

A New Evidence on Sequence of Deglacial Warming in the Tropical Indian Ocean

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Abstract

Transition from the last glacial maximum to Holocene has undergone a sequence of fluctuations which exhibit large spatial and temporal variations in different regions of the world. Here we show that deglaciation warming in the northern Indian Ocean was initiated ~19 ka, which is contemporary to the deglaciation warming in the Antarctica and southern ocean. A gradual warming occurred during the glacial to Holocene transition in the northern Indian Ocean unlike two step warming noticed in the Greenland and north Atlantic. Synchronous deglacial warming ~19ka in the Antarctica and northern Indian Ocean suggest a strong connection in propagating climate signals between Antarctica and the Indian Ocean probably through the Indonesian through flow and/or Sub Antarctica Mode Water.

KEYWORDS: Indian Ocean, deglaciation, sea surface temperature, Last Glacial Maximum, Antarctica

Introduction

The last deglaciation was not a smooth transition from one climate state to another and, is punctuated by various high frequency oscillations such as Bolling-Allerado warm phase, the Heinrich Event 1 (H1) and Younger Dryas (YD) cold period. The present picture of climate pattern during deglaciation has largely focused on high latitude records in particular from Greenland and Antarctica ice-cores that have been synchronized by correlating globally recordable methane fluctuations (EPICA, 2006). However, this correlation reveals ambiguities over the interval of the beginning deglacial warming in the southern hemisphere making the analysis of interhemispheric climate pattern over this important interval more difficult. Geographic distribution of these oscillations and their global extent is not clearly established yet (Clark *et al.*, 2002). Switching of glacial to interglacial mode has caused various changes in the circulation of oceans, thus this transition has gained importance in the paleoclimate studies. The exact start of deglaciation and duration of the transition from the last glacial maximum to the current Holocene is not uniform in all the oceans. For example, in the Atlantic Ocean the deglaciation has began around 17 ka (Bard *et al.*, 2000), in the Pacific around 19 ka (Kiefer *et al.*, 2005), in Greenland at 17 ka (Grootes *et al.*, 1993) and in the Antarctica at 19 ka (EPICA, 2006). The exact start of deglaciation in the Indian Ocean is not documented due to lack of high resolution records with robust chronology. There are still a number of open questions regarding the exact timing and the mechanisms involved in the initiation of deglaciation and the subsequent interhemispheric pattern of the warming. Understanding the mechanism of this termination requires that the precise relative timing of abrupt climate warming in the tropics versus the high latitudes should be known. Therefore, the present communication is aimed to address the start of deglaciation in the Indian Ocean based on sea surface temperature (SST) derived from Mg/Ca of planktic foraminifer *Globigerinoides ruber* from the Arabian Sea and Bay of Bengal and

discussed other published SST records based on Mg/Ca ratios in planktic foraminifera and planktic foraminifera assemblages from the northern Indian Ocean..

Approach

SST records of AAS9/21 from the Arabian Sea and SK218/1 from the Bay of Bengal are presented here along with other published SST records from the northern Indian Ocean. In this paper, only high resolution SST records with robust chronology were considered for defining deglaciation SST pattern and the core locations are shown in Fig. 1. Here, we have considered the SST reconstructions based on Mg/Ca and Artificial Neural Net Work Techniques (table 1). Although absolute SST values might differ among the proxies, but generally the start of deglacial warming is in agreement among all methods used in this study. However, direct comparison of SST records derived from different sources of geochemical and planktic foraminifer assemblage might impose few distortions to our interpretations. As we are presenting SST records of two cores AAS9/21 and SK218/1 for the first time hence it is described below more details of chronology and analytical procedures followed to derive Mg/Ca and $\delta^{18}\text{O}$ values from planktic foraminifer species *G. ruber*.

Chronology of both AAS9/21 and SK218/1 cores were established based on AMS ^{14}C dates up to 40 ka, beyond 40 ka chronology was established by correlating $\delta^{18}\text{O}$ of *Globigerinoides ruber* ($\delta^{18}\text{O}_c$) record with the low latitude $\delta^{18}\text{O}_c$ global isostack curve of Martinson *et al.*, (1987). Age versus depth and sedimentation rates variations were shown in Fig. 2. AMS ^{14}C dating were performed on monospecific samples of the planktic foraminifera *G. ruber* using Tandem Accelerator at Leibniz Labor fur Altersbestimmung und Isotopenforschung, Christian-Alberchts-Universitat, Kiel, Germany. The measured ^{14}C ages were converted to sediment ages using the online CalPal version quickcal 2005 ver1.4 (Weninger *et al.*, 2006). The radiocarbon dates were

corrected for reservoir effect (400 years) based on the reservoir corrections for the Indian Ocean (Southon *et al.*, 2002) before calibration.

