Centennial to millennial climate variability in the far northwestern Pacific (off Kamchatka) and its linkage to East Asian monsoon and North Atlantic from the Last Glacial Maximum to the Early Holocene

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Abstract

High resolution reconstructions based on productivity proxies and magnetic properties measured from sediment core 41-2 (off Kamchatka), reveal prevailing centennial -millennial productivity/climate variability in the northwestern (NW) Pacific from the Last Glacial Maximum (LGM) to the Early Holocene (EH). The age model of core 41-2 is established by AMS ^{14}C dating using foraminifera shells and by correlating the productivity cycles and relative paleomagnetic intensity records with those of well-dated nearby core SO201-12KL. Our results show a pronounced feature of centennial -millennial productivity/climate cycles of the NW Pacific had occurred synchronicity with the summer East Asian Monsoon (EAM) at sub-interstadial scale during the LGM (3 cycles), Heinrich Event 1(3 cycles), Bølling/Allerød warming (4 cycles), and over the EH (3 cycles). Our comparison of the centennial-millennial variability to the Antarctic EDML (EPICA Dronning Maud Land) ice core suggests a “push” effect of Southern hemisphere temperature gradients on the summer EAM intensifications.

Besides the linkages of NW Pacific high productivity and summer EAM, we observed that five low productivity cycles during EH are nearly synchronous with cooling in Greenland, with weakening of the summer EAM, and with decreases in solar irradiance. We propose that such centennial-millennial productivity/climate variability in the NW Pacific associated with sub-interstadials/stadials in the EAM from the LGM to EH are a persistent regional features, synchronous with the Greenland/NorthAtlantic short-term changes. We speculate that such climate synchronicity was also forced by changes in Atlantic meridional overturning circulation coupled with Intertropical Convergence Zone shifting and the northern westerly jets reorganization.

1. Introduction

Model simulations and proxy-based interpretations led to contradictory results concerning the millennial environmental variability in the northwestern (NW) Pacific and its underlying mechanisms during the last deglaciation. These model and proxy studies suggested either in-phase relationships of deglacial variability between the North (N) Atlantic and N Pacific (Caissie et al., 2010; Chikamoto et al., 2012; Kienast and McKay, 2001; Seki et al., 2002) or out-of-phase responses (Gebhardt et al., 2008; Okazaki et al., 2010; Sarnthein et al., 2006). The in-phase relationship has been attributed to rapid atmospheric teleconnection in the N hemisphere on the decadal time scale (Max et al., 2012). The winter Arctic Oscillation, which resembles the North Atlantic Oscillation, influences directly the surface air temperature and sea level pressure over the region northwards of 35ºN in East Asia; in turn, Siberian High significantly influences on the East Asia Winter Monsoon (Wu and Wang, 2002).The out-of-phase response, however, was proposed to be driven by a seesaw mechanism, with oceanic readjustments between the Atlantic meridional overturning circulation (AMOC) and Pacific meridional overturning circulation (Saenko et al., 2004). Recent studies on high-resolution and precisely-dated sediment cores from the subarctic NW Pacific, the Sea of Okhotsk, and the western Bering Sea show a deglacial sea surface temperature (SST) evolution similar to the northeastern (NE) Pacific and to the N

Atlantic and Greenland temperature variability (Max et al., 2012). The studies suggest a close linkage to deglacial variations in AMOC associated with rapid atmospheric teleconnection, which were responsible for a quasi-synchronous SST development between the N Atlantic and N Pacific during the last deglaciation. On the basis of high resolution X-ray fluorescence (XRF) and sediment color reflectance studies on western Bering Sea cores Riethdorf et al. (2013) further suggest a close linkage between millennial-scale productivity changes to the Dansgaard–Oeschger variability were registered in the North Greenland Ice Core Project (NGRIP) ice core, which had been interpreted to support the atmospheric coupling mechanism. A study comparing the subarctic N Pacific dust record to dust content in the NGRIP ice core also shows synchronicity of the timing of abrupt millennial changes during the last 27 ka (Serno et al., 2015). While a recent study by Praetorius and Mix (2014) based on multidecadal-resolution foraminiferal oxygen isotope records from the Gulf of Alaska reveals a synchronicity of rapid climate shifts between the N Atlantic/Greenland (NGRIP core record) and the NE Pacific between 15.5 to 11 ka. During the Holocene and Heinrich Event (HE) 1, inverse relationships between the Atlantic/Pacific are suggested in this paper, while the short-term variability is either not sufficiently resolved or decoupled.

All the instances indicate that a lack of high resolution proxy records in the NW Pacific prohibits precise assessments of any possible climatic teleconnection mechanisms across the basins. Although abrupt centennial-millennial precipitation anomalies over the Last Glacial Maximum (LGM) to the Holocene have been reported in cave sediment δ^{18}O records of the East Asian monsoon (EAM) (Dykoski et al., 2005; Wang et al., 2001, 2005, 2008; Yuan et al., 2004), the timing and the trend of variability of the Early Holocene (EH) regional climate changes are still controversial. In particular, though the EH climate has started from a strong warming in most cases, a Hani peat δ^{18}O record from northeastern China instead suggest cooling events which are primarily superimposed on a Holocene long-term warming trend (Hong et al., 2009).

Here we present the high resolution results of a suite of productivity proxies, magnetic properties, and lithological changes from the NW Pacific sediment core LV 63-41-2 (hereafter, 41-2) (off Kamchatka) that reveal a sequence of centennial-millennial climate/productivity variability over 20 ka to 8 ka. An age model of this core was constructed by AMS ^{14}C dating and by correlating the productivity cycles and relative paleomagnetic intensity (RPI) variability with ones of the well-dated nearby core SO-201-12KL(hereafter, 12KL) (Max et al., 2012, 2014). With our methodologically robust age controls, we are able to infer a tight linkage between the centennial-millennial productivity variability in the NW Pacific and the sub-interstadial summer EAM intensifications expressed in cave sediment $\delta^{18}O$ records. Our results have enabled us to investigate further any mechanisms controlling the in-phase relationships of the centennial-millennial variability in the NW Pacific/EAM with those underlying the Greenland/N Atlantic and Antarctic climate changes during the LGM – HE 1 – Bølling/Allerød (B/A) – Younger Dryas (YD) – EH (~20-8 ka).

