two large depletions in $\delta^{15}N$ bracket this interval and occur as *Chaetoceros* RS decrease in relative percent abundance (Fig. 10). The organic matter is primarily sourced from marine phytoplankton, similar to the organic matter found during the two glacial intervals and distinctly different from the organic matter found during the rest of peak MIS 11 (Fig. 8). Detailed grain size analysis shows a fining upward trend of clay sized grains as well as a broad increase in sand sized grains and in particular grains greater than 250 µm (Fig. 10). All samples are poorly to very poorly sorted (See Supplemental Material). Shipboard data shows an increase in the presence of pebbles, several sand layers (Fig. 10), and a thick

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interval of silty sand (Takahashi et al., 2011) at 404 ka (Fig. 4). While the presence of coarse material implies a terrestrial source for the sediments during this interval, this terrestrial matter must have been largely devoid of organic matter. The sum of this evidence leads us to investigate further three different interpretations of the interval highlighted in grey on Fig. 10: a reversal of flow through Bering Strait, a tidewater glacial advance, and a turbidite.

5.2.3.1 Reversal of Bering Strait Through Flow

As sea level rose after MIS 12, the connection between the Pacific and the Atlantic was reestablished via Bering Strait. De Boer and Nof (2004) suggest that under high sea level conditions, if freshwater is suddenly released into the North Atlantic, the Bering Strait might act as an "exhaust valve" allowing fresh water from the Arctic Basin and the North Atlantic to flow into the Arctic Ocean and then flow south through the Bering Strait, thus preventing a shut-down in thermohaline circulation (DeBoer and Nof, 2004).

On St. Lawrence Island (Fig. 1), evidence for Arctic mollusks entering the Gulf of Anadyr suggests that flow through Bering Strait was reversed at some point during the Middle Pleistocene (Hopkins, 1972). Unfortunately, this event is poorly dated.

If flow were reversed due to a meltwater event (DeBoer and Nof, 2004), we would expect a temporary reduction in North Atlantic Deep Water (NADW) formation and an increase in southerly winds from Antarctica (DeBoer and Nof, 2004). In the Bering Sea, we would expect to see an increase in common Arctic or Bering Strait diatom species and a decrease in North Pacific indicators. In addition, the clay minerals in the Arctic Ocean are overwhelmingly dominated by illite (Ortiz et al., 2012), which tends to adsorb large amounts of ammonium (Schubert and Calvert, 2001). So, if net flow were to the south, one might expect to find increased illite and decreased C_{org}/N and $\delta^{15}N$ values.

Proxy evidence for NADW ventilation indicates that between 412 and 392 ka, NADW formation decreased for short periods (< 1 ka) (Poli et al., 2010). In contrast, AABW formation appears to have drastically slowed around 404 ka, suggesting a decrease in sea ice and winds from around Antarctica as the southern hemisphere warmed (Hall et al., 2001).

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At U1345, diversity is highest around 400 ka, due to the multiple contributions of Arctic species (fresh water, shelf, coastal, sea ice) and common pelagic diatoms, while the North Pacific indicator, *N. seminae* maintains low relative abundances and does not change throughout this interval. No marked increase in illite is observed during this interval in either U1345 or elsewhere on the Bering Slope (Kim et al., 2016) (Fig. 9). However, chlorite, which dominates North Pacific sediments (Ortiz et al., 2012) decreases at 407 ka (Fig. 9), suggesting a reduced Pacific influence. C_{org}/N values began decreasing linearly starting at 409 ka, productivity sharply decreases at 406 ka, $\delta^{15}N$ values are the most depleted at 405 ka, just 1 kyr before a conspicuous peak in *P. sulcata,* a common diatom found in the Bering Strait. Because there is conflicting evidence of both northward and southward flow, we reject the hypothesis of reversed flow through Bering Strait during MIS 11.

5.2.3.2 Glacial Advance

At its maximum, the Nome River Glaciation is the most extensive glaciation in central Beringia and is dated to Middle Pleistocene. Although it has not been precisely dated, it is likely correlative with late MIS 11 or MIS 10 (Kaufman et al., 1991; Miller et al., 2009). Nome River glaciomarine sediments recording the onset of rapid tidewater glacial advance are found in places such as St. Lawrence Island (Gualtieri and Brigham-Grette, 2001; Hopkins, 1972), the Pribilof Islands (Hopkins, 1966), the Alaska Arctic coastal plain (Kaufman and Brigham-Grette, 1993), Kotzebue (Huston et al., 1990), Nome (Kaufman, 1992), and Bristol Bay (Kaufman et al., 2001) (Fig. 1). At these sites glaciers advanced, in some cases more than 200 km, and reached tidewater while eustatic sea level was high (Huston et al., 1990).

Although global sea level was near its maximum, and much of the world was experiencing peak MIS 11 conditions (Candy et al., 2014), there is evidence that the high latitudes were already cooling. At 410 ka, insolation at 65° N began to decline (Berger and Loutre, 1991), and cooling began at 407 ka in Antarctica, expressed both isotopically and as an expansion of sea ice (Pol, 2011). Millennial scale cooling events were recorded at Lake Baikal (Prokopenko et al., 2010). By 405 ka, there was some evidence globally

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for ice sheet growth (Milker et al., 2013) as Lake Baikal began to shift towards a dryer, more continental climate (Prokopenko et al., 2010) and productivity declined at Lake El'gygytgyn (Melles et al., 2012).

Solar forcing coupled with a proximal moisture source, the flooded Beringian shelf, drove snow buildup (Brigham-Grette et al., 2001; Huston et al., 1990; Pushkar et al., 1999) and glacial advance from coastal mountain systems. Precipitation at Lake El'gygytgyn, just west of the Bering Strait, was two to three times higher than today at 405 ka(Melles et al., 2012). A similar "snow gun" hypothesis has been invoked for other high latitude glaciations (Miller and De Vernal, 1992); however, Beringia is uniquely situated. Once sea level began to drop, Beringia became more continental and arid (Prokopenko et al., 2010) and the moisture source for these glaciers was quickly cut off.

Subaerial and glaciofluvial deposits below the Nome River tills and correlative glaciations indicate that Beringian ice, especially from the western Brooks Range, advanced as the climate grew colder. Ice wedges and evidence of permafrost are common (Huston et al., 1990; Pushkar et al., 1999) in sand and gravel deposits later overridden by Nome River till.

If evidence of the Nome River glaciation in central Beringia was present at U1345, we might expect to see evidence of glacial ice rafting. Previous work has suggested that sediments deposited by icebergs should be poorly sorted and skew towards coarser sediments (Nürnberg et al., 1994). Sediments greater than 150 μm are likely glacially ice rafted (St. John, 2008), however it is not possible to distinguish sediments deposited by glacial versus sea ice on grain size alone (St. John, 2008). Both types of ice commonly carry sand-sized or larger sediments (Nürnberg et al., 1994). Sea ice diatoms should not be found in glacial ice, instead, we would expect glacial ice to be either barren, or to carry fresh water diatoms from ice-scoured lake and pond sediments. At U1345, there is a brief coarse interval (405-402 ka) followed by deposition of fresh water diatoms until 394 ka.