For determination of Mg/Ca, 30 to 40 individuals of planktic foraminiferal species *G. ruber* (white variety) with a size range of 250 to 350 μ m were picked and gently crushed while viewed with a binocular microscope. Care was taken not to pulverize broken shell fragments. Clay lumps and shell fragments containing clays were removed manually. Crushed samples were cleaned following the protocol described in Barker *et al.* (2003). 500 μ l of 0.075M HNO₃ was added to cleaned samples and left overnight to dissolve foraminiferal shell fragments completely. Solutions were transferred into clean vials and diluted with 0.001M HNO₃ to make a ~1 ml solution for analyses. Mg and Ca analyses were carried out on a Thermo Finnigan Element2 sector field inductively coupled plasma mass spectrometer. Elemental concentrations were derived from the isotopes ²⁵Mg and ⁴³Ca; ⁸⁹Y served as internal standard. ²⁷Al, and ⁵⁵Mn were also routinely measured simultaneously to monitor the effectiveness of the cleaning protocol. The analytical error for Mg/Ca was better than 0.7%. 40 sample solutions were measured in replicate on different days and found that repeatability for Mg/Ca was +0.1mmol/mol (1 σ).

SST was estimated using a relationship obtained from core-tops from the North Atlantic (Dekens *et al.*, 2002): $Mg/Ca = 0.38\exp(0.09 (SST))$, where Mg/Ca is in mmol/mol and SST is in °C. This calibration equation was selected because derived temperatures of the core tops were close to modern values at the core location, which is within error estimate of +0.3°C.

For the $\delta^{18}O$ analyses, new splits of cleaned *G. ruber* specimens (250 to 350 μ m size range) were analysed using a Finnigan MAT 252 mass spectrometer equipped with an automatic carbonate preparation device at the Universität Bremen, Germany. The mean external error and reproducibility (1 σ) of carbonate standard is better than +0.07‰ and

+0.05‰ for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, respectively. Oxygen and carbon isotopic values are expressed as per mil (‰) deviation Vienna Pee Dee belemnite (VPDB) standard, calibrated by NBS 18, 19 and 20 standards.

Results and Discussion

Simultaneous warming in the North Indian Ocean and Antarctica

SST records derived from Mg/Ca of planktic foraminifer species *G. ruber*, Alkenones, and Artificial Neural Net Work from different regions of the northern Indian Ocean are compared here. After the last glacial maximum (LGM), initiation of warming started between 19 and 18 ka in the AAS9/21 core and SK218/1 core from the eastern Arabian Sea and the Bay of Bengal, respectively (Fig. 3). Similarly, in the eastern Arabian Sea (SK17 core), the western Arabian Sea (NIO929, NIOP905 and ODP Site 723) and the Andaman Sea (RC12-344) also the deglaciation warming started between 19 and 18 ka (Fig. 4). Comparison of SST records of SK218/1 and AAS9/21 (Fig. 3) and other SST records from the northern Indian Ocean (Fig. 4) with the Vostok temperature record suggest that the exact timing of deglaciation started around 19 ka (within dating uncertainty).

Further, a gradual warming trend correspond very well in both northern Indian Ocean SST record and in Vostok temperature changes (Fig. 3 and 4). At the same time northern Indian Ocean SST records and Vostok temperature differ with the Greenland temperature record in two ways: i) a two step warming as documented in the Greenland (Grootes *et al.*, 1993) and in north Atlantic (Bard *et al.*, 2000) was not documented in the SST records of the north Indian Ocean, and ii) and unlike Greenland and North Atlantic temperature records (two step warming) the deglaciation warming in the northern Indian Ocean is gradual. However, the rise in SST which corresponds to the *Bolling-Allerado* warm period started around 14 ka in the northern Indian Ocean (Fig. 4). Similarly, a drop in SST during Younger Dryas is not documented in the northern Indian Ocean SST

records (Fig. 4), instead in couple of cores SST has increased during Younger Dryas (Fig. 4). Besides, synchronous deglaciation between 18 and 19 ka occurrence

The SST records presented here (Fig. 3 and 4) exhibit synchronous deglaciation between 18 and 19 ka, however, the absolute SST change during deglaciation varied among these sites, which is attributable to localized influence on SST in the region. Besides, a decline SST trend during late Holocene in cores NIOP 929, NIOP 905 and ODP 723 were related to the influence of upwelling.