2 Materials and methods

2.1 Coarse fraction measurement

Sediment core 41-2 was recovered in the NW Pacific off Kamchatka peninsula (water depth 1924 m; 52°34’N; 160°00,6’E; core length 467 cm) during the joint Russian-Chinese expedition at R/V “Akademik M.A. Lavrentyev” in 2013. Weight percentage of coarse fraction (CF) >63 μm and <2000 μm, sampled every 1 cm and separated by sieve washing, was calculated as ratios of CF weight to the weight of the dry bulk sediment. We made semi-quantity estimations of various components input in sediment CF including terrigenous and volcanogenous particles (tephra), benthic and planktonic foraminifera, diatom frustules, and radiolarians using the microscope and comparative percentage charts for estimating proportions of sedimentary components (Rothwell, 1989).The indicators of materials mainly transported to the study region by sea ice, such as CF and MS of sediments (Gorbarenko et al., 2003; Lisitzin, 2002; Sakamoto et al., 2005), are used as an ice rafted debris (IRD) proxy only for core interval with insignificant input of tephra.

2.2 Chlorin content measurement

The chlorin content of core 41-2 was measured with 1-cm resolution and with 2-cm resolution in core 12KL through the whole cores using a Shimadzu UV-1650PC spectrophotometer according to the modified method of Harris et al. (1996).

2.3 Total organic carbon (TOC), calcium carbonate, and color b* measurements

Total carbon content and inorganic carbon in core 41-2 were measured every 2 cm through the core depth by coulometry using an AN-7529 analyzer (Gorbarenko et al., 1998). TOC content was determined by calculating the difference between total carbon and inorganic carbon content. A color b* index (psychometric yellow–blue chromaticness) was measured with 1-cm resolution using a Minolta CM-2002 color reflectance spectrophotometer that generates visible-light reflectance data (400 to 700 nm wavelengths) (Harada, 2006) of the core. It has been shown that variability in color b* correlates well with the changes in biogenic opal contents in sediment cores (Nürnberg and Tiedemann, 2004).

2.4 Radiocarbon dating (AMS ^{14}C)

AMS ^{14}C-ages were measured on monospecific samples of the planktic foraminifers *Neogloboquadrina pachyderma* sinistral (*N. pachyderma* sin.) from the 125–250 µm fraction and benthic foraminifera *Epistominella pacifica,* and *Uvigerina parvocostata* from the 250–350 µm fraction of the core. The radiocarbon dating has been performed by the Dr. John Southon at the Keck Carbon Cycle AMS Facility (UCIAMS) in the Earth System Science Department of the University of California, USA. The constant reservoir age (900 ± 250 yr) of the NW Pacific surface water (Max et al., 2012) was adopted in this study to calibrate the ^{14}C ages of our samples into calendar ages for establishing consistent AMS ^{14}C chronologies of cores 41-2 and 12KL. All reservoir age corrected ^{14}C data were converted into calendar age by using Calib Rev

6.0 (Stuiver and Reimer, 1993) with the Marine13 calibration curve (Reimer et al., 2013).When using benthic foraminifera for AMS ^{14}C dating on our cores, we take the age difference of 1400 yrs between coexisting benthic and planktic foraminifera ages (Max et al., 2014).

2.5 Magnetic property measurements

Magnetic properties were measured with 2.2-cm resolution in the both cores. Volume magnetic susceptibility (MS) of these samples was measured using an AGICO MFK1-FA device. The characteristic remnant magnetization (ChRM) of the samples was measured in the same way by studying the stability of natural remanent magnetization (NRM) in the alternative magnetic fields of up to 80-100 mT on the basis of analysis of Zijderveld vector plots, using an AGICO LDA-3A device and rock-generator AGICO JR-5a (Zijderveld, 1964). The module and direction of NRM were measured on a JR-5A rock-generator after the stepwise demagnetization of reference samples by alternating magnetic fields with a vanishing amplitude (Malakhov et al., 2009). Ahysteretic remanent magnetization (ARM) was generated using an AGICO AMU-1A device and measured by the JR-5A rock-generator. Relative paleomagnetic intensity (RPI) of the studied core sediments was determined by the normalization of the ChRM after demagnetization at 20 mT by ARM (ChRM/ARM) (Tauxe, 1993). The sediment paramagnetic magnetization (PM) was measured for each sample from curves of magnetic hysteresis by a J Meter coercitive spectrometer at Kazan State University, Kazan, Russia (Enkin et al., 2007; Jasonov et al., 1998). PM was formed in marine sediments of silicate, paramagnetic iron sulphide (FeS), and fine clay minerals transported from land as an eolian dust through atmosphere circulation by westerly jets. Therefore, the sediment PM may serve as a proxy of the land aridity and/or atmosphere circulation pattern changes in response to climate changes.

2.6 XRF measurements

Core 41-2 elemental composition, given in peak area (counts per second, cps), was measured with 0.5 cm resolution using the Itrax XRF core scanner at the First Institute of Oceanography, State Oceanic Administration, China. The Itrax XRF core scanner was set at 20 s count times, 30 kV X-ray voltage, and an X-ray current of 20 mA. Though absolute elemental concentrations are not directly available from the micro-XRF measurements, the count values can be used as estimates of the relative concentrations. The count values may be influenced by the changes in the physical properties of the sediment, such as the surface roughness of the core (Röhl and Abrams, 2000). However, the grain size of the 41-2 core is rather fine and the surface has been processed to be as flat as possible to minimize any effects from changing physical properties or roughness during the scanning.

