Response of the Bering Sea to 11-year solar irradiance cycles during the Bølling-Allerød

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Abstract

Previous studies find decadal climate variability possibly related to solar activity, although the details regarding the feedback with the ocean environment and ecosystem remain unknown. Here, we explore the feedback system of solar irradiance change during the Bølling-Allerød period, based on laminated sediments in the northern Bering Sea. During this period, well-ventilated water was restricted to the upper intermediate layer, and oxygen-poor lower intermediate water preserved the laminated sediment. An 11-year cycle of diatom and radiolarian flux peaks was identified from the laminated interval. Increased fresh meltwater input and early sea-ice retreat in spring under the solar irradiance maximum follow the positive phase of Arctic Oscillation which impacted the primary production and volume of upper intermediate water production in the following winter. Strength of this 11 year solar irradiance effect might be further regulated by the pressure patterns of Pacific decadal oscillation and/or El Niño-Southern Oscillation variability.

1. Introduction

Signals of an 11 year solar cycle in various meteorological and oceanographic fields have been reported [e.g., Roy and Haigh, 2010]. Doubt regarding how small variations in solar irradiance of less than 0.2 W m⁻² amplitude [Foukal et al., 2006] could be affected to the measurable 11 year responses may be explained by the identification of positive feedbacks linked to the variation of ozone concentration and the ocean-atmosphere system. Such system can be explained by the greater heat and moisture transportation by the increased wind stress under the peak of solar irradiance in the low- and mid-latitude regions. This intensified heat and moisture transport strengthens the air circulation in the troposphere, which produced anomalously greater Ekman pumping and ocean upwelling. These strengthened circulations produce less cloud conditions in the east equatorial and mid-latitude regions, which causes even more solar radiation to reach the surface, resulting in a positive feedback [Marsh et al., 2007; Meehl et al., 2009; Scaife et al., 2013]. However, responses of climate and ecosystem to changes in solar irradiance are not straightforward. The possibility that feedback system will be changed by the environmental factor cannot be ruled out. Accordingly, accurate annually-resolved data on a longer time scale are necessary for more robust correlation among the primary ecosystem signals, climate, and solar forcing.

The Bering Sea is sensitive to the amplified solar effects [Roy and Haigh, 2010; Ineson et al., 2011]. Laminated sediment layers deposited during the rapid warming Bølling-Allerød (BA) and Preboreal periods were preserved in the continental slope of the Bering Sea [Cook et al., 2005; Itaki et al., 2009; Caissie et al., 2010; Kim et al., 2011; Rella et al., 2012]. Based on siliceous microfossil analysis of the BA laminated layers, we reveal the 11-year solar irradiance cycle effects on the surface water ecosystem and environment in the Bering Sea. Solar radiation is regulated by cloud cover change due to pressure pattern shift [Chiacchio et al., 2010]. Thus, we discuss the regulation of solar cycle effects by the other periodic climate oscillations.

2. Materials and Methods

A piston core PC-23A (60°09.52'N, 179°27.82'W; 1002 m water depth) was obtained from the northern continental slope (NCS) of the Bering Sea during the R/V Mirai Cruise MR06-04 in September of 2006 (Figure 1).
The core sediments primarily consist of diatomaceous silty or sandy clay, together with several laminated layers (Figure 2a) composed of sets of diatom-rich dark layers (including the high sulfur containing black layers) and terrigenous sediment gray layers (Figure 2j). Between the depths of 370 and 423 cm within the laminated layer, we extracted the lamination thickness data using X-ray sediment images (Figure 2h). These data were converted from the core-depth scale into a time scale (317 years intervals) by counting the annual laminations (Figure 2i). There is a possibility that less than 10% year interval was underestimated because of the sediments including several lamina layers were lost from the core edge when the sediment sample was subdivided. The periodic components in the thickness of dark lamina were examined by the evolution wavelet power spectrum [Torrence and Compo, 1998], computed with a Morlet wavelet. Samples for diatom and radiolarian analyses were obtained by 20 cm long plastic case (1.5 x 1.5 x 20 cm) between 390 and 410 cm depth. Thirty-five sub-samples were cut by cover glass in each two or four lamina set depending on the lamina thickness.