In the same way the tropical and subtropical Pacific SST record show an onset of deglacial warming at 19 ± 1 ka, coeval with the onset of the deglacial rise in sea level (Kiefer and Kienast, 2005), which coincides with the deglacial warming recorded in the Vostok Ice core of Antarctic. The available data from the southern ocean (Shemesh *et al.*, 2002) and southern mid latitudes (Pahnke *et al.*, 2003) also show deglacial warming ~ 18 ka which is generally consistent with Antarctic record. Similarly the high resolution SST records from the tropical Pacific Ocean (Visser *et al.*, 2003; Lea *et al.*, 2006) are in phase with the CO₂ increase in Antarctica ice-cores. Comparison of $\delta^{18}\text{O}$ records from GISP2 Ice Core and Byrd Ice Cores suggest that in the beginning of the last deglaciation, a warming in the Antarctica began approximately 3000 years before the onset of the *Bollin-Allerado* warm period in Greenland. Also, atmospheric CO₂ and methane concentration began to rise 2000 to 3000 years before the warming began in Greenland (Sowers and Bender, 1995).

In addition to SST records, the pattern of $\delta^{18}\text{O}$ changes from the Bay of Bengal and the Arabian Sea during deglaciation are compared with the $\delta^{18}\text{O}$ data of Antarctica (Byrd Ice Core) and Greenland (GISP2 Ice Core), which represent air temperature changes in these regions. The $\delta^{18}\text{O}$ fluctuations of SK218/1 from the Bay of Bengal and AAS9/21 from the Arabian Sea show a great resemblance with the $\delta^{18}\text{O}$ changes of Antarctica Ice Core (Fig. 5). Further, in both Bay of Bengal and Arabian Sea $\delta^{18}\text{O}$ values show a

depleting trend from 17 ka onwards as a consequence of deglaciation (Fig. 5). Apparently, the response of $\delta^{18}\text{O}$ to the deglacial warming in the Indian ocean show a 2 ka lag with the SST record. Similarly, the tropical Pacific Ocean also document SST lead over the $\delta^{18}\text{O}$ record during deglaciation. Also, rise in concentrations of CH_4 in Greenland (Chappellaz *et al.*, 1993), CO_2 in Antarctica (Neftel *et al.*, 1988) and onset of sea level rise in Barbodas (Fairbanks, 1989) started around 17 ka which coincides with depleting trend of $\delta^{18}\text{O}$ in the northern Indian Ocean records. Solar insolation at 65°N started to increase ~ 21 ka, northern Indian Ocean SST started to rise ~ 19 ka and $\delta^{18}\text{O}$ values started to respond deglaciation ~ 17 ka (Fig. 5), this suggest that solar insolation changes of 65°N led the SST and $\delta^{18}\text{O}$. SST respond much faster to the solar insolation changes rather than $\delta^{18}\text{O}$ and ice sheet, therefore the deglaciation start was felt first in the SST and subsequently in the $\delta^{18}\text{O}$ record.

Link between Antarctica and the northern Indian Ocean During Deglaciation

Paleoceanographic records over the last glacial cycle indeed demonstrate that SST variations coeval with Antarctica air temperature were a wide spread feature in the southern hemisphere (Lamy *et al.*, 2007; Lea *et al.*, 2006). Similarly, the intermediate water temperature in the SE Pacific has also varied along with temperature of Antarctica over the last 30 ka (Kiefer *et al.*, 2006), supporting a strong connection between mid-high latitude surface ocean climate and intermediate water properties (Ninnemann, 2006). The present study demonstrate that not only in the southern hemisphere but also in the northern Indian Ocean SST records also document the timing of deglacial warming coincides with the onset of deglaciation in the Antarctica and the similarities of $\delta^{18}\text{O}$ changes during deglaciation in the northern Indian Ocean is largely consistent with Antarctica ice-core records (Figs. 3 and 4).

Although, much has been published on the casual link between the changes of Asian monsoon and north Atlantic and Greenland temperatures (Schulz *et al.*, 1998; Gupta *et al.*, 2003; Wang *et al.*, 2004), a physical mechanism how the air temperature in the Greenland influences the Asian monsoon is not clear yet. Therefore, either the thermohaline changes driven by the melt water flux in the north Atlantic or atmospheric signals can account the deglaciation warming in the Indian Ocean which was started around 19 ka. Though, the sea saw mechanism proposed by Clark *et al* (2004) may explain the start of deglaciation in the Antarctica around 19 ka, but this mechanism may not explain the occurrence of deglaciation in the Indian Ocean for two reasons. i) how does the NADW formation in the north Atlantic effect SST in the northern Indian Ocean? ii) as suggested earlier, if atmospheric teleconnections prevail between north Atlantic and the Indian Ocean, then one would expect the start of deglaciation around 17 ka in the northern Indian Ocean as in the case of Greenland. On the contrary deglaciation warming in the northern Indian Ocean started at 19 ka which coincides with the starting time deglaciation warming in the Antarctica and southern ocean. Therefore, it is argued here that the deglaciation sequence in the Indian Ocean is strongly coupled with climate changes in the Antarctica. This suggests an existence of strong connection between Antarctica and northern India Ocean in propagating the climate signals through oceanic circulation or through atmosphere. Such type of connection between Antarctica and Indian Ocean could be possible due to two mechanisms, i) by changes in transport of heat and fresh water from the western Pacific through Indonesia Through Flow (ITF), ii) Sub Antarctica Mode Water (SAMW).