In this study, we paid attention to the scanning results for estimating biogenic Ba, Br and Si (Ba-bio, Br-bio and Si-bio respectively) contents in our sediment cores, which serve as proxies of productivity. The content of Ba-bio was estimated by subtraction of its terrigenous component (Ba-ter) from the total bulk Ba concentration in sediment (Ba-tot). The terrigenous component, in turn, was calculated from empirical regional $(Ba/Al)_{ter}$ ratios in the sediment core with the lowest Ba-tot contents:

$$\text{Ba-bio} = \text{Ba-tot} - (\text{Ba/Al})_{ter} * \text{Al} \text{ (by Goldberg et al. (2005)).}$$

Br-bio and Si-bio were calculated using the same technique.

3. Results

AMS radiocarbon data for core 41-2 are presented in Table 1. The variability of suite of productivity proxies (color b* and content of TOC, chlorin, $CaCO_3$, Ba-bio, Si-bio and Br-bio) plus magnetic properties (RPI, sediment PM and MS) are presented for core 41-2 versus depth (Fig. 2). Increased productivity at the interval ~315-230 cm according to several productivity proxies and available AMS ^{14}C data could be chronologically assigned to the B/A warming right after the termination of the last glaciation (467-315 cm) (Fig. 2). The high productivity during the B/A warming is a common feature in the far NW Pacific and its marginal seas (Galbraith et al., 2007; Gorbarenko, 1996; Gorbarenko et al., 2005; Gorbarenko and Goldberg, 2005; Keigwin, 1998; Seki et al., 2004). The interval at ~230-190 cm with a decreased trend of productivity is likely associated with the YD cooling. After this low productivity/cold climate event the high productivity/warm trend in the upper 190 cm of the core is presumably related to the Holocene warm climate condition.

In core 41-2 the time resolutions of measured chlorin content and color b*; TOC, $CaCO_3$ content and magnetic parameters (PM, MS and RPI); and Ba-bio, Br-bio, Si-bio concentration over the LGM-YD periods are nearly 30 years, 15 years and 60 years respectively. The resolution is high enough to allow us to detect centennial-millennial scale climate variability in the far NW Pacific. Presented high resolution productivity and magnetic records reveal quasi-synchronously centennial-millennial productivity cycles associated with abrupt environmental variability (Fig. 2) via mechanisms similar to established earlier regularities at the orbital-millennial scale (Broecker, 1994; Ganopolski and Rahmstorf, 2002; Sun et al., 2012). Therefore, in particular we suggest that the sharp increased productivity events demonstrate quickly response of the NW Pacific environment associated with abrupt regional warming and vice versa similar as for interstadials events in the NW Pacific and Okhotsk and Bering Seas. The rises in SST of surface water and environment amelioration in the NW Pacific and Japan, Okhotsk and Bering Seas correlated with interstadials in $\delta^{18}O$ records in NGRIP ice core (North Greenland Ice Core Project members, 2004) and Chinese cave stalagmites promote to increase in productivity at the millennial scales (Gorbarenko et al., 2005; Nagashima et al., 2011; Seki et al., 2002, 2004). Although an each used productivity proxy have own specific peculiarities in his response to climate and environmental changes, the used complex of proxies allow us to more definitely determine increased productivity events in the past. In results, presented productivity proxies and sediment paramagnetic magnetization (PM) records show that 6 short increased productivity/warmer events happened during the last glacial and 4 ones during the B/A warming (Fig. 2). During the EH we find 5 short lower productivity/colder events and 3 higher productivity/warmer events. We notice that a colder event at depth 117-122 cm with an age of ~9.12 ka (Table 1) is well-correlated with the 9.3 ka cold event in Greenland ice core records (Rasmussen et al., 2014). Moreover, a colder event identified at depth 106-109 cm of core 41-2 also links well with the 8.2 ka cold event in Greenland ice cores, a well-known chronostratigraphic marker in the Early to Middle Holocene boundary (Walker et al., 2012).

The share of tephra in sediment CF show significantly increase in upper part of core since 130 cm (Fig. 2); therefore, below this interval, CF and MS variability was mostly responded to IRD input. The CF and MS records, controlled by tephra share in CF, indicate high IRD input in sediment of lower part of core and strong decrease to top in interval 325-315 cm. MS and CF records also show some increase of IRD at the interval of 230-200 cm related to the YD (Fig. 2).

Available productivity proxies (chlorin, Ca/Ti ratio, color b*) plus magnetic properties RPI and PM for core 12KL were compared with results of core 41-2 versus cores depth (Fig. 3). For simplicity, a suite of productivity proxies for core 41-2 (color b* and chlorin, TOC, CaCO3, Ba-bio, Br-bio and Si-bio content and PM record) was replaced with the calculated stack of productivity proxies. The color b* index and Ca/Ti ratios (analog of $CaCO_3$ content) of core 12KL were extracted from Max et al. (2012, 2014) available on PANGAEA Data Publisher for Earth & Environmental Science (http://dx.doi.org/10.1594/PANGAEA.830222).

4. Age model

An age model of core 41-2 was constructed using all available AMS ^{14}C dating, with more age control points identified by correlating the centennial-millennial events of the productivity proxies, RPI and PM of studied core with those of the well-dated nearby core 12KL (Max et al., 2012, 2014) (Fig. 3). The age tuning used in this study assumes a synchronous pattern of productivity, RPI and PM variability in the far NW Pacific since the last glacial especially for close located cores. With this conception of age model developments, the centennial-millennial variability of productivity proxies with increased productivity events, relative paleointensity (RPI) of Earth magnetic field and paramagnetic magnetization (PM) identified in cores 41-2 and 12KL have to be closely matched in the both cores over the last glaciation, the B/A warming to the EH (Fig. 3). We noticed that the available for core 12KL the Tiedemann/Max age model 2

(Max et al., 2012, 2014) was based on the AMS ^{14}C data and correlation of color b* index with the NGRIP δ^{18}O curve (PANGAEA Data Publisher). By adopting an age model of core 41-2, AMS ^{14}C dating of core 12KL of Max et al. (2012, 2014) were transferred successfully to core 41-2 according to correlation of related increased productivity events and RPI values (Fig. 3). Color b* minimum in core 12KL at depth of 706 cm, which R. Tiedemann/L. Max correlates with minimum in NGRIP δ^{18}O curve at 16.16 ka, is also clearly correlate with color b* minimum of core 41-2 at depth of 348 cm (Fig. 3). All correlated AMS ^{14}C key points are also well-matched between measured RPI curves of both cores (Fig. 3). Core 41-2 AMS ^{14}C data of 9.45 ka, 10.6 ka , 14.39 ka and 14.61 ka at depth 127.5 cm, 156 cm, 298 cm and 306 cm respectively are rather closed to nearby projected ^{14}C datum from core 12 KL (Table 2) and confirm validity of this age projection. But here we prefer to used ^{14}C data of core 12KL because this core have higher sedimentation rate and planktonic foraminifera for these measurements were picked from intervals with highest Ca content that significant decrease a bioturbation effect.