Although it is tempting to assign this to the Nome River Glaciation, there are too many unknowns including whether the coarse grains were transported by sea ice, glacial ice, or some other method. Further work is ongoing to look for the onset of the Nome River

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Glaciation in both MIS 11 and MIS 13 as well as to distinguish the transport mechanism for these quartz grains.

5.2.3.3 Turbidite

The location of Site U1345 on a high interfluve was chosen to minimize the likelihood that sediments could have been transported and deposited here by turbidites or other down-slope currents, yet evidence for a turbidite during this interval is very strong. Although there is no evidence of slumping or distorted sediments, clear erosive surfaces, or any structures that would indicate a turbidite during the anomalous interval, there are folded laminations elsewhere in the sediment core (Takahashi et al., 2011). If this interval was a turbidite, we would expect an erosive surface, overlain by clasts and perhaps a coarse sand layer followed by a fining up sequence. We see intermittent sand layers and small pebbles coupled with a linear increase in the percent clay throughout the interval (Fig. 10). Sediments are poorly sorted throughout the interval, consistent with rapid turbidite deposition and the presence of neritic and fresh water diatoms suggest redeposition of these sediments offshore from shallow water. Sancetta and Robinson (1983) argue that benthic pennate species were transported out of shallow water by rivers and turbidity currents during glacial periods; however, they do not consider ice as a transport mechanism. In this study, we have considered most benthic pennate species as members of either the epontic or both ice ecological niches (von Quillfeldt et al., 2003). However, it is striking that the pattern of benthic pennate species at U1345 is nearly identical to that of the fresh water species.

Although the evidence is strongest for a turbidite, it is unusual to find just one turbidite as we might expect a turbidity flow to exist in the same place for a prolonged period. Further investigation of this and other Bering Sea cores can elucidate how common intervals like this are along the slope and if there is temporal consistency between deposits. The presence of a turbidite may suggest that the age model for this core needs to be slightly revised; however, there is no evidence of an erosive surface, nor a clear indication that all of the material deposited during this interval is allochthonous. In

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addition, the presence of a turbidite does not change the overall orbital and millennial scale interpretations of this record. Therefore, we choose to keep the age model as is.

6 Conclusions

This study aimed to describe orbital- and millennial-scale changes in productivity and sea ice extent in the Bering Sea, specifically at the shelf-slope break Site U1345. We further tested two hypotheses: 1) in Beringia, tidewater glaciers advanced while sea level was high and 2) Bering Strait Through Flow reversed shortly after the MIS 12 glacial termination (Termination V).

The interval between MIS 12 and MIS 10 is marked by large changes in productivity but only minor changes in sea ice extent at Site U1345. Productivity changed in concert with changes in insolation and water temperature. During warmer periods, high stratification appears to have led to lowered productivity. Site U1345 sites in the present-day oxygen minimum zone, and the presence of laminations frequently throughout the core indicates that oxygen is low. Evidence of denitrification is prevalent for much of the record, likely due to dysoxic conditions.

During MIS 12, productivity was low and seasonal sea ice dominated the Bering Sea with highly stratified waters during the ice-melt season. At Termination V, diatom productivity increased by two orders of magnitude while nitrogen utilization decreased. At 423 ka, an 11 kyr long laminated interval began. This interval was highly productive for multiple phytoplankton groups. The surface waters were relatively unstratified, and sea ice, though still present, decreased. This period is marked by the highest terrigenous organic matter input of the record possibly due to scouring of the continental shelf as sea level rose. During peak and late MIS 11, SSTs appear to have been warm, but seasonal sea ice lasted longer. And at the end of MIS 11, sea ice increased as sea level declined.

Laminations at the end of MIS 11 correspond with millennial scale stadials seen in the N Atlantic. These deposits represent possible evidence of teleconnections between the Atlantic and the Pacific as eustatic sea level fluctuated near the Bering Strait sill depth.

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Decreased NADW formation and species transport from the Arctic Ocean southward support a reversal of the Bering Strait Current at 405 ka; however, there is no evidence for the transport of Arctic Ocean clay minerals or oceanographic forcing related to an increase in winds in Antarctica. Therefore, there is inconclusive evidence for a reversal of the Bering Strait Current during MIS 11.

When global sea level was at its maximum, insolation dropped and Beringia began to cool in sync with other polar regions. Sediments deposited during the so called, “anomalous interval” may have been carried by tidewater glaciers bringing neritic species far off shore. This glacial advance is attributed to humid conditions in Beringia that allowed rapid glacial growth. Alternatively, this interval may be a turbidite which could shift the age model for this core and cause this section to be omitted from the paleoceanographic record.

Previous studies have referred to MIS 11 as an analog for the next century of climate change. Today sea ice barely reaches Site U1345 even in winter and does not reach any other Bering Sea or North Pacific sites (U1340, U1341, U1343 or ODP 884). In contrast, during MIS 11, sea ice diatoms are present throughout the entirety of MIS 11 at U1345 and seasonal sea ice appears to have reached both slope sites and the eastern Bowers Ridge (Onodera et al., 2016; Stroynowski et al., 2015; Teraishi et al., 2016). However, evidence for a reduction of sea ice in the Arctic Ocean during MIS 11 (Cronin et al., 2013) implies that while winter sea ice was expanded in the Bering Sea compared to today, summer sea ice was likely reduced. Such a significant difference may indicate that MIS 11 is not an ideal analog for climate change over the next 100 years.

However, there are lessons to be learned from the paleo-record. When sea ice declined during early MIS 11, nutrients were upwelled from the deep Bering Sea and flooding of the land bridge further brought nutrients into the surface waters. This caused productivity to increase at Sites U1345 and U1343. However, at Bowers Ridge Site U1341, productivity declined at this time. The pattern of primary productivity across the Bering Sea underscores that understanding the myriad drivers of primary productivity is essential as we prepared for decreased sea ice in the future.

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Data used in this manuscript are archived at the National Center for Environmental Information (https://www.ncei.noaa.gov; specific doi and web address pending).