Freeze-dried sub-samples (about 0.05 g for diatom and 1–4 g for radiolarian) were weighed and then treated with H2O2 and HCl solution to remove organic matter and calcium carbonate, respectively. For diatom analysis, hexametaphosphate solution was then added to the mixture to disaggregate the particles. The solution was taken from the suspension using a micropipette and dropped onto a glass slide. At least 250 valves were counted in each slide, including unidentified Chaetoceros spp. resting spores, using an optical microscope at 1000× magnification.
For radiolarian analysis, the chemically treated samples were wet-sieved (45 μm mesh), after which two types of slides were made using the residue for quantification of the abundance (Q-slide) and for the faunal analysis (F-slide). To prepare the Q-slides, all of the residues were transferred to a 100 ml beaker that contained 50 ml of distilled water, and 0.2 ml of the well-mixed solution was dropped onto a glass slide, dried and mounted with Canada Balsam. F-slides were made from the remaining residue in the beaker. More than 300 radiolarian skeletons were observed under an optical microscope at 100× and 400× magnifications. The total number of radiolarians contained in 1 g of dry sediment (the radiolarian concentration, RC) was estimated using the following equation: RC (#/g) = total # on Q-slide × 250 / sample weight (g).

The flux was calculated using the following formula:

\[
\text{Flux (numbers m}^{-3}\text{day}^{-1}) = N \times S1 / S2 \times V \times D \times T / 365
\]

where \(N\) is the counted number of microfossils, \(S1\) is the counted area (mm²), \(S2\) is the area of cover glass (mm²), \(V\) is the sample volume for observation slide (g), \(D\) is the sediment density (g cm \(^{-3}\)), and \(T\) is the thickness of a lamina set (cm).

### 3. Results and Discussions

#### 3.1. Laminated Layer of Core PC-23A

Ten AMS \(^{14}\)C dates were obtained using planktonic foraminifera (>63 μm) from the top 550 cm in core PC-23A (Figure 1b). The \(^{14}\)C activities of Neogloboquadrina pachyderma and Globigerina bulloides were measured using the NIES-TERRA Accelerator Mass Spectroscopy facility at the National Institute for Environmental Studies in Japan [Uchida et al., 2004, 2005]. The measured radiocarbon dates were converted into calendar years using the Intcal/Marine09 calibration curve [Reimer et al., 2009] and Calib 6.0 software [Stuiver and Reimer, 1993]. Calendar ages were temporally corrected by a 780 year reservoir age, which was suggested by Rella et al. [2012]. In addition, calendar ages were tuned by comparison between core PC-23A and NGRIP δ\(^{18}\)O curves [North Greenland Ice Core Project members, 2004; Rella et al., 2012; Figures 2f and 2g], because poorly oxygenated and aged deepwater has been known to upwell to the surface layer during the examined time window [Rella et al., 2012; Jaccard and Galbraith, 2013], resulting in an increased reservoir age of the surface water during this time interval. Tuned ages were younger than \(^{14}\)C calendar ages by about 100–560 years.

As an example, the laminated layer deposited during the warmer BA, which dated 13.1–15.0 kyr B.P. of radiocarbon age, was finally tuned to 12.6–14.6 kyr B.P.

Several laminated layers were preserved in core PC-23A (Figure 2a). According to the NGRIP δ\(^{18}\)O curve tuning age, the early BA lamina layer between 337 and 423 cm depths can be assigned an age spanning from 14.0 to 14.6 ka (Figures 2f and 2g). As 493 lamina sets were counted within this 550 year interval, the dark and gray laminated set seems to be typical of annual deposition. Furthermore, the annual flux of primary production in the Bering Sea is mainly a result of the spring diatom bloom that occurs once a year [Takahashi et al., 2002]. Thus, each dark lamina enriched in diatoms represents spring deposition, while the gray laminae including dominant terrigenous particles likely reflect summer-winter deposition.