A close time correlation of these NW Pacific productivity increasing/environmental amelioration events with sub-interstadials in summer EAM become apparent after projection of the radiocarbon datum of both cores on the absolute U-Th dated δ^{18}O record of the China caves stalagmites (Wang et al., 2008) over the 20-8 ka (Fig. 3). Such inferred synchronicity of NE Pacific productivity abrupt events and EAM sub-interstadials was used for further fine age model construction by tuning of increased productivity events with related sub-interstadials of δ^{18}O Chinese stalagmites for depth beyond the projected AMS ^{14}C data (Fig. 3; Table 2).

5. Discussion

With the constructed age model of core 41-2 different kinds of productivity proxies and magnetic results combined with some of them for AMS ^{14}C dated core 12KL (Max et al., 2012, 2014) reveal sequence of noticeable centennial-millennial scale productivity cycles in the far NW Pacific occurred in-phase with Chinese sub-interstadials (CsI) associated with stronger summer EAM (Wang et al., 2008) over the 21–8 ka (Fig. 4). These linkages suggest the centennial-millennial increase productivity events in the far NW Pacific were likely associated with shifts to warmer climate and/or higher nutrient conditions in surface water synchronously with CsI of the summer EAM. Presented high resolution records show clearly that three centennial-millennial increase productivity/environment amelioration events correlated with (CsI) had occurred during the LGM, three CsIs during the HE1, four CsIs during the B/A warming, and three CsIs during the EH (Fig. 4) (Table 3). The possible mechanisms responsible for the in-phase relationships or the synchronicity of the centennial-millennial scale events between the NW Pacific productivity and summer EAM are discussed and proposed below.

5.1. N-S hemispheres climatic linkages of centennial-millennial climate/environment changes over the LGM - HE 1- B/A warming

Identifying any linkages of centennial–millennial climate changes in the Northern Hemisphere between the NW Pacific, EAM, and N Atlantic/Greenland and the climate changes recorded in Antarctic ice core responsible for the Southern Hemisphere is important to us, to deepen understanding of the mechanisms responsible for the timing and spatial propagation patterns that resulted from the abrupt variability in the global climate and environmental system. In order to test the linkages, we demonstrate here the correlation among the highly resolved U-Th dated δ^{18}O records of the composite Hulu and Dongge caves sediments (Dykoski et al., 2005; Wang et al., 2008), the ~20-year averaged resolution δ^{18}O and Ca^{2+} content records of the GISP2 and NGRIP with 5 point running mean on the annual-layer counted GICC05 age scale (Rasmussen et al., 2014), the δ^{18}O record of the EPICA Dronning Maud Land (EDML) ice core from Antarctica (EPICA Community Members, 2006) on the methane synchronized timescale with the NGRIP core, and the Siberian climate calculated from pollen results of the Lake Baikal region (Bezrukova et al., 2011) over the past 25 ka (Fig. 5). The Ca^{2+} content in the Greenland ice cores serves as a proxy for dust mobilization on the land and transferring in the high latitudes of the N Hemisphere by atmosphere governed by climate and atmosphere circulation changes

(Sun et al., 2012). It has been suggested that the nearly synchronous ice core δ^{18}O and Ca^{2+} millennial scale changes reflect the shifting of Greenland atmospheric dust loading which is closely linked with the atmospheric circulation and climate changes in the high-latitude of N Hemisphere, where EAM plays important role (Ruth et al., 2007). Initially the persistent millennial scale changes shown in the Greenland ice core records were defined as interstadials (GI) and stadial (GS) (Johnsen et al., 1992), but have been refined by INTIMATE stratigraphy studies which introduced the subdivision of the GI-1 into sub-interstadials GI-1a to GI-1e. Furthermore, the GS-2.1 was subdivided into sub-Stadial GS-2.1a (over the HE 1), GS-2.1b (LGM), and GS-2.1c (Björck et al., 1998; Rasmussen et al., 2014) (Fig. 5).

Established in the studied off Kamchatka cores the NW Pacific centennial-millennial productivity/environment cycles with stack of productivity and color b* on the base of its chronology (Table 2) were put on the N-S hemispheres climate variability over the LGM-HE1-B/A (Fig. 5). In addition to established in the NW Pacific studied cores the six centennial-millennial productivity/environment cycles over the LGM-HE1, we suggest that coeval with CsIs an additional three abrupt events likely took place in the NW Pacific over the interval of 25-20 ka (Fig. 5). Therefore, we found the three EAM/NW Pacific sub-interstadials which occurred within GS-2.1a (namely CsI-GS2.1-1, CsI-GS2.1-2 and CsI-GS2.1-3), four CsIs within GS-2.1b (CsI-GS2.1-4 to CsI-GS2.1-7), and two within GS-2.1c (CsI-GS2.1-8 and CsI-GS2.1-9) (Fig. 5).