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driven by decreasing insolation, reduced seasonality, and high humidity due to high sea level and ice-free summers

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Eccentricity was low, obliquity was high and the amplitude of precessional changes was low {Loutre, 2003 #119}. In addition,

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Globally, MIS 11 is easily recognizable in the sediment record by an abrupt and distinct transition from high to low $\delta^{18}O$ values at the MIS 12/11 boundary and subsequent prolonged low values of $\delta^{18}O$ during MIS 11 {Lisiecki, 2005 #1520}. Furthermore, MIS 11 was unique in the polar regions. Antarctica experienced temperatures 2° C warmer than pre-industrial temperatures {Jouzel, 2007 #1927}, and boreal forest extended across Greenland, which may have been largely ice free {de Vernal, 2008 #1908}. Large lakes in Siberia were anomalously productive and record warmer air and lake temperatures than today. Lake Baikal was 2° C warmer {Prokopenko, 2010 #1887} and Lake El'gygytgyn was 4° C warmer {Lozhkin, 2013 #1965;Vogel, 2013 #4569}. MIS 11 is also unique in Beringia because coastal glaciers advanced midway through the long interglacial cycle while sea level was still high {Brigham-Grette, 2001 #2177;Kaufman, 2001 #846;Pushkar, 1999 #147;Huston, 1990 #170}. This implies that parts of Beringia were glaciated rapidly as high latitude insolation fell in the northern hemisphere, but before global sea level dropped in response to the buildup of large ice sheets reaching lower latitudes. MIS 11 ice (i.e., leading to the Nome River Glaciation in MIS 10) is widely believed to be the last of the most extensive glaciations in central Beringia {Brigham-Grette, 2001 #2177;Gualtieri, 2001 #850;Kaufman, 1991 #845;Manley, 2001 #851}.

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Study Area and Sampling

The Integrated Ocean Drilling Program's (IODP) Expedition 323, Site U1345, is located on an interfluve ridge near the shelf-slope break in the Bering Sea (Fig. 1). Navarin Canyon, one of the largest submarine canyons in the world {Normack, 2003 #1905} is located just to the northwest of the site. Sediments were retrieved from ~1008 m of water, placing the site within the center of the modern day oxygen minimum zone {Takahashi, 2011 #1024}. We focus on this site because of its proximity to the modern marginal ice zone in the Bering Sea and observed high sedimentation rates.

Site U1345 was drilled five times during Exp. 323 and cores from four of these holes were described onboard the JOIDES Resolution. This study focuses on a splice of 3 holes that were correlated onboard the ship, so that core gaps in one hole are covered by core material in other holes. In addition to the original analyses presented here, we refer to the shipboard core descriptions and physical properties data {Takahashi, 2011 #1024} in our interpretations. Depths are reported in CCSF-A, a correlated depth scale that allows for direct comparison between drill holes. Units are meters below sea floor (mbsf). A small syringe was used to collect approximately 1 cc of sediment periodically between 112.96 m and 136.40 mbsf. Sampling resolution varied for each analysis. Hyalochaete *Chaetoceros* resting spores were counted on average every 20 cm (~600 yr resolution), full diatom counts were carried out every 36 cm (~1000 yr resolution), calcareous nannofossils were counted every 40 cm (~1200 yr resolution), grain size was analyzed every 23 cm (670 yr resolution), and geochemistry was analyzed every 30 cm (800 yr resolution).

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Diatom

1.2

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Diatom

1.3

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In order to quantify the number of diatom valves deposited per gram of sediment, d

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In order to quantify the number of diatom valves deposited per gram of sediment, d

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Calcareous Nannofossils

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Calcareous Nannofossils

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Calcareous Nannofossils

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Calcareous Nannofossils

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Grain Size

Volume percent of grains in 109 size bins ranging from 0.01 µm to 3500 µm

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Geochemistry

Sediment samples were freeze-dried then ground. An aliquot of homogenized sediment was treated to remove carbonates using pH 5 buffered acetic acid.

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Geochemistry

Sediment samples were freeze-dried then ground. An aliquot of homogenized sediment was treated to remove carbonates using pH 5 buffered acetic acid.

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Geochemistry

Sediment samples were freeze-dried then ground. An aliquot of homogenized sediment was treated to remove carbonates using pH 5 buffered acetic acid.

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Relative percent abundances of *Chaetoceros* RS are highest (up to 69%) during the Termination V Laminations and, in general, mimic the pattern of both diatom accumulation rate and insolation at 65° N {Berger, 1991 #154}. The lowest relative abundances (15-20%) of high productivity species occur between 403 and 390 ka (124.21 to 120.07 mbsf) when both obliquity and insolation are low.When insolation is low, *Chaetoceros* RS are also low (Fig. 7). *T. antarctica* RS, in contrast, are lowest during the Termination V Laminations (as low at 1%) and higher during MIS 12 and after 406 ka (above 125.00 mbsf and 112.97 mbsf). This taxon peaks at 38% relative abundance at 390 ka (120.45 mbsf; Fig. 6).

Relative percent abundances of the characteristic marginal ice zone species, *F. oceanica* and *F. cylindrus* {Caissie, 2010 #900;von Quillfeldt, 2003 #677;Saito, 1978 #804;Sancetta, 1982 #213}, oscillate between ~10% and less than 3% of the diatom assemblage and are highest during MIS 12 and all laminated intervals. They are both at their lowest between ~411 to ~400 ka (126.62 to 123.45 mbsf). *L.* cf. *ocellata* is the dominant taxa in the fresh water group

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The neritic species and moving water indicator, *P. sulcata* is lowest during the laminated intervals. It reaches a maximum (34% relative abundance) at 404 ka (124.61 mbsf). *P. sulcata* remains moderately high (~10%) during non-laminated intervals. *L.* cf. *ocellata* is the dominant taxa in the fresh water group and the variability in its abundances is discussed below. *S. trifultus* follows a very similar distribution to the fresh water group and *L.* cf. *ocellata*. It is relatively high (~4%) during MIS 12, is virtually absent from the sediments during the Termination V Laminations, and then increases again until it peaks at 10% relative abundance at 400 ka (123.22 mbsf). *Thalassiosira binata* and other small (<10 µm in diameter) *Thalassiosira* species have similar distributions with low relative abundances throughout the record (< 6%) except for a small peak between 397 and 386 ka (122.62 and 119.07 mbsf.

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L. cf. *ocellata* is the dominant taxa in the fresh water group

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is often used as a tracer of North Pacific water, in particular the Alaskan Stream {e.g. \Katsuki, 2005 #215;Caissie, 2010 #900}. But its distribution also varies on glacial-interglacial time scales within the Pacific Ocean {Sancetta, 1984 #179}. It is adapted to the low productivity of the North Pacific gyre and is heavily silicified which could lead to high proportions of *N. seminae* reflecting simply dissolution of finely silicified diatoms {Sancetta, 1982 #213;Sancetta, 1981 #335}. *N. seminae*

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Low proportions of *N. seminae* during the Termination V Laminations are likely due to the overwhelming proportion of *Chaetoceros* RS during this time.

The relative percent abundances of *N. seminae* are discussed below. The largest peak in *N. seminae* is at 392 ka (121.2 mbsf) (Fig. 6).

Diatom Proxies

Diatoms, like many organisms, thrive under a specific range of environmental conditions or optima and these optima are different for each species. For this reason, diatom assemblages are excellent paleoceanographic indicators {Smol, 2002 #1911}. Table 1 delineates which species were grouped together into specific environmental niches. Our interpretations of the paleoceanographic sea surface conditions at the Bering Sea shelf-slope break during MIS 12 to 10 are based on changes in these 8 groups and the variability of *Neodenticula seminae*, an indicator of the Alaskan Stream and North Pacific water {Sancetta, 1982 #213;Katsuki, 2005 #215} (Fig. 7).