Changes in transport of heat and freshwater from the western Pacific through the Indonesian passage into the Indian Ocean depends on sea level changes. The global sea level at 19 ka was approximately 100m lower than the present day sea level (Fairbanks, 1989), therefore a reduced ITF mass flux around 19 ka is expected to have modified the

vertical structure of the ITF towards a more intensified flow that would have warmed the entire upper layer of the Indian Ocean (Song and Gordon, 2004). Although, it was proposed that SubAntarctica Mode Water (SAMW) would control the tropical Indian Ocean sea surface temperature and hydrography rather than the ITF (Kiefer *et al.*, 2006), the coincidence of deglacial warming in the Antarctic and the northern Indian SST derived by the surface dwelling planktonic foraminifer *G. ruber* suggest that ITF would have contributed significantly in initiating deglacial warming in the northern Indian Ocean. Therefore, ITF and/or SAMW would play an important role in propagating the Antarctica warming signature simultaneously into the tropical Indian Ocean. However, based on the present data set it would be difficult to discuss the partition of role played by ITF and SAMW in propagating the deglacial warming signature from the Antarctica to the Indian Ocean.

Role of Antarctica to initiate Deglaciation

Ice core evidence from the Antarctica reveals a direct relationship between the extent of warming across Antarctica and the duration of cold, stadial conditions over Greenland (EPICA, 2006). The contrast behavior of temperature variations between the Greenland and Antarctica has led the concept of bipolar see-saw, whereby the Atlantic meridional overturning circulation (AMOC) affect the distribution of heat between the southern and northern hemispheres. Thus, the thermohaline circulation changes in North Atlantic were responsible to the early deglacial warming in the southern hemisphere and the tropics (Alley and Clark, 1999; Clark *et al.*, 2002). Modelling results suggest that a reduction in strength of the AMOC would give rise to immediate decrease in northward heat transport (Vellinga and Wood, 2002). As a result surface air temperature over the north Atlantic would cool and those over south Atlantic would warm.

Although the bipolar see-saw can explain the anti-phase relationship between Greenland and Antarctica temperature fluctuations through changes in the strength of the

AMOC, it does not immediately account for the contrasting nature of the two signals and an early onset of deglaciation in the Antarctica, southern ocean and in the north Indian Ocean. Recently, it has been demonstrated that the importance of the southern Ocean for the development and transmission of deglacial climate change and the associated rise in atmospheric carbon dioxide (Barker *et al.*, 2009). Similarly, warming at terminations, is led from the south (Wolff *et al.*, 2009) and Antarctica warmings are associated with each of 25 identified Dansgaard-Oeschger events (EPICA, 2006) and Antarctica isotopic maxima was linearly related to the duration of Dansgaard-Oeschger cold events (Wolff *et al.*, 2009). Therefore, we invoke here that Antarctica and southern Oceans played an important role in initiating deglaciation and subsequently Greenland responded the change through the insolation changes at 65°N.

Conclusions

Sea surface temperatures derived from Mg/Ca ratios in planktic foraminifera *G. ruber* and $\delta^{18}\text{O}$ over the last 30 ka show that deglaciation warming was initiated around 19 ka in the northern Indian Ocean, which is coeval with the Pacific and Antarctica deglaciation timing, but leading Atlantic and Greenland deglaciation. Northern Indian Ocean SST documents a gradual warming during glacial to Holocene transition rather than a two step rapid warming as in the Greenland and north Atlantic. Simultaneous occurrence of deglaciation in the Antarctica and northern Indian Ocean and a strong resemblance of the $\delta^{18}\text{O}$ of planktic foraminifer fluctuation pattern during glacial to Holocene transition in the northern Indian Ocean with the Antarctica ice core data evoke a common climate forcing, such type of connection between these two regions would be through Indonesia through flow and/or Sub Antarctica Mode Water.

The early onset of deglaciation in the northern Indian Ocean provides an additional support to invoke that the southern hemisphere triggers the initiation of deglaciation.

This has an implication on the role played by Antarctica and tropics of the Indian and Pacific oceans in triggering sub-orbital time scale climate changes.