It also has been noted that the some δ^{18}O differences in coeval δ^{18}O values between Summit and NGRIP ice cores over the LGM-HE1 period, were likely governed by changes in the N American Ice Sheet volume and N Atlantic sea-ice extent, that results in the changes of meridional gradients in the Greenland ice δ^{18}O (Seierstad et al., 2014). Probably, such δ^{18}O differences in the Summit - NGRIP δ^{18}O values may explain that correlation of the EAM/NW Pacific sub-interstadials with Greenland sub-interstadials recorded in δ^{18}O and Ca^{2+} of the GISP2 and of the NGRIP over the HE1 (GS-2.1a) was less pronounce then ones during LGM. On the basis of the high-resolution NGRIP core investigation (less one year) over 15-11 ka, Steffensen et al. (2008) have suggested that at the beginning of the GI, the initial northern shift of the Intertropical Convergence Zone (ITCZ), identified in a sharp decrease of dust within a 1-3 year interval, triggered an abrupt shift of Northern Hemisphere atmospheric circulation. Such circulation pattern changes forced a more gradual change (over 50 years) of the Greenland air temperature associated with high latitude atmosphere circulation and westerly jets ways reorganization. Evidence from a loess grain size record in NW Chinese Loess Plateau (Sun et al., 2012), infer the linkage of the changes in EAM strength and Greenland temperature over the past 60 ka, and suggests a common force driving both changes (Sun et al., 2012). Using a coupled climate model simulation Sun et al. (2011) investigated the effect of a slow-down of AMOC on the monsoon system and found that a stronger winter EAM accompanied with a reduction in summer monsoon precipitation over East Asia supplies more dust to the Chinese Loess Plateau and likely into the NW Pacific. This study indicates that AMOC is a driver of abrupt change in EAM system, with the northern westerlies as the transmitting mechanism from the N Atlantic to the Asian monsoon regions. Other evidences of teleconnection between the EAM and N Atlantic on a millennial timescale come from the investigation of the Japan Sea sediments. Nagashima et al. (2011) infer that temporal changes in the provenance of eolian dust in Japan Sea sediments reflect changes in the westerly jet path over East Asia, happened in-phase with Dansgaard-Oeschger cycles.

EPICA community members (2006) show that methane synchronization of the EDML and the NGRIP δ^{18}O records reveal one-to-one alignment of each Antarctic warming with a corresponding stadial in Greenland ice cores, implying a mechanism of bipolar seesaw on these time scales. Changes in the heat and freshwater flux were connected to the AMOC and a stronger AMOC leads to increased transport of heat from the Southern Ocean heat reservoir. In results of EAM investigations (Wang et al., 2001) have suggested that between 11,000 and 30,000 yr BP the Chinese interstadials (CI) recorded in δ^{18}O calcite of cave stalagmites had happened apparently synchronously with the GIs and therefore CIs were, likely, related to Antarctica cold events also. For example, smoothed warmer condition in the Antarctic at 23.6-24.3ka was synchronous with abrupt climate cooling and increases in dust content in the Greenland ice cores NGRIP and GISP2, coeval to HE2 of the N Atlantic and in-phase with summer EAM weakening (GS/CS-3.1) (Fig. 5). Subsequent Antarctica cooling since 23.4 ka was accompanied by Greenland warming with two sharp interstadials GI-2.2 and GI-2.1 with nomenclature of Rasmussen et al. (2014) and China interstadial CI-2 coeval with sub-interstadial CsI-GS2.1-9 associated with summer EAM intensification (Fig. 5). Over the LGM-HE1 period, the most of sub-interstadials in the N hemisphere had occurred during abrupt Antarctica temperature decrease as well (Fig. 5).

It also has been suggested that a monsoon intensity index including the EAM was controlled not only by Northern Hemisphere temperature (‘pull’ on the monsoon, which is more intense during boreal warm periods), but also by the pole-to-equator temperature gradient in the Southern Hemisphere (‘push’ on the monsoon which is more intense during the boreal cold periods) that leads to enhanced boreal summer monsoon intensity and its northward propagation (Rohling et al., 2009; Rossignol-Strick, 1985; Xue et al., 2004). Since the summer EAM transports heat and moisture from the West Pacific Warm Pool (WPWP) across the equator and to higher northern latitudes (Wang et al., 2001), the temperature gradient in the Southern Hemisphere “pushes” the summer EAM intensity by means of its influence on the latitudinal/longitudinal migrations or expansion/contraction of the WPWP. This also explains the difference of responses of EAM and Greenland interstadials and sub-interstadials, because the migration of the WPWP may have responded more slowly than the atmospheric changes. All the above interpretations are mostly consistent with variability between the EAM and Antarctica temperature (Fig. 5), when cooling in Antarctica promote to increase summer EAM. The δ^{18}O record of Chinese EAM changes were more gradual then in the δ^{18}O of Greenland ice cores, and the amplitude changes of the EAM are more similar to the Antarctic air temperature changes (Fig. 5).

During B/A warming when Antarctic temperature was decreased, four EAM sub-interstadials (CsI-GI1-a – CsI-GI1-e) coeval with established NW Pacific centennial-millennial productivity/environment cycles have varied in-phase with Greenland sub-interstadials (Björck et al., 1998) as well (Fig. 5). Recent high-resolution investigations on Bering Sea sediment cores from the "Bering Green Belt" (Kuehn et al., 2014) have documented four well-dated laminated sediment layers during the B/A warming-beginning of Holocene, with three of them within the B/A. The synchronicity of Bering Sea laminated sediment layers with the Greenland sub-interstadial during B/A warming provides one more piece of evidence supporting the close atmospheric teleconnection between the N Pacific, EAM and N Atlantic.

Inferred a tight in-phase linkages between the NW Pacific centennial-millennial productivity/environment cycles and the summer EAM intensity sub-interstadials over GS-2.1–GI-1 (Figs. 4 and 5) allow us to suggest that the centennial-millennial changes in the NW Pacific and EAM have been forced by similar/or may be less pronounced mechanisms as for interstadials by the shifting of the ITCZ with reorganization of the N Hemisphere atmospheric circulation and the northern westerly jets.