Sea Ice Species

Epontic diatoms are those that bloom attached to the underside of sea ice or within brine channels in the ice. This initial bloom occurs below the ice as soon as enough light penetrates to initiate photosynthesis in the Bering Sea, which can occur as early as March {Alexander, 1981 #1870}. The centric diatom, *Melosira arctica,* and pennate diatoms, *Nitzschia frigida* and *Navicula transitrans* are among the major components of the epontic diatom bloom {von Quillfeldt, 2003 #677} and all are found in the sediments at U1345A, although they tend to be quite rare.

A second ice-associated bloom occurs as sea ice begins to break up on the Bering Sea shelf. This bloom is referred to as the marginal ice zone bloom and many of its members are common species in the sediment assemblage including the pennate diatom, *Staurosirella* cf. *pinnata* (=*Fragilaria* cf. *pinnata*), and the centric diatoms, *Bacterosira bathyomphala* and several *Thalassiosira* species including *Thalassiosira antarctica* {Shiga, 2000 #595;Schandelmeier, 1981 #1930;von Quillfeldt, 2003 #677}. *T. antarctica* resting spores have been classified in various ways in the past and their ecology is not well understood. However, *T. antarctica* is a member of the marginal ice zone flora {von Quillfeldt, 2003 #677} and was the only organism found in thick pack ice {Horner, 1985 #199}. The resting spores are associated with coastal or ice-margin waters that range from −1 to 4° C and have relatively low salinity (25–34‰) {Barron, 2009 #1845;Shiga, 2000 #595}. In Antarctica, *T. antarctica* blooms in concert with frazil and platelet ice growth in the fall {Pike, 2009 #1659}. This same association has not yet been observed in the Arctic, though it is a possibility. High abundances might indicate that ice formed early enough in the fall that light and/or nutrients were high enough to support *T. antarctica* growth then.

Several diatom species are present in both types of sea ice blooms, and so while they are indicators of ice presence, they cannot be used to distinguish between types of sea ice. These species are grouped under "both ice types" and include such common diatoms as *Fragilariopsis oceanica, Fragilariopsis cylindrus, Fossula arctica,* and many Naviculoid pennate diatoms {Schandelmeier, 1981 #1930;von Quillfeldt, 2001 #214;von Quillfeldt, 2003 #677;Sancetta, 1981 #335;Saito, 1978 #804}.

Epontic species are present in low relative percent abundances (< 5%) throughout much of the record, but there is a marked absence of them during the laminated interval from 423 to 410 ka (129.96-126.45 mbsf). Marginal ice zone species fluctuate between 4% and 14% throughout the record and do not show any trends in abundance changes. The grouping of species found both within the ice and in the water surrounding ice, however, is also somewhat reduced during laminated intervals (Fig. 7).

Warmer Water Species

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Diatoms associated with warmer water or classified as members of temperate to subtropical assemblages are rare in this record; however, they are present. This group includes *Azpeitia tabularis, Thalassiosira eccentrica, Shionodiscus oestrupii* (=*Thalassiosira oestrupii*)*,* and *Thalassiosira symmetrica.* {Sancetta, #213;Sancetta, 1986 #134;Lopes, #1877;Fryxell, 1972 #1929}.

Relative abundances of warmer water species are quite low throughout the record (<5%), and are highest (3-4%) during mid to late MIS 11 approximately ~410 to 391 ka (126.74 to 116.50 mbsf) (Fig. 7).

Alaskan Stream Species

Neodenticula seminae is often used as a tracer of North Pacific water, in particular the Alaskan Stream {e.g. \Katsuki, 2005 #215;Caissie, 2010 #900}. But its distribution also varies on glacial-interglacial time scales within the Pacific Ocean {Sancetta, 1984 #179}. It is adapted to the low productivity of the North Pacific gyre and is heavily silicified which could lead to high proportions of *N. seminae* reflecting simply dissolution of finely silicified diatoms {Sancetta, 1982 #213;Sancetta, 1981 #335}. *N. seminae* is used here as a tracer of Pacific water with the above caveats.

Absolute abundances of *N. seminae* began to increase at 422 ka as global eustatic sea level rises above -50 mapsl. Abundance then decreases slowly over the course of the Termination V Laminations and peaks again at 392 ka and 382 ka. As sea level drops below -50 mapsl, *N. seminae* is no longer present at U1345. Relative percent abundances remain stable at ~2% relative percent abundance between 422 and 400 ka (129.62-123.62 mbsf), then peaks at 13% at 392 ka (121.22 mbsf) (Fig. 6). Low proportions of *N. seminae* during the Termination V Laminations are likely due to the overwhelming proportion of *Chaetoceros* RS during this time.

High Productivity Species

Chaetoceros resting spores are the dominant taxa included in the high productivity group. Chaetoceros RS have been used as indicators of high productivity {e.g. \Caissie, 2010

#900} and are often found in locations influenced by intense upwelling {Lopes, 2006 #1877;Sancetta, 1982 #213}. In addition, Chaetoceros socialis can be a common member of the marginal ice zone bloom {von Quillfeldt, 2001 #214} and a dominant member of the sub ice bloom {Melnikov, 2002 #1596}. Chaetoceros furcellatus is also associated with the marginal ice zone bloom {von Quillfeldt, 2001 #214}. Unfortunately, the morphology of Chaetoceros resting spores is quite variable, and they cannot be classified definitively without the more labile vegetative cell also present {Tomas, 1996 #762}. Odontella aurita, Thalassionema nitzschioides are also included in the high productivity group although they are also associated with the marginal ice zone {von Quillfeldt, 2003 #677}, areas of high productivity {Aizawa, 2005 #1856}, and upwelling {Sancetta, 1982 #213;Lopes, 2006 #1877}. It should be noted that we can not discern between high productivity due to upwelling and high productivity due to other factors because the diatom proxies are not sufficiently refined to distinguish between the two.

It may be that the combination of upwelling and ice melt at the shelf slope break in the Bering Sea is responsible for correlation between these two environmental niches. The spring-blooming Thalassiosira pacifica and small (<10 µm) Thalassiosira species round out the high productivity group due to their associations with high productivity and upwelling specifically in the Bering Sea and North Pacific {Katsuki, 2005 #215;Saito, 1978 #804;Hay, 2007 #1928;McQuoid, 2001 #1912;Aizawa, 2005 #1856;Lopes, 2006 #1877}.

Like Chaetoceros RS, high productivity species mimic the trend of the insolation curve {Berger, 1991 #154} with highest relative abundances (60-70%) occurring during high levels of insolation (Fig. 7). The lowest relative abundances (15-20%) of high productivity species occur between 403 and 390 ka (124.21 to 120.07 mbsf) when both obliquity and insolation are low. High productivity species are high during both the Termination V Laminations and during the late MIS 11 laminations (Fig. 7).