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Table 1. Details of cores used in the present study

Core	Region	Latitude	Longitude	Water Depth (m)	Age constraint	SST Proxy	Reference
SK218/1	Bay of Bengal	14°02'.1"N	82°00.12"E	3000	¹⁴ C ages	Mg/Ca PF	Present study
AAS9/21	Eastern Arabian Sea	14°30'.539"N	72°39'118"E	1807	¹⁴ C ages	Mg/Ca PF	Present study
NIOP905	Western Arabian Sea	10.46'9"N	21°.56'4"E	1586	¹⁴ C ages	Mg/Ca PF	Anand et al (2008)
NIOP929	Western Arabian Sea	13°42'21"N	53°14'76"E	2490	¹⁴ C ages	Mg/Ca PF	Saher et al (2007)
SK17	Eastern Arabian Sea	15°15'N	72°58'E	840	¹⁴ C ages	Mg/Ca PF	Anand et al (2008)
ODP 723	Western Arabian Sea	18°03'N	57°37'E	808	¹⁴ C ages	ANN	Naidu and Malmgren, (2005)
RC12-344	Andaman Sea	12.46°N	96.04°W	2140	¹⁴ C ages	Mg/Ca PF	Rashid et al (2007)

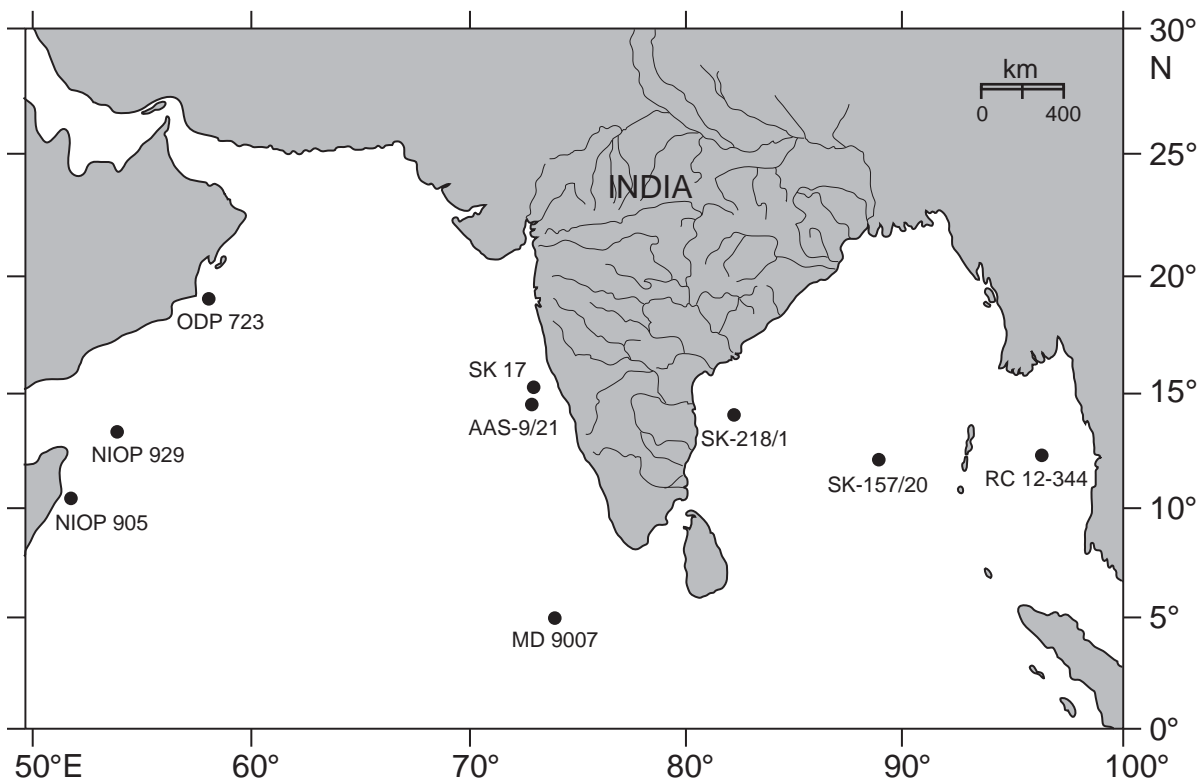


Figure 1. Cores location used in the present study.

