SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
CLIMATE SCIENCES
CLIMATE CHANGE
EARTH AND ENVIRONMENTAL SCIENCES
CLIMATE-CHANGE IMPACTS

Received
10 June 2013

Accepted
6 September 2013

Published
25 September 2013

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Solar forcing of the Indian summer monsoon variability during the Ållerød period

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Rapid climatic shifts across the last glacial to Holocene transition are pervasive feature of the North Atlantic as well as low latitude proxy archives. Our decadal to centennial scale record of summer monsoon proxy *Globigerina bulloides* from rapidly accumulating sediments from Hole 723A, Arabian Sea shows two distinct intervals of weak summer monsoon wind coinciding with cold periods within Ållerød inerstadial of the North Atlantic named here as IACP-A1 and IACP-A2 and dated (within dating uncertainties) at 13.5 and 13.3 calibrated kilo years before the present (cal kyr BP), respectively. Spectral analysis of the *Globigerina bulloides* time series for the segment 13.6–13.1 kyr (Ållerød period) reveals a strong solar 208-year cycle also known as de Vries or Suess cycle, suggesting that the centennial scale variability in Indian summer monsoon winds during the Ållerød inerstadial was driven by changes in the solar irradiance through stratospheric-tropospheric interactions.

The Indian or South Asian monsoon is a fully coupled ocean-land-atmosphere feature marked by seasonal wind reversals which drive significant biogeochemical changes in the Arabian Sea. The Indian summer monsoon (ISM), also known as southwest monsoon, has a direct bearing on the socioeconomic conditions of people of South Asia which houses one-third of world population. The sensible heating of the land and troposphere during boreal summer has been suggested to intensify the land-sea thermal contrast that drives the ISM wind field[1]. Recent climate models suggest that by removing Tibet, the monsoon largely remains unaffected provided the narrow orography of the Himalaya was preserved[2]. These authors[2] suggest that monsoon is also sensitive to changes in surface heat fluxes from non-elevated regions of the Indian landmass as well as to changes in heat fluxes from adjacent elevated regions.

Recent studies establish centennial to millennial scale climate connections between North Atlantic climate and ISM during the last glacial and the Holocene with dry monsoon phases aligned with intervals of cold spells in the North Atlantic[3–5]. The transition from the last glacial to the Holocene assumes great significance in understanding how Earth's climate system can abruptly switch from one mode to another. The most detailed records of this transition are found in the North Atlantic[6], the Arabian Sea[3] and China[7], indicating that such shifts were pervasive throughout the Northern Hemisphere as well as the tropics since the last glacial period. In monsoonal Asia, such abrupt events have been observed in the East Asian monsoon records from the Hulu[7] and Dongge[8] caves of China, and Indian monsoon records from the Pakistan Margin[3] and Timta cave of India[9].

What drives centennial or millennial changes in the monsoon is still debatable, although sun has been suggested as by far the most important driving force[10–12]. The sun-climate link has been intensely debated in recent years[13,14], though the idea that changes in solar activity may affect the Earth's climate was first discussed by Herschel[15]. There is a growing realization that Sun plays an important role in driving small scale changes in the climate as is evident in numerous Holocene paleoclimate records[4,16,17]. It has been suggested that the Asian monsoon could be sensitive to small changes in solar output[5,10–12]. To understand if pronounced centennial changes in the ISM were related to solar variability, we analyzed summer monsoon wind record of 14–11 kyr period (covering the Ållerød period) from biogenic sediments of the Oman margin, northwest Arabian Sea where biological activity is elevated during summer monsoon season[18]. We further investigate if changes in the monsoon were more rapid during warm intervals when solar activity was high[12].

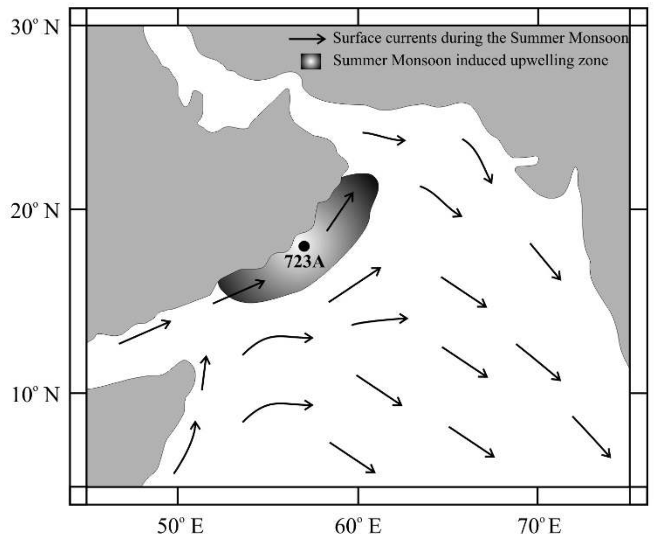

Figure 1 | Location of ODP Hole 723A in the Arabian Sea. Also shown are surface currents during summer and winter monsoon seasons. Grey shaded area off Oman Margin is major summer monsoon-driven upwelling zone (after Prell and Curry[19]).