Dicothermal Water Indicators and Late Summer Species

A cold layer of water found between seasonally warmer surface and warmer deep water characterizes dicothermal water. It is stable because of its very low salinity. In the Sea of

Okhotsk and the Bering Sea, the dicothermal layer is often associated with melting sea ice. The highest abundances of *Shionodiscus trifultus* are found associated with this highly stratified, cold water in the Sea of Okhotsk today {Sancetta, 1986 #134;Sancetta, 1981 #335}.

Actinocyclus curvatulus has been observed living in water surrounding sea ice {von Quillfeldt, 2003 #677}; however, it is neither a common member of the marginal ice zone flora, nor is its spatial distribution in the Bering Sea consistent with the distribution of sea ice {Sancetta, 1982 #213}. Its relative percent abundances are more closely associated with those of *S. trifultus* {Sancetta, 1982 #213}, and so it was grouped with *S. trifultus* as an indicator of dicothermal water.

Genera present in the Bering Sea during late summer (*Coscinodiscus, Leptocylindrus,* and *Rhizosolenia*) {von Quillfeldt, 2003 #677;Aizawa, 2005 #1856;Lopes, 2006 #1877} tend to co-vary with the dicothermal water indicators, so the two groups were merged for comparison with other diatom groups.

These two groups are highest (18% relative abundance) at ~401 ka (123.62 mbsf) as insolation declines. This peak is coeval with the peak in fresh water species and an intermediate peak in *N. seminae* and occurs immediately following a peak in neritic species. Dicothermal water indicators and summer species are lowest (< 1%) during the Termination V Laminations (~424-412 ka). Intermediate relative abundances (1% to 5%) occur during MIS 12 and above 392 ka (121.04 mbsf) (Fig. 7).

Shelf to Basin Transport Indicators

Freshwater species are rare, but present in the record. They include the centric species *Lindavia* cf. *ocellata* and *L. radiosa* {Hakansson, 2002 #1876}. Additional freshwater diatoms found in the record are species also found in sea ice (*S.* cf. *pinnata*) {von Quillfeldt, 2003 #677} or in the neritic zone (*Cyclotella stylorum)* {Barron, 2009 #1845} and so these species were placed in the marginal ice zone and neritic groups respectively.

The dominant species in the neritic group is *Paralia sulcata,* which is an interesting species because it can be either planktic or benthic {Kariya, 2010 #1889} and is associated both with river deltas and the species *Melosira sol* {Sancetta, 1982 #213}. It can be a member of the marginal ice zone assemblage {von Quillfeldt, 2003 #677} though Pushkar {, 1999 #147} asserts that *P. sulcata* indicates water shallower than 20 m. Its high abundances in Bering Strait may mean that it is adapted to moving water {Sancetta, 1982 #213}. *P. sulcata* thrives in water that is warmer than 3 degrees {Zong, 1997 #1919}, with low light {Blasco, 1980 #1917} and low salinity {Ryu, 2008 #1918}.

The fresh water group is notably absent from much of the core, but prevalent between 401 and 392 ka (123.70 mbsf and 121.20 mbsf); it reaches its highest relative percent abundance (12%) at 401 ka (123.62 mbsf). Neritic species, on the other hand maintain ~10% relative abundance throughout the core. They are lowest during the Termination V Laminations and increase dramatically around 404 ka (124.61 mbsf) to almost 50% of the assemblage (Fig. 7).

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Neodenticula seminae is often used as a tracer of North Pacific water, in particular the Alaskan Stream {e.g. \Katsuki, 2005 #215;Caissie, 2010 #900}. But its distribution also varies on glacial-interglacial time scales within the Pacific Ocean {Sancetta, 1984 #179}. It is adapted to the low productivity of the North Pacific gyre and is heavily silicified which could lead to high proportions of *N. seminae* reflecting simply dissolution of finely silicified diatoms {Sancetta, 1982 #213;Sancetta, 1981 #335}. *N. seminae* is used here as a tracer of Pacific water with the above caveats.

Absolute abundances of *N. seminae* began to increase at 422 ka as global eustatic sea level rises above -50 mapsl. Abundance then decreases slowly over the course of the Termination V Laminations and peaks again at 392 ka and 382 ka. As sea level drops below -50 mapsl, *N. seminae* is no longer present at U1345. Relative percent abundances remain stable at ~2% relative percent abundance between 422 and 400 ka (129.62-123.62 mbsf), then peaks at 13% at 392 ka (121.22 mbsf) (Fig. 6). Low proportions of *N. seminae* during the Termination V Laminations are likely due to the overwhelming proportion of *Chaetoceros* RS during this time.

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The lowest relative abundances (15-20%) of high productivity species occur between 403 and 390 ka (124.21 to 120.07 mbsf) when both obliquity and insolation are low.

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The ratio, C/N is one of two proxies used as indicators of marine versus terrigenous organic matter, with marine values typically ranging from 5-7 and terrigenous ratios over 20 {Redfield, 1963 #4622;Meyers, 1994 #1871}.

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The ratio, C/N is one of two proxies used as indicators of marine versus terrigenous organic matter, with marine values typically ranging from 5-7 and terrigenous ratios over 20 {Redfield, 1963 #4622;Meyers, 1994 #1871}.

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C/N indicates primarily a marine source for

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Bulk Sedimentary Stable Isotopes

Carbon Isotopes

Stable isotopes of carbon are also used as an indicator of marine vs. terrigenous organic matter with $\delta^{13}C$ values near -27 indicating C3 plant-sourced organic matter; values between -22 and -19 are typical for Arctic Ocean marine phytoplankton and -18.3 is average for ice-related plankton {Schubert, 2001 #593}. However, it has been shown that $\delta^{13}C$ is sometimes related more to growth rate, cell size, and cell membrane permeability, so it may reflect changing phytoplankton groups instead of simply marine vs. C3 plant sources of organic matter in U1345.

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and are generally anticorrelated with C/N values

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These values indicate a mix of marine phytoplankton and C3 plants as the main contributors to organic matter at the site.

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Keeping in mind the effects of nitrification of oxygen rich and poor sediments {Brunelle, 2007 #653}, the efficiency of nitrogen utilization can be estimated by examining the $^{15}N/^{14}N$ ratio of nitrogen in either bulk sedimentary organic matter, with enriched values of $\delta^{15}N$ indicating higher nutrient utilization.

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Similarly, the North Atlantic was also highly stratified with significantly reduced NADW production {Poli, 2010 #1892}. High stratification appears to have led to lowered productivity in both the Atlantic and Pacific.