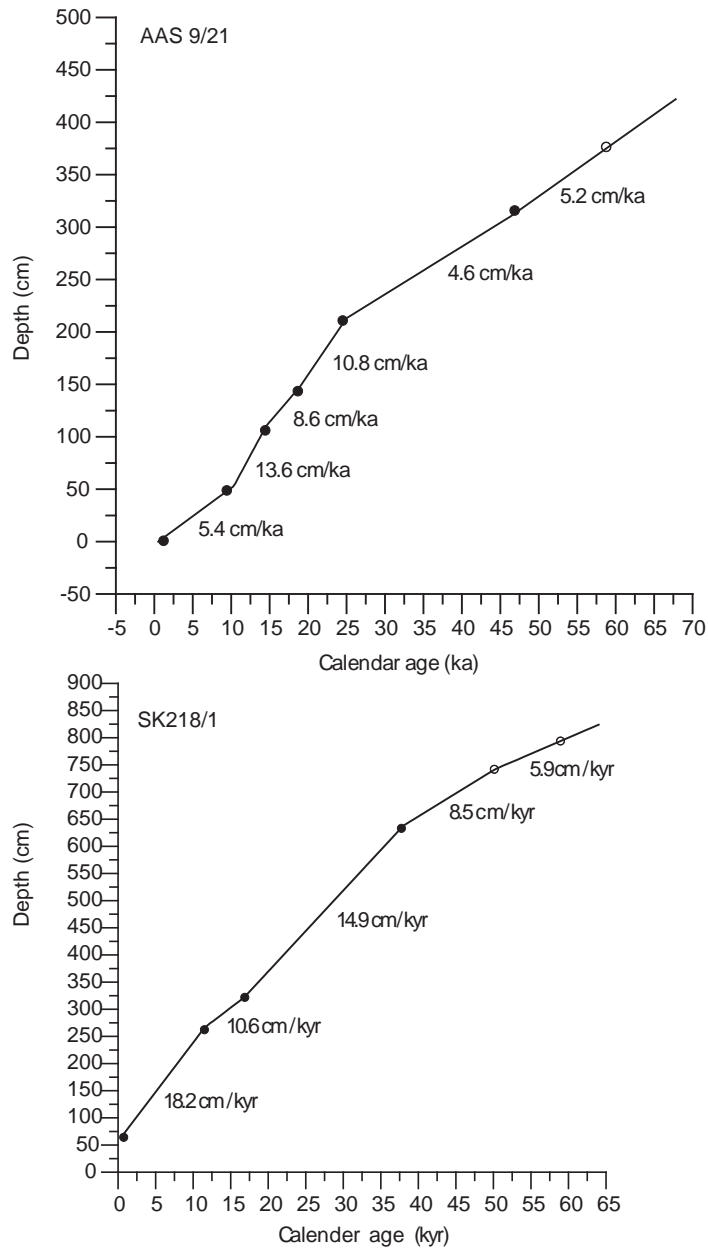


Figure 2. Age versus depth plots for Core AAS9/21 and SK218/1 and sedimentation rates.