Although the Bering Sea was a source of ventilated intermediate water during deglaciation [Itaki et al., 2009], well-ventilated water was restricted to the upper intermediate layer [200–500 m] during the BA [Cook et al., 2005; Itaki et al., 2012; Jaccard and Galbraith, 2013]. The lower intermediate layer (500–1000 m) was occupied by an oxygen-poor water mass due to reduced vertical ventilation and/or increasing organic matter supply [Khim et al., 2010; Rella et al., 2012], which was also shown by the well-preserved lamina layer within the interval. Under the warmer conditions prevalent during the BA, high diatom production was reflected in increased abundances of sea-ice indicator diatom taxa (Figures 2c–2e). The relative abundance of genus Fragilariopsis suggests that site PC-23A in the NCS was covered with seasonal sea ice for around 4–8 months during the BA [Caisse et al., 2010]. Fragilariopsis cylindrus became the dominant taxon under the polynyas and/or ice-edge bloom during the spring ice melt [von Quillfeldt, 1997, 2000]. Extensive polynyas likely developed on the NCS of the Bering Sea during this period, and they appeared to form in response to increased cold offshore direct wind similar to the glacial periods [Horikawa et al., 2010; Lam et al., 2013]. However, enhanced surface freshening due to freshwater input from glacial melt during the BA might not produce the dense water capable of reaching lower intermediate depth. Then, well-ventilated water made by the extensive polynyas was supplied into the upper intermediate depth.
were the dominant sea-ice diatom taxa in core PC-23A during the BA, occur frequently under sea ice and were likely related to timing of the annual spring sea-ice retreat. Relative abundances in years in which there were low total diatom flux showed that distinct peaks occurred every 11 years (Figures 4a and 4b), clearly indicating an 11 year periodicity of primary productivity. Fluxes of all major diatom taxa also exhibited parallel timing of peaks (Figure 4). Accordingly, it is possible that these diatom flux changes were dependent on the nutrient concentration and/or nutrient-utilization efficiency in the sea surface. Large amounts of terrestrial nutrients were released into the Bering Sea through the massive runoff of glacial meltwater discharge during the BA [Itaki et al., 2009; Khim et al., 2010], and the nutrient-utilization efficiency in the surface layer increased as a result of the intensified halocline and high light condition [Nakatsuka et al., 1995; Brunelle et al., 2007; Lam et al., 2013]. At present, freshwater discharge during May from the Yukon River in Alaska shows highly interannual fluctuations, with large discharge of freshwater tending to occur in correspondence of solar irradiance maxima, except for around 1995 [Ge et al., 2013]. Thus, the 11-year diatom flux cycle observed during the BA was probably related to changes in freshwater discharge during spring. The radiolarian Cycladophora davisiana also showed an 11-year cycle, and these peaks occurred simultaneously with diatom flux peaks (Figures 4h and 4i). This coincidence is attributed to the fresh meltwater input in the spring under the solar irradiance maximum which likely influenced the production rate of intermediate water in the following winter.

Peaks in the relative abundance of Thalassiosira hyalina and Neodenticula seminae coincided with those in total diatom flux (Figures 4b, 4e, and 4g). Even other sea ice-related and spring productivity diatoms showed high relative abundances in years in which there were low total diatom fluxes (Figures 4c, 4d, and 4f). These changes were likely related to timing of the annual spring sea-ice retreat. F. cylindrus, F. oceanica, and T. hyalina, which were the dominant sea-ice diatom taxa in core PC-23A during the BA, occur frequently under sea ice and polynyas [von Quillfeldt, 1997, 2000]. However, although high relative abundance of the genus Fragilariopsis was reported soon after sea-ice retreat (March–April) in the southern Bering Sea, T. hyalina became the principal taxon under the remaining meltwater in May [Taniguchi et al., 1976; Schandelmeier and Alexander, 1981]. Moreover, N. seminae is an open ocean species with a peak in relative abundance during May and June [Takahashi et al., 2002].