Sea level was low during this interval {Rohling, 2010 #1903}, placing U1345 proximal to the Beringian coast (Fig. 2). With the Beringian shelf exposed, the continent was relatively cold and arid {Glushkova, 2001 #1961}. In western Beringia, Lake El'gygytgyn was perennially covered with ice, summer air temperatures were warming from 4 to 12° C and annual precipitation was low (200-400 mm) {Vogel, 2013 #4569}.
In contrast, the North Atlantic is surrounded by ice sheets readily calving ice bergs and MIS 12 is characterized as an intense glacial period with ice rafted debris found as far south as Bermuda {Poli, 2000 #150}. Evidence for warming and the reduction of IRD begins as early as 430 ka in the North Atlantic {Kandiano, 2012 #4570} and the strength of the Gulf Stream increases in step with this glacial ice loss {Chaisson, 2002 #1890}.T

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based on changes in diatom assemblages and lithology (Fig. 7)

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. Non-organic, terrigenous material could be transported to U1345 by

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icebergs, or sea ice. It is unlikely that meltwater rivers played a large role in sediment transport at this time because terrigenous organic matter and fresh water diatoms are absent and there are only moderate amounts of diatoms transported from shallow waters (Fig. 8). This may also reflect the reduced area of submerged continental shelf. In addition, g

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Terrigenous materials found in MIS12 sediments are most likely evidence of

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Termination V is the transition from MIS 12 to MIS 11. Worldwide, it is a rapid deglaciation that is followed by a long (up to 30 kyrs) climate optimum {Milker, 2013 #4568}. At U1345, it can be broken into two stages, the first part from 425-423 ka, and the second part from 423-410 ka, which is notably dominated by laminated sediments and is discussed in the next section. The first part of Termination V corresponds with a local maxima in insolation at 65°N {Schimmelmann, 1990 #2137} and increasing temperatures in Antarctica {EPICA community members, 2004 #38}, the North Atlantic {Voelker, 2010 #4617}, and globally {Milker, 2013 #4568}.

At U1345, the first part of Termination V is expressed as

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At the same time, episodic increases in productivity were occurring in places as distant as Lake Baikal {Prokopenko, 2010 #1887} and the North Atlantic {Poli, 2010 #1892;Chaisson, 2002 #1890;Dickson, 2009 #1899} and NADW formation was intensifying {Poli, 2010 #1892}. Ventilation of NADW generally continues to increase from 424 to 410 ka to its strongest and then weakens over the course of the interglacial {Thunell, 2002 #1891}. In addition, the flux of terrigenous dust was decreasing near Antarctica reflecting perhaps a decrease in the strength of Southern Ocean winds {Wolff, 2006 #509}. Evidence for higher productivity in the Bering Sea, possibly caused by intensified upwelling, suggests teleconnections between NADW formation, the strength of the southern winds, upwelling in the North Pacific, and northward flow through Bering Strait {e.g. \DeBoer, 2004 #24}.

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The $\delta^{13}C$ pattern of depleted values at the start of the laminated interval and increasingly enriched values until about 409 ka is very similar to the C_{org}/N story (Fig. 7) reflecting the

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The sum of this evidence of high productivity, reduced sea ice, and terrigenous input is similar to changes in productivity in this region during Termination I {Brunelle, 2007 #653;Caissie, 2010 #900}. At the start of Termination I, productivity initially increased while nitrogen utilization decreased, then an abrupt increase in productivity and nitrogen utilization was recorded {Brunelle, 2007 #653;Brunelle, 2010 #2051}. It is plausible that increased nitrogen availability drove higher primary productivity as floods scoured fresh organic matter from the submerging continental shelf {Bertrand, 2000 #1909}. Rapid input of bioavailable nitrogen as the shelf was inundated has been suggested to explain increasing productivity during the last deglaciation in the Sea of Okhotsk {Shiga, 2000 #595} and during MIS 11 in the North Atlantic {Poli, 2010 #1892} and also may have contributed to dysoxia by ramping up nutrient recycling, bacterial respiration, and decomposition of organic matter in the Bering Sea.

The brief nitrogen utilization decrease just prior to the laminations (Fig. 7), suggests that productivity was limited by some other factor, such as light or micronutrients, and could not increase proportional to the increase in available nitrogen. Lam {, 2013 #3194} suggests that during the last deglaciation, a breakdown in stratification limited productivity by creating a very deep mixed layer that extended below the photic zone. This seems possible during Termination V, since diatom indicators for stratified waters (dicothermal species) and epontic diatoms decline coeval with the increase in productivity indicators (Fig. 7), though seasonal sea ice remains and likely provides a mechanism for maintaining stratification to some extent. As the interglacial began however, we would expect this light limitation to be removed when stratification was re-established. However, if dicothermal diatoms are indicators for stratification, then stratification is not re-established until long after $\delta^{15}N$ values increase (Fig. 7), suggesting that if there is a limit on productivity during the early deglacial it is likely not light via a deep mixed layer {Obata, 1996 #4621}. In contrast, a nearby core (HLY 0202 JPC3) displayed laminated sediments for only about 500 years during the last deglaciation {Cook, 2005 #32}, suggesting that the two Terminations were very different.

There is a “Younger Dryas-like” temperature reversal seen midway through Termination V in the North Atlantic {Voelker, 2010 #4617}, Antarctica {EPICA community members, 2004 #38} and at Lake El'gygytgyn {Vogel, 2013 #4569}, however there is no evidence for such an event in the Bering Sea.

Peak MIS 11 (423-394 ka)

Globally, peak interglacial conditions (often referred to as MIS 11.3 or 11c) are centered around 410 ka, though the exact interval of the temperature optimum varies and lasted anywhere from 10 to 30 kyrs {Kandiano, 2012 #4570;Kariya, 2010 #1889;Milker, 2013 #4568}. At U1345, peak interglacial conditions begin during the Termination V Laminations and continue until 394 ka.

Both decreasing C_{org}/N and increasing $\delta^{13}C$ indicate that input of terrigenous organic matter decreases from the onset of the Termination V Laminations until mid MIS 11 (400 ka) at which time the organic matter remains solidly marine sourced for the remainder of the record (Fig. 7). Sea level is high and the Pacific water indicator, *N. seminae*, is found at the site beginning at 424 ka.

Throughout MIS 11, *Chaetoceros* RS, a species indicative of high productivity, is generally higher when insolation is higher and lower when isolation is lower (390-404 ka; Fig. 7). However, although their fluctuations are small, warm water species show the opposite trend, with higher proportions of warm water diatoms when insolation is low (Fig. 7). If higher proportions of warm water diatoms indicate warmer water, then this suggests that productivity is highest in colder waters but when insolation is high, and lowest in warmer waters when insolation is low.

During MIS 11c, global ice volume was the lowest that it has been for the past 500 kyrs {Lisiecki, 2005 #1520}, and generally continental temperatures were warmer than today {Vogel, 2013 #4569;D'Anjou, 2013 #4620;Melles, 2012 #2158;Pol, 2011 #1880;Lyle, 2001 #149;Prokopenko, 2010 #1887;de Vernal, 2008 #1908;Tzedakis, 2010 #1888;Raynaud, 2005 #101;Tarasov, 2011 #1897;Lozhkin, 2013 #1965} with a northward expansion of boreal forests in Beringia {Kleinen, 2014 #4563}. However, it was not warm uniformly world-wide.