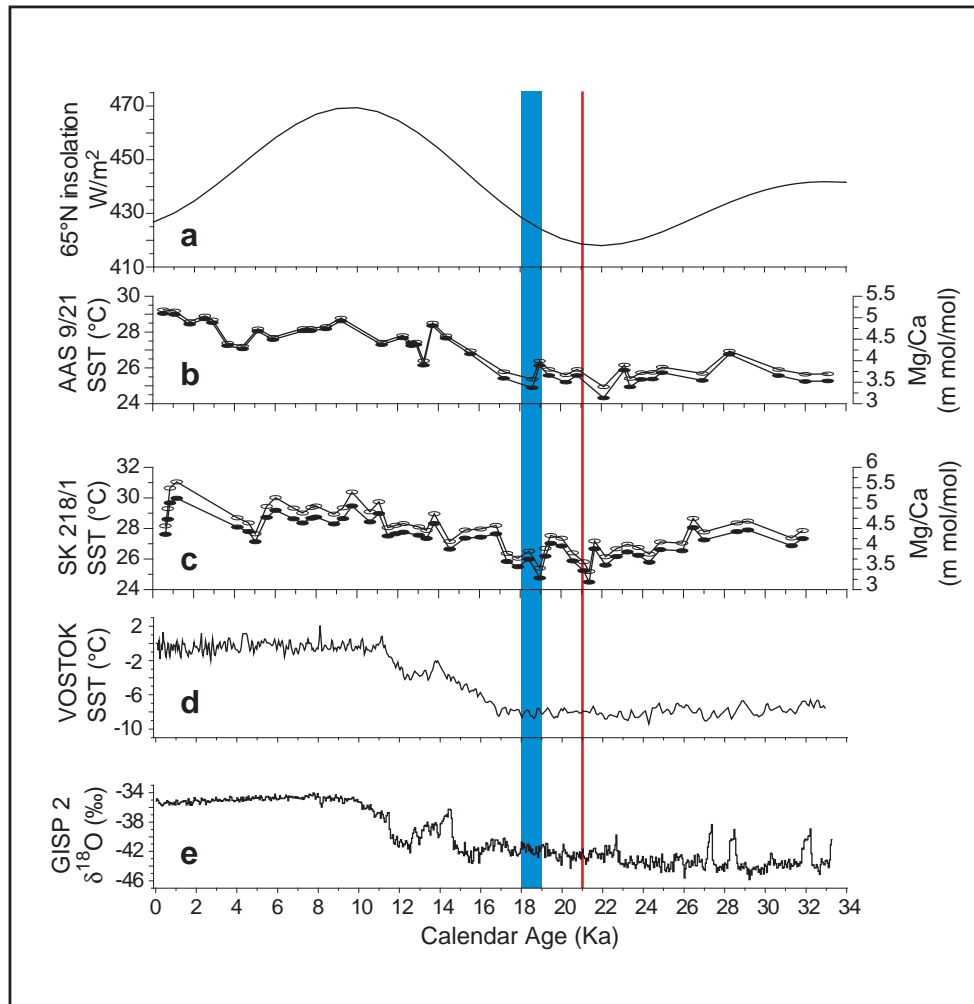


Figure 3. a) Solar insolation changes at 65°N, (b) Sea surface temperature and Mg/ca profiles of AAS9/21, (c) Sea surface temperature and Mg/ca profiles of SK218/1, (d) Temperature changes in the Antarctic derived from VOSTOK Ice Core and (Petit et al., 1999) (e) $\delta^{18}\text{O}$ profile of GISP2 Ice Core (Grootes et al., 1993). SST estimates from SK218/1 and AAS9/21 are based on Mg/Ca of planktic foraminifer *G. ruber*. The blue color band represent the deglaciation timing in the northern Indian Ocean and the red line denote the starting time of solar insolation rise.