In the Bering Sea, the characteristics of spring blooms are determined by a combination of the timing of sea-ice retreat involving a certain degree of surface water stratification and increased solar irradiance. Over the annual cycle, when sea-ice retreat occurs earlier than usual, insufficient light is not able to support a large ice-edge bloom, and the resulting excess surface nutrients are consumed instead by the late spring open-ocean bloom.
Figure 4. (a) Temporal variation in dark lamina thickness, (b) total diatom flux, (c) Fragilariopsis oceanica, (d) Fragilariopsis cylindrus, (e) Thalassiosira hyalina, (f) Chaetoceros spp. resting spore, (g) Neodenticula seminae, (h) total radiolarian flux, and (i) Cycladophora davisiana. Solid lines indicate fluxes, and dashed lines indicate relative abundance of diatoms and radiolarians. The interval between 390 and 410 cm depths of core PC-23A represents 110 years. Vertical light gray lines mark the layers of high total diatom fluxes.
[Hunt et al., 2002]. Accordingly, a maximum primary production on the NCS, representing a large open-ocean bloom, is commonly associated with an early sea-ice retreat. The sea-ice distribution is strongly affected by the strength of the AL pressure system [Niebauer, 1998], which is closely related to the Arctic Oscillation (AO) and PDO [Overland et al., 1999; Mantua and Hare, 2002]. In fact, the AO seems to modulate the strength and/or location of the AL, as in over one-third of the winters since 1900 [Overland et al., 1999; Mantua and Hare, 2002]. Variations in surface pressure and temperature at the solar minimum follow the negative phase of the AO [Ineson et al., 2011]. Thus, the 11-year solar cycle seems to control the primary production in the Bering Sea through AO. In fact, the change of the Yukon River discharge into the Bering Strait also has the positive relationship with the AO phase [Déry and Wood, 2005]. AO affected the primary production of the NCS via both of timing of sea-ice retreat and freshwater discharge.

Significant periodicity close to the 11-year band was limited and appeared discontinuously in the laminated layer of core PC-23A, whereas other periodicities were recognized throughout the laminated layer (Figure 3). Such occasionally prominent 11-year cycle modulating the phase of pressure patterns as decadal ENSO and/or PDO was reported from the other mid-latitude area. Prominent 11-year cycles of diatom data in the Effingham Inlet (Northeast Pacific) sedimentary record were modulated by the PDO and/or strong ENSO phases throughout the coastal upwelling and cloud cover changes [Patterson et al., 2013]. At present, the surface solar radiation in the Bering Sea is strongly regulated by both PDO phase and further ENSO variability through the cloud cover change [Chiacchio et al., 2010]. These phenomena seem to indicate that the effect of the 11-year solar irradiance cycle on the ecosystem might be regulated by the pressure patterns of PDO and/or ENSO, because the variation of the cloud cover modulated the surface solar radiation. Discontinuous 11-year cycle and occasional high diatom peaks of core PC-23A may be associated with this regulation.

4. Summary

An 11 year cycle of diatom and radiolarian flux peaks was identified from the laminated interval of the BA in the Bering Sea, which was closely related to the solar irradiance cycle. Solar irradiance variations have influenced the ecosystem and the production rate of upper intermediate water through the massive runoff of glacial meltwater discharge and the timing change of the spring sea-ice retreat. Because the surface solar radiation varied by the extent of cloud cover, 11-year solar irradiance cycle might be modulated by the pressure patterns of PDO and/or ENSO.

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