5.2 The EH

During EH the presented records demonstrate a series of abrupt increase/decrease productivity events in the NW Pacific correlated with sub-interstadials (CsI-EH-1, CsI-EH-2, CsI-EH-3)/sub-stadials (CsS-EH-1, CsS-EH-2, CsS-EH-3, CsS-EH-4, CsS-EH-5) of the $\delta^{18}O$ records of Dongge and Hulu caves (Dykoski et al., 2005; Wang et al., 2008) and Greenland ice core (North Greenland Ice Core Project members, 2004) (Figs. 4, 5; Table 3). Visual comparison with the EAM and Greenland ice cores records show synchronicity (positive correlation) of the increased productivity events in the NW Pacific with the Greenland abrupt warmer climate cycles and summer EAM intensity events and vice versa over the EH as well (Figs. 4 and 5). The dated pollen reconstructed the vegetation /climate variability of the southeastern Siberia (Lake Baikal region) (Bezrukova et al., 2011) demonstrated nearly the same type of the centennial-millennial climate variability that confirms their common patterns of changes in the North Hemisphere (N Atlantic, NW Pacific, EAM) over the EH (Fig. 5). Well-dated high resolution lithological and geochemical results from the Yanchi playa (NE China) also clearly show a separation of three sharp cooling events at 8.2 ka, 9.9-10.1 ka, and 11.0-11.2 ka, synchronous with the cooling shown in the Greenland ice core records (Yu et al., 2006). Yu et al. (2006) explain that correlation by linkages of the tropical Pacific and the N Atlantic. Moreover, high resolution geochemical and lithological analyses of the Arolik Lake sediments (southwestern Alaska) provide evidence that centennial-scale climate shifts during the Holocene were similar between the subpolar regions of the N Atlantic and N Pacific (Hu et al., 2003).

These regional climate shifts had also occurred coherent with the periodicities of solar activity and production of the cosmogenic nuclides ^{14}C and ^{10}Be. The production rates of these cosmogenic nuclides are negatively correlated with total solar irradiance through the strength of magnetic fields embedded into solar winds speed. Small variations in solar irradiance could be responsible for pronounced changes in northern high-latitude climate and environments (Hu et al., 2003). Nearly synchronicity in the changes of the centennial-millennial productivity and magnetic proxies obtained in the two studied cores with the $\delta^{18}O$ records of Chinese cave speleotherm, the Greenland ice cores, and with the nuclide ^{14}C production during the EH (Figs. 4, 5) imply that variability of the NW Pacific climate and environmental condition has been tightly related with EAM and N Atlantic/Greenland climate changes by atmospheric coupling mechanisms over the studied period of 20-8 ka. In summary, ~~our~~ presented results indicates a tight linkage and coherent, persistent pattern of the centennial-millennial scale climate changes in the N Hemisphere over the LGM-EH which may be serve as template in high resolution paleoceanography and sediment stratigraphy of the moderate-high latitudes.

The uncertainties in the chronologies of the Greenland and EAM records is very small (< 2 %) thus suggest statistic estimation of their correlation during the last 25 ka. Cross correlation (CC) of the EAM intensity and Greenland climate variability calculated by correlation of $\delta^{18}O$

values between the calcite of Chinese stalagmites responsible for EAM variability (Wang et al., 2008) and NGRIP and GISP 2 ice cores responsible for the Greenland climate (Rasmussen et al., 2014) by moving windows at 1000, 2000 and 3000 years show their more significant synchronization (correlation ranging from -0.6 to -0.9) during period of 16.5-8.5 ka (Fig. 6). During earlier (25-16.5 ka) and later (8.5-1 ka) periods there are differences in CC between the EAM-NGRIP and the EAM-GISP2. But both CC during these periods demonstrate occurrence of weak synchronization/or absence of significant correlation (within ranging at ±0.25) (Fig. 6). Significant synchronization was indicated also by CC between EAM-NGRIP during the Middle-Late Holocene. More discrepancies in both CC were observed over 19.5-16.5 ka, that may be explained by errors in ages measurements and/or by different atmospheric teleconnection between the EAM and the GISP2/NGRIP cores due to its differ locations in the Greenland. So the statistics imply that the seesaw mechanism between the EAM/NW Pacific and the Greenland/N Atlantic during 25-1 ka is not effective, however being in line with empiric results of the EAM and the Greenland teleconnection by shifting of the westerly jet path (Nagashima et al., 2011; Sun et al., 2012).

5.3 NW Pacific productivity trends over the LGM-HE 1

Beside of the centennial -millennial productivity/environmental cycles, we find common NW Pacific productivity trends over the LGM and HE1 with some differences in other types of productivity proxies. According to the sharp increase of Antarctica temperature, dust content in the Greenland ice cores and significant decrease in the summer EAM we put boundary of LGM/HE1 on nearly the 17.8 ka (Fig. 5). This age is a little earlier to that being placed at ~17.5 ka which is a timing for the beginning of catastrophic iceberg discharges in the HE1, but nearly coincides with the abrupt increase of the $^{231}Pa/^{230}Th$ ratio in the N Atlantic core OCE326-GGC5, which marks the beginning of the collapse of AMOC (McManus et al., 2004).

During the LGM most of productivity proxies demonstrate minimum primary production in the far NW Pacific without definite trends, although the Si-bio of core 41-2 and color b* of core 12KL show even small negative trend through time (Fig. 4). Severe environmental condition in the central Asia inferred from vegetation reconstruction (Bezrukova et al., 2011) (Fig. 5) promote to increase in winter sea ice covering consistently with high IRD accumulation in studied region inferred from CF and MS records (Fig. 4) that hamper productivity. It is in concord with early established minimum of productivity in the NW Pacific due to strong stratification prevented nutrients supply for supporting productivity in surface waters (Gebhardt et al., 2008).