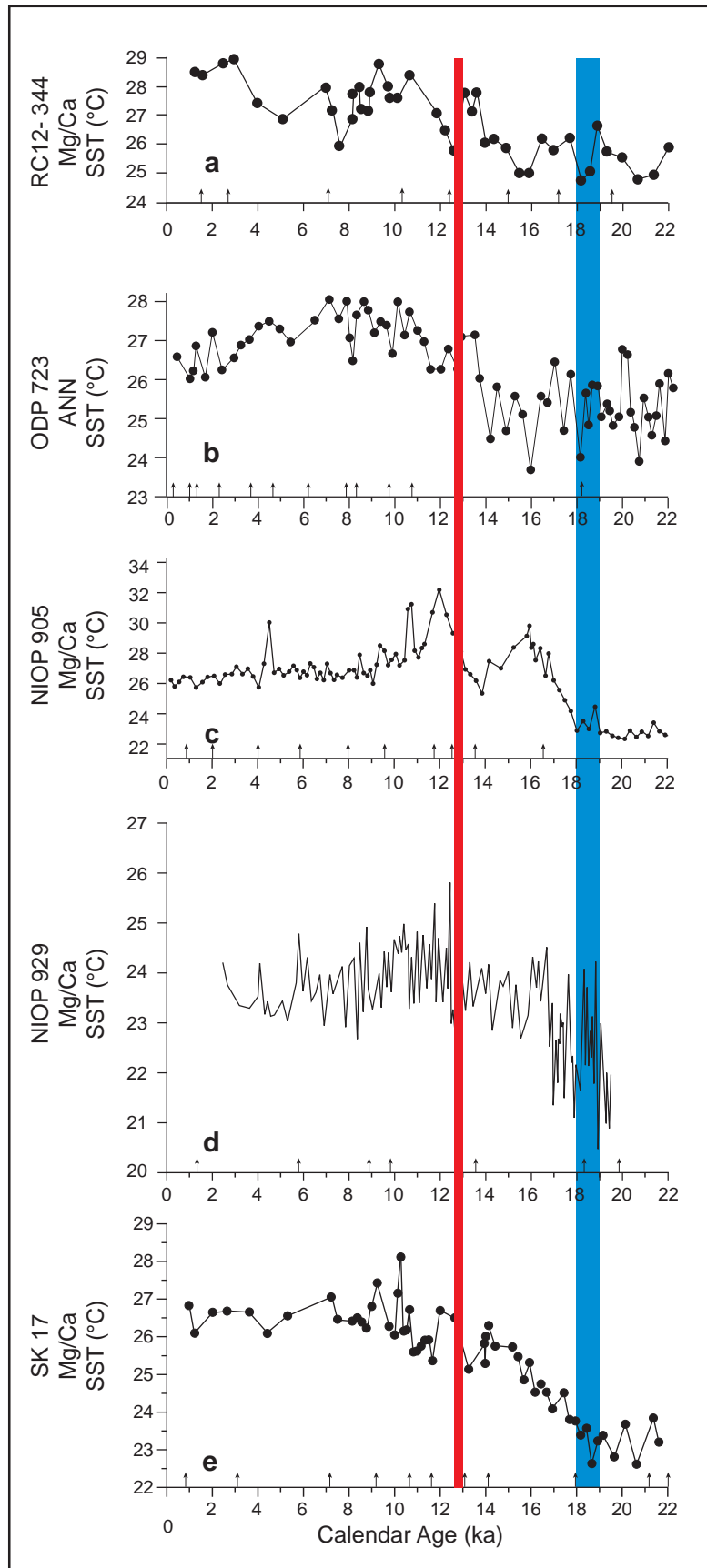


Figure 4. SST profiles of (a) RC12-334, (b) ODP Site 723, (c) NIOP 905, (d) NIOP 929, (e) SK17. NIOP 929 and NIOP 905 are based on Mg/Ca and SST estimates from ODP Site 723 are based on Artificial Neural Net Work Techniques. The blue color band reflects the rise of SST as a consequence of deglaciation in a suite of cores from the northern Indian Ocean and Younger Dryas Event is marked with red color band. The age control points that were used in the age model in each of these cores are shown with an arrow on X axis.

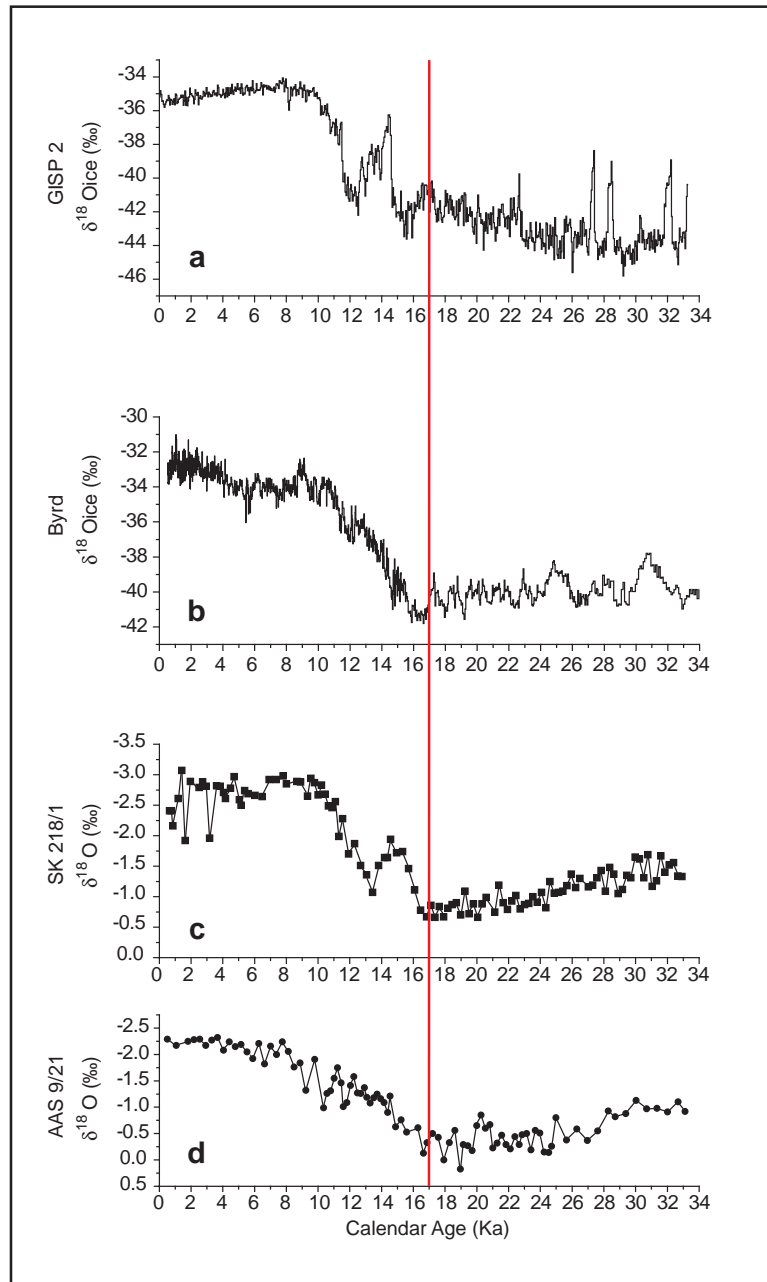


Figure 5. $\delta^{18}\text{O}$ profiles of (a) GISP2 Ice Core (Grootes et al., 1993), (b) Byrd Ice Core (Johnsen et al., 1972), (d) SK218/1 and (e) AAS9/21. Fluctuations of $\delta^{18}\text{O}$ in both these cores resembles the $\delta^{18}\text{O}$ profile Byrd Ice Core, suggests that the timing and pattern of deglaciation changes of northern Indian Ocean mimics that of Antarctica. Red color line denotes the starting response of $\delta^{18}\text{O}$ timing to deglaciation warming.