At U1345, the relative percent warm water species suggest that SSTs during MIS 11c were only slightly warmer than during MIS 12. Indeed, MIS 11 is not the warmest interglacial in most marine records {Candy, 2014 #4566}. This is especially evident in the Nordic Seas where MIS 11 SSTs were lower than Holocene values, although no IRD was deposited between 408 and 398 ka {Bauch, 2000 #156}.

However, MIS 11c was very humid in many places. In the Bering Sea, modeling studies estimate up to 50 mm more precipitation than today at 410 ka {Kleinen, 2014 #4563}. The most humid, least continental period recorded in the sediments at Lake Baikal occurs from 420-405 ka {Prokopenko, 2010 #1887}, and extremely high precipitation are recorded at Lake El'gygytgyn on the nearby Chukotka Peninsula from 420-400 ka {Melles, 2012 #2158}. Conditions in Africa during MIS 11c were similar to the Holocene African humid period. In addition, pollen records from Western Europe also reflect humid environments {Candy, 2014 #4566}. A warmer, moister climate in Western Europe and Africa is indicative of increased Atlantic Meridional Overturning Circulation (AMOC) {Bauch, 2013 #4619}. AMOC appears to be stable over MIS 11 {Milker, 2013 #4568} as evidenced by high carbonate in the North Atlantic {Poli, 2010 #1892;Chaisson, 2002 #1890}. Interestingly, small carbonate peaks in the Bering Sea are contemporaneous with those on the Bermuda Rise, suggesting teleconnections between the two regions (Fig. 7). These conditions are similar to a modern day negative North Atlantic Oscillation (NAO) which is linked to wet conditions in N. Africa, weaker westerlies, more zonal storm tracks, a dry Northern Europe, colder Nordic Seas and increased sea ice in the North Atlantic {Kandiano, 2012 #4570}.

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Most of these laminations show an increase in sea ice diatoms and a decrease in productivity indicators. These roughly correspond with millennial scale stadial events that occurred during MIS 11a in the North Atlantic (Fig. 7) {Voelker, 2010 #4617}. Late

MIS 11 is characterized as a series of warm and cold cycles {Voelker, 2010 #4617;Candy, 2014 #4566}, though there is not agreement on the timing of these cycles.

It is tantalizing to note that the laminations occur at a time when global sea level was fluctuating around -50 mapsl {Rohling, 2010 #1903} (see grey line at -50 m on Fig. 7). Increased productivity and repeating laminated sediments could be related to shelf to basin nutrient dynamics as rising sea levels carry fresh organic matter from the shelf out over the southern Bering Sea {e.g. \Bertrand, 2000 #1909}. In addition to the correspondence between laminations and North Atlantic stadials, carbonate peaks in the Bering Sea also occur coeval with carbonate peaks at Blake Ridge {Chaisson, 2002 #1890} suggesting teleconnections between productivity in the Bering Sea and the North Atlantic at this time. This suggests that sea level fluctuation driven by the closure of Bering Strait may also be occurring at the end of MIS 11 as well as during the last glacial maximum {Hu, 2010 #872}, though this hypothesis requires further testing and rethinking of dynamic topography in the Bering Strait region over time.

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Between 405 and 394 ka, there is an unusual diatom assemblage and grain size distribution at Site U1345. There are several possible explanations for deposition of shallow water and fresh water species along with large changes in sediment grain size. We will consider two possibilities in detail: Bering Strait current reversal and glacial surge in Beringia.

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resulting from increased illite deposition

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A warm Arctic Ocean during MIS 11 suggests increased Pacific water input through Bering Strait {Cronin, 2013 #3181}.

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Glacial Inception in Beringia (405-394 ka)

Regardless of whether flow through Bering Strait reversed during peak MIS 11, the interval between 405 and 394 ka contains an unusual diatom assemblage and grain size distribution. Diatom assemblages are similar to that found in sediments from the Anvillian Transgression 800 km northeast of U1345 near Kotzebue (Fig. 1) {Pushkar, 1999 #147}. In the Bering Sea, a large peak in neritic species occurs at 404 ka followed by the highest relative percentages of fresh water species at the site and a slight increase in sea ice diatoms from 400 to 394 ka (Fig. 7).

Despite the deposition of shallow and fresh water species, the proportion of marine to terrestrial carbon was the highest in the entire interval. However, primary productivity was quite low during this interval with high nitrogen utilization reflected in the $\delta^{15}N$ values. Two large depletions in $\delta^{15}N$ bracket this interval and occur as *Chaetoceros* RS decrease in relative percent abundance, but only the older depletion is also associated with a decrease in the number of diatom valves per gram of sediment (Fig. 8). The older depletion may reflect an environment that is limited by micronutrients such as iron as sea level approaches its maximum.

Detailed grain size analysis shows a trend of increasing clay sized grains as well as a broad increase in sand sized grains and in particular grains greater than 250 μm (Fig. 8). All samples are poorly to very poorly sorted (See Supplemental Material). In addition, shipboard data shows an increase in the presence of large, isolated clasts > 1 cm in diameter, a cluster of sand layers (Fig. 8), and a thick interval of silty sand {Takahashi, 2011 #1024} around 411 ka (Fig. 4).

The sum of this evidence leads us to propose that the interval highlighted in grey on Figure 8, reflects a glacial advance that may be the onset of the Nome River Glaciation at ~404 ka. This advance is short-lived in the Bering Sea and is followed by a period when intensified winds blew fresh water diatoms more than 1000 km off shore to Site U1345.

Glacial ice is effective at carrying terrigenous and near shore particles far from land. Previous work has suggested that sediments deposited by icebergs should be poorly sorted and skew towards coarser sediments {Nürnberg, 1994 #1473}. Sediments greater than 150 μm are likely glacially ice rafted {St. John, 2008 #1086}, however it is not possible to distinguish sediments deposited by glacial versus sea ice on grain size alone {St. John, 2008 #1086}. Both types of ice commonly carry sand-sized or larger sediments {Nürnberg, 1994 #1473}. Sea ice diatoms should not be found in glacial ice, instead, we would expect glacial ice to be either barren, or to carry fresh water diatoms from ice-scoured lake and pond sediments.

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Mollusks and pollen in these sediments reflect a tundra environment with temperatures similar to today {Hopkins, 1972 #451;Kaufman, 1993 #148} or warmer than today {Pushkar, 1999 #147} with significantly reduced or absent sea ice {Kaufman, 1993 #148;Pushkar, 1999 #147}.

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We suggest that Beringian glaciation during MIS 11 was initiated ~404 ka by decreasing insolation when eccentricity was high and perihelion coincided with the equinox

{Schimmelmann, 1990 #2137}. Solar forcing coupled with a proximal moisture source, the flooded Beringian shelf, to drive snow buildup {Pushkar, 1999 #147;Huston, 1990 #170} and glacial advance. Precipitation at Lake El'gygytgyn, just west of the Bering Strait, was two to three times higher than today {Melles, 2012 #2158}. A similar "snow gun" hypothesis has been invoked for other high latitude glaciations {Miller, 1992 #1955}; however, Beringia is uniquely situated. Once sea level began to drop, Beringia became more continental and arid {Prokopenko, 2010 #1887} and the moisture source for these glaciers was quickly cut off.