Since 17.8 up to 15.3 ka, the core 41-2 productivity proxies such as Ba-bio, Br-bio, TOC and chlorin associated with production of calcareous phytoplankton (mostly coccolithophores), show significant increased trends simultaneous to gradual Antarctic warming accompanied by strongly diminished of AMOC (McManus et al., 2004). The diminished AMOC resulted in a major cooling of the N Atlantic surface water and, most likely, reduced water evaporation in the N Atlantic and therefore Atlantic–Pacific moisture transport. This condition facilitates a reduction of precipitation and hence an overall increase of surface water salinity and decrease of surface stratification in the N Pacific. Moreover, this condition promotes an intensification of the intermediate water ventilation in the N Pacific and therefore nutrient supply into euphotic layer. The observed trends of productivity proxies are in concord with strong intensification of the intermediate depth water ventilation in the N Pacific during HE1 (Max et al., 2014) based on the δ^{13}C foraminifera data from the intermediate water and radiocarbon-derived ventilation ages. However, rather constant $CaCO_3$ values in both cores (water depth 1924-2145 m) during LGM-HE1 do not indicate the changes of the water ventilation at these depths in the N Pacific over that time span because carbonate concentration in the sediment strongly defined by the ventilation (Yu et al., 2014). While the productivity proxies Si-bio and color b*, associated with siliceous phytoplankton production (mostly diatoms), do not show significant trends since HE1 to ~15.3 ka. The strong sea ice effect with high IRD input up to 15.3 ka, shown by CF and MS records, (Figs. 2; 4) was more significant in our studied area and likely overwhelm the productions of diatom algae for coccolithophores due to a large spring-early summer surface water stratification during seasonal sea ice melting.

A sharp increase of NW Pacific primary production and rise of diatom production since ~15.3 ka indicated by most productivity proxies and Si-bio and color b* records with culmination at sub-interstadial GI1-e of B/A warming was, likely, induced by decrease of sea ice influence and its spring melting favoring for weakening of surface stratification (Figs. 4 and 2). The timing of decrease in the sea ice cover since ~15.3 ka is consistent with the surface water warming (Max et al., 2012) and with the central Asia vegetation/environment amelioration inferred by Bezrukova et al. (2011) by pollen reconstructions (Fig. 5). Such pattern of the productivity changes in the N Pacific and the Bering Sea during glacial/interglacial transition was observed in other cores (Caissie et al., 2010; Galbraith et al., 2007; Gebhardt et al., 2008; Keigwin, 1998) and was, likely, a persistent feature for the N Pacific and its realm forced by resumption of the AMOC at the B/A beginning coeval with the cooling in the Antarctica (Fig. 5). In the Okhotsk Sea, being strongly intruded in the NE Asia continent, the beginning of the diatom production and accumulation of the diatomaceous sediments had occurred only since the Middle Holocene (5-6 kyr BP) due to the later diminish of sea-ice cover and later breakdown of spring/early summer surface water stratification (Gorbarenko et al., 2014).

6. Conclusion

This study presents high resolution records of a suite of productivity proxies (TOC, $CaCO_3$, chlorin, color b*, Ba-bio, Br-bio, Si-bio), sediment lithological (CF) and magnetic properties (PM, MS and RPI) from a sediment core 41-2 taken from the NW Pacific (East Kamchatka slope). Presented results reveal a sequence of 13 centennial-millennial scale regional productivity increased/environment amelioration events over the LGM-EH (20-8 ka) in the far NW Pacific.

The age model of core 41-2 was constructed by using available AMS ^{14}C dating, with more age control points identified by correlating the centennial-millennial events of the productivity proxies, RPI and PM of studied core with those of the well-dated nearby core 12KL (Max et al., 2012, 2014). Thus all available AMS ^{14}C dating of core 12KL were transferred successfully to core 41-2. Based on projected radiocarbon datum of both cores on the $\delta^{18}O$ record of the Chinese caves stalagmites (Wang et al., 2008) the close time correlation of NW Pacific productivity events with sub-interstadials in summer EAM over the 20-8 ka was used for further fine age model construction. In results, established three NW Pacific abrupt productivity increase events are tightly linked to CsIs during the LGM (20-17.8 ka), three during HE1 (17.8-14.7 ka), and four during B/A warming and three over the EH.

Presented reconstruction suggests that the NW Pacific centennial-millennial productivity increase/summer EAM intensified events are positively correlate with Greenland warming, indicating a tight atmospheric teleconnection between the N Pacific and the N Atlantic, most likely by ITCZ shifting and reorganization of the northern westerlies and echoes the similar mechanism proposed in previous studies for the N hemisphere interstadials and stadials (Caissie et al., 2010; Kienast and McKay, 2001; Max et al., 2012; Riethdorf et al., 2013). Especially highlighted here is that our comparison to $\delta^{18}O$ records of the EDML ice core and of the Chinese stalagmites on the centennial-millennial time scale over glacial and deglaciation suggests a Southern Hemisphere “push” effect on the boreal summer EAM propagation.

During the LGM our results indicate productivity minima that are consistent with previous observations in the NW Pacific, severe vegetation/climate condition in the central Asia (Bezrukova et al., 2011) and therefore strong regional sea ice covering are consistent with the hypothesis that proposes a strong stratification prevented nutrients supply for supporting productivity in surface waters (Gebhardt et al., 2008). The productivity proxies associated with calcareous phytoplankton productions show increased trends since 17.8 to 15.3 ka. These trends share the same structure and the rate of changes of the gradual Antarctic warming accompanied by significantly diminished AMOC (McManus et al., 2004). The cooling of the N Atlantic surface water reduced water evaporation in the N Atlantic and Atlantic–Pacific moisture transport, which in turn, facilitates the increased surface water salinity and decreases surface stratification in the N Pacific. The weakening stratification further intensifies the intermediate water ventilation in the N Pacific and nutrients supply into the euphotic layer. Especially noticed is that a sharp increase of NW Pacific primary production since nearly 15.3 ka was indicated by nearly all productivity proxies accompanied by some climate warming and decrease in sea ice covering. Subsequent a strong productivity spike of sub-interstadial GI-1e at beginning of the B/A warming is associated with a resumption of the AMOC and the further decrease of sea ice influence accompanied by rise of diatom production.

The synchronicity in changes of the NW Pacific centennial-millennial productivity events with the $\delta^{18}O$ of Chinese stalagmites calcite, Greenland ice cores and with the nuclide ^{14}C production during the EH (Figs. 4 and 5) imply that variability of the NW Pacific climate is tightly linked to summer EAM and N Atlantic/Greenland climate changes. The linkage is likely driven effectively by atmospheric coupling mechanisms forced by solar irradiance variability. Regardless what specific driving mechanisms are responsible for the linkage, the centennial-millennial and sub-stadial/interstadial productivity variability in the NW Pacific and the linkage to EAM from the LGM to EH reported here is a persistent feature of the high resolution far NW Pacific paleoceanography and sediment stratigraphy, synchronous with the Greenland/N Atlantic short-term changes.

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Figure captures

Fig. 1. Bathymetry, surface water currents and location of the cores 41-2 (star) and 12KL (cross) (Max et al., 2012) in the North Pacific. Surface currents as in (Favorite et al., 1976) with modifications. EKC–East Kamchatka Current, WKC– West Kamchatka Current.

Fig. 2. Records (from bottom to top) of the share of volcanic grains in the sediment fraction more 150 μm, weight percentages of the CF, magnetic susceptibility (MS), paramagnetic magnetization (PM), color b*; TOC, chlorin, $CaCO_3$, Ba-bio, Si-bio (opal) and Br-bio content versus core 41-2 depth. Preliminary boundaries of B/A warming, YD cooling and Holocene are shown according to total reguliarities of productivity variability in the NW Pacific, Sea of Okhotsk and Bering Sea (Galbraith et al., 2007; Gorbarenko, 1996; Gorbarenko and Goldberg, 2005; Keigwin, 1998; Seki et al., 2004) and AMS ^{14}C data (calendar ka) shown at the base.Yellow (blue) bars depict the centennial-millenial increased productivity/environmental ameloiration (cooling) events according to most productivity proxies and decreases in PM.

Fig. 3. Correlation of the increased productivity event cycles in the cores 41-2 (low panel) with ones of 12KL (middle panel) versus depth with sub-interstadials of the $\delta^{18}O$ calcite of Chinese stalagmites (Wang et al., 2008) (upper panel). Productivity cycles for cores 41-2 based on stack of productivity proxies and PM records (Fig. 2) and 12KL (Ca, chlorin, color b* and PM records) were correlated according to sychronously changes in productivity proxies, paramagnetic magnetization, magnetic relative paleomagnetic intensity (RPI) and ^{14}C AMS data of the both cores. AMS ^{14}C data of core 41-2 shown at the base. According to correlation of the productivity cycles and curves of RPI, the red lines related with key time points of core 12KL (middle panel) and the green lines with relative Chinese sub-interstadials of the $\delta^{18}O$ calcite of Chinese stalagmites (Wang et al., 2008) (upper panel) were projected into corresponded depths of core 41-2 (bottom panel). Color b* and Ca content, AMS ^{14}C data of core 12KL and its depth-age correlation with the Greenland NGRIP ice core were introduced from site http://dx.doi.org/10.1594/PANGAEA.830222. Yellow (blue) bars depict the centennial-millenial increased productivity/environmental ameloiration (cooling) events according to most productivity proxies and decreases in PM.

Fig. 4. High resolution variability of the productivity and lithologic proxies in NW Pacific (off Kamchatka) over the 21-8 ka period. CF percentages, MS, paramagnetic magnetization and color

b*, chlorin, $CaCO_3$, TOC content determined in cores 41-2 (blue lines) and 12KL (red lines) are shown from bottom to top. The NW Pacific centennial-millennial productivity cycles characterized by increase in most productivity proxies are clearly associated with the abrupt summer EAM intensification revealed in Chinese cave stalagmites called as sub-interstadial and less pronounced with short term events in the Greenland ice cores $\delta^{18}O$ records. Linear trends shown for the productivity indices over LGM and HE 1. Yellow (blue) bars depict the centennial-millenial increased productivity/environmental ameloiration (cooling) events according to most productivity proxies and decreases in PM.

Fig. 5. Compilation on N-S hemisphere milestone climate records, solar activity, NW Pacific productivity cycles and Southern Siberia environment during the last 25 ka. From bottom to top: absolutely dated $\delta^{18}O$ calcite of Chinese cave stalagmites (Dykoski et al., 2005; Wang et al., 2008) characterized EAM activity; the residual atmospheric $\Delta^{14}C$ record of around 2000-year moving average (Reimer et al., 2004) indicated solar irradiance variability; oxygen isotope EDML records after methane synchronization with North Greenland ice core (EPICA Community Members, 2006); the petrologic tracer of drift ice in N Atlantic (Bond et al., 2001); the $\delta^{18}O$ and Ca^{2+} records in the Greenland NGRIP and GISP 2 ice core indicated air temperature and dust variability on GICC05 age scale (Rasmussen et al., 2014), pollen reconstructed Southern Siberia environment changes (Lake Kotokel, Lake Baikal region) (Bezrukova et al., 2011); productivity stack for core 41-2. Yellow (blue) bars depict the centennial-millenial increased productivity/environmental ameloiration (cooling) events. NW Pacific centennial-millennial productivity cycles are accompanied by interstadial and sub-interstadial intensification of the summer EAM over 25-8 ka and increase of solar irradiance during B/A and EH short term warmings. Their correlation with short term increased Greenland temperature (NGRIP ice core) and a decreased Antarctic temperature are less pronounced but seem to be marked as well.

Fig. 6. Cross correlation of the EAM and Greenland climate variability calculated by correlation of $\delta^{18}O$ values of the calcite of Chinese stalagmites (Wang et al., 2008) with ones of the NGRIP

(lower panel) and GISP 2 (upper panel) ice cores (Rasmussen et al., 2014) by moving windows at 1000 years (purple lines), 2000 years (red lines) and 3000 years (green lines) over the last 25 ka. Yellow bars show areas with insignificant cross correlation ranging between +0.25 and -0.25. Cross correlation between the EAM and Greenland by moving window 3000 years is negative during period of 16.5-8.5 ka and insignificant or weakly negative during earlier and later periods of 25-16.5 ka and of 8.5-0 ka confirmed the EAM and the Greenland synchronicity.