In central Beringia, glaciers from coastal mountains on chukotka advanced to St. Lawrence Island and glaciers from the western Brooks Range advanced into Kotzebue Sound as global eustatic sea level dropped coincident with decreased insolation during Northern Hemisphere summers {Berger, 1991 #154}, Lake El'gygytgyn returned to glacial conditions by 398 ka, and globally MIS 11.3 ended {Poli, 2010 #1892;Voelker, 2010 #4617;Milker, 2013 #4568}.

Alternative Explanations

There are several other explanations for how these sediments could have been carried more than 300 km from the coast out over the shelf-slope break and deposited in 1000 m of water: turbidites or strong density currents on the shelf, sediment reworking and winnowing, sea ice transport, and eolian deposition

The location of Site U1345 on a high interfluve minimizes the likelihood that sediments will have been transported and deposited here by turbidites or other down-slope currents. Sancetta and Robinson {, 1983 #136} argue that benthic pennate species were transported out of shallow water by rivers and turbidity currents during glacial periods. They do not consider ice as a transport mechanism {Sancetta, 1983 #136}. If turbidites were present, we would expect fining up sequences in the detailed grain size analysis, slumping or distorted sedimentation in the core and clear erosive surfaces. But there is no evidence of turbidite deposition {Takahashi, 2011 #1024}. If winnowing were a dominant transport mechanism, the sediments should be well sorted. Instead, the presence of multiple terrigenous grain sizes indicates that the sediments are relatively poorly sorted and the

Folk and Ward method {Blott, 2001 #2086} classifies all samples as either poorly sorted or very poorly sorted (See supplemental material).

Sea ice could bring neritic (though probably not freshwater) diatoms out to deeper waters as it preferentially entrains silt and clay size particles {Reimnitz, 1998 #887}. However, if there was an increase in sea ice, we would expect to see a significant increase in sea ice diatoms during this interval. Instead we see only a small increase in sea ice related species, primarily epontic species. Additionally, during this time, the marginal ice zone assemblage is dominated by *T. antarctica* RS which is a taxon primarily found in coastal, low salinity areas {Barron, 2009 #1845;Shiga, 2000 #595}, so its presence may be further support for increased shelf to basin transport.

Eolian deposition of diatoms is a common event in Antarctica where strong katabatic winds transport mainly small (up to 50 μm in diameter), non-marine diatoms {McKay, 2008 #4561}. The freshwater diatoms that are abundant between 409 and 405 ka are dominated by species that tend to be quite small. *Lindavia* cf. *ocellata* ranges from 8-20 μm and *Lindavia radiosa* from 7-35 μm. Wind-driven deposition of these species is the most probably explanation for their transport more than 800 km from shore, therefore, this interval may represent a period of time when northerly winds intensified over Beringia

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Late MIS 11 (younger than 394 ka)

After 394 ka, upwelling indicators are the lowest in the record and linearly increase to the top of the record. This is in contrast to a slight increase in diatom abundance, which increases at 393 ka and then remains relatively stable to the top of the record. Sea ice indicators also remain relatively high from 392 to the top of the record and dicothermal species reflect moderately stratified waters. Warm water species decrease from 390 ka to the top of the record (Fig. 7). The sum of this evidence indicates that at the end of MIS 11, summers were warm and sea ice occurred seasonally, perhaps lasting a bit longer than at other times in the record. Modelling results indicate that at 394 ka, temperatures were below modern by 0° to 2° C, and precipitation in Beringia was relatively low, like today {Kleinen, 2014 #4563}. These patterns reflect general cooling worldwide {de Abreu, 2005 #1447;Prokopenko, 2010 #1887;Raynaud, 2005 #101}. IRD is again deposited in the North Atlantic beginning around 390 ka.

Eustatic sea level decreased beginning about 402 ka {Rohling, 2010 #1903}, but sea level was high enough though to allow *N. seminae* to reach the shelf slope break until about 380 ka (Fig. 7). As sea level dropped, significant parts of the Beringian continental shelf were exposed, cutting off the moisture supply for the Nome River Glaciation {Pushkar, 1999 #147;Prokopenko, 2010 #1887@@hidden}. Subaerial and glaciofluvial deposits above the Nome River tills and correlative glaciations indicate that Beringian ice retreated, while climate remained cold or grew colder. Ice wedges and evidence of permafrost are common {Huston, 1990 #170;Pushkar, 1999 #147} above Nome River glaciation deposits.

Laminations are again prominent in the sediment record and deposited intermittently between 394 and 392 ka and again after 375 ka (Fig. 4) as the climate transitioned into MIS 10. These laminations are quite different from the Termination V Laminations due to their shorter duration and lack of obvious shift in terrigenous vs. marine carbon source. In addition, these Type II laminations have increased diatom abundances and $CaCO_3$, but not necessarily increased upwelling indicators reflecting increased primary production that is perhaps not linked to nutrient upwelling along the shelf-slope break.

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{Voelker, 2010 #4617;Candy, 2014 #4566}{Voelker, 2010 #4617}{Chaisson, 2002 #1890}{Rohling, 2010 #1903}{Knudson, 2015 #4651}{Voelker, 2010 #4617}{EPICA community members, 2004 #38}{Vogel, 2013 #4569}

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{Voelker, 2010 #4617;Candy, 2014 #4566}{Voelker, 2010 #4617}{Chaisson, 2002 #1890}{Rohling, 2010 #1903}{Knudson, 2015 #4651}{Voelker, 2010 #4617}{EPICA community members, 2004 #38}{Vogel, 2013 #4569}

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There is inconclusive evidence for a reversal of the Bering Strait current at 405 ka, but evidence for teleconnections between the Atlantic and the North Pacific is strong when eustatic sea level fluctuated near the Bering Strait sill depth at the end of MIS 11. Tidewater glaciers advanced in Beringia when eustatic sea level was high, insolation was declining in the Arctic, and other high latitude regions saw decreasing SSTs.

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During MIS 12, seasonal sea ice dominated the western Bering Sea with highly stratified waters during the ice-melt season. Sea ice was at a minimum from 423 to 410 ka when the Termination V Laminations were deposited. After this, although summer

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Evidence of glaciation is short lived in the western Bering Sea and followed by an intensification of northerly winds that brought freshwater diatoms out over the open ocean.

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Laminations at end MIS 11 correspond with millennial scale stadials seen in the N Atlantic. These deposits represent further possible evidence of teleconnections between the Atlantic and the Pacific as eustatic sea level fluctuated near the Bering Strait sill depth.

This study supports hypotheses that the region responds to insolation changes at 65° N and that Bering Strait modulates climate in both the North Atlantic and Pacific regions. Future work should focus on leads and lags between changes in the North Atlantic, North Pacific and Antarctic regions to determine how upwelling, deep water formation, and climate are related.

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