Results

We used planktic foraminifer *Globigerina bulloides* time series combined with published solar proxy records to understand monsoon-solar link during the transition from the last glacial to the Holocene. The surface biological response to the monsoon wind activity is preserved as increased abundance of *Globigerina bulloides*[19]. This species is a near surface dwelling taxon, conventionally known from the transitional and sub-polar water masses but has also been found in significant proportions in tropical and subtropical wind-induced upwelling regions of the Indian Ocean[19]. This proxy has been calibrated using modern sea-floor samples[19] and sediment trap time series[20]. Advantages of the *G. bulloides* proxy include its unique association with the summer monsoon wind, linear correlation with the surface cooling due to upwelling, and strong sensitivity to wind stress. Also this species is not influenced by precipitation as the other proxies are.

We produced a 3 kyr record of *G. bulloides* encompassing 14–11 cal kyr BP interval by sampling cores from Ocean Drilling Program (ODP) Hole 723A (Fig. 1), every 5 mm giving an average age interval per sample of 4–5 years during 14–13 cal kyr BP (the Ållerød period) and 4 to 24 years during 13–11 cal kyr BP (including the Younger Dryas period). The average age per sample is based on linear interpolation of eight unpublished and published calibrated (http://calib.qub.ac.uk/calib/) AMS ^{14}C dates (Table 1). Hole 723A is located off the Oman Margin (18°03.079′N, 57°36.561′E; water depth 807.8 m) in the core of an oxygen minimum zone (OMZ) where summer monsoon winds exert maximum stress driving high production of phyto- and zooplanktons. Hole 723A provides a high-resolution sedimentary record of biotic changes linked to summer monsoon winds. Offshore Oman Margin, strong summer monsoon winds induce intense upwelling that enhances the primary production and thus high sediment accumulation at Hole 723A (average ~35 cm/kyr) with peak rates (~100 cm/kyr) during 14–13 cal kyr BP. The bioturbation smoothing at this hole is minimal owing to high sediment accumulation rate and presence of strong OMZ in the study area[5].

We identified two discrete intervals of summer monsoon wind minima for the first time in the summer monsoon wind record from the Arabian Sea during the Ållerød period (Fig. 2; supplementary information). These two Intra–Ållerød Cold Periods (IACPs), here named as IACP-A1 and IACP-A2, representing weak summer monsoon wind events are dated, within the radiocarbon age uncertainties, at 13.5 cal kyr BP and 13.3 cal kyr BP, respectively (Fig. 2). Both the dry/weak monsoon wind events lasted ~140 years with a pronounced peak lasting ~40 years (Fig. 2). These events coincide with reduced solar activity (Fig. 2). The GISP2 record shows only one pronounced IACP that began ca. 13,260 cal yr BP and lasted for 140 yrs with a negative $\delta^{18}O$ excursion of 2.5‰[21].

Spectral analysis of the *G. bulloides* time series shows statistically most significant (strongest) periodicity (>95% confidence level) centered at 208 year (Fig. 3). The other significant periodicities lie at 95, 21, 19 and 14 years. Spectral analysis of the entire 14–8 kyr interval with the same parameters produce peaks of 227, 209, 196 and 189 years, indicating that the 208-yr cycle was also present across the last glacial to Holocene transition although with a weak amplitude (Fig. 4).

Discussion

The 208-yr period (the de Vries cycle, also known as Suess cycle) has been observed in the $\Delta^{14}C$ spectrum[13] and ^{10}Be record[22] of the North Atlantic and has been attributed to solar modulation of $\Delta^{14}C$ production[23]. The maxima of the de Vries cycle in the $\Delta^{14}C$ data coincide with the Spörer (1420–1540 AD) and Maunder (1645–1715 AD) sun spot minima, suggesting that solar forcing evidently played a major role in producing the 208-yr cycle[24]. This solar cycle has been reported in climate proxies from different archives of monsoon variability[7,10,12], suggesting a strong link between changing solar activity and monsoon on time scales of centuries to millenniums.

The Ållerød period ranging from 14.08 (14,075 yrs) to 12.9 (12,896 yrs) cal kyr BP, was marked by abrupt climatic changes[25]. Isotope record from Timta Cave shows repeated occurrences of

Table 1 | Calibrated AMS ^{14}C dates of foraminiferal samples from ODP Hole 723A determined by Accelerated Mass Spectrometer (AMS) using CALIB 5.0.2 program (http://calib.qub.ac.uk/calib/). Ages marked with single asterisks are from Gupta *et al.* (2003)[5] and with double asterisks is from Gupta *et al.* (2005)[12]

NOSAMS¶ Lab. code	Species	Depth (cmbsf)†	AMS ^{14}C age‡	Calendar age (years before 1950)	1 s.d. (year)
34266	*G. bulloides*	186	7,700*	7,938	45
34267	*G. bulloides*	218	8,110*	8,359	40
34268	*G. bulloides*	274	9,510*	9,854	40
34269	*G. bulloides*	316	10,500*	10,877	40
34437	*G. bulloides*	339	11,000**	12,155	40
44750	*G. bulloides*	352	11,500	12,692	40
82174	Mixed planktics	370	11,950	13,210	55
82175	Mixed planktics	410.5	12,350	13,573	55

¶NOSAMS = National Ocean Sciences Accelerator Mass Spectrometer Facility.
†cmbsf=centimeters below sea floor.
‡Calibrated to calendar before 1950 using CALIB REV5.0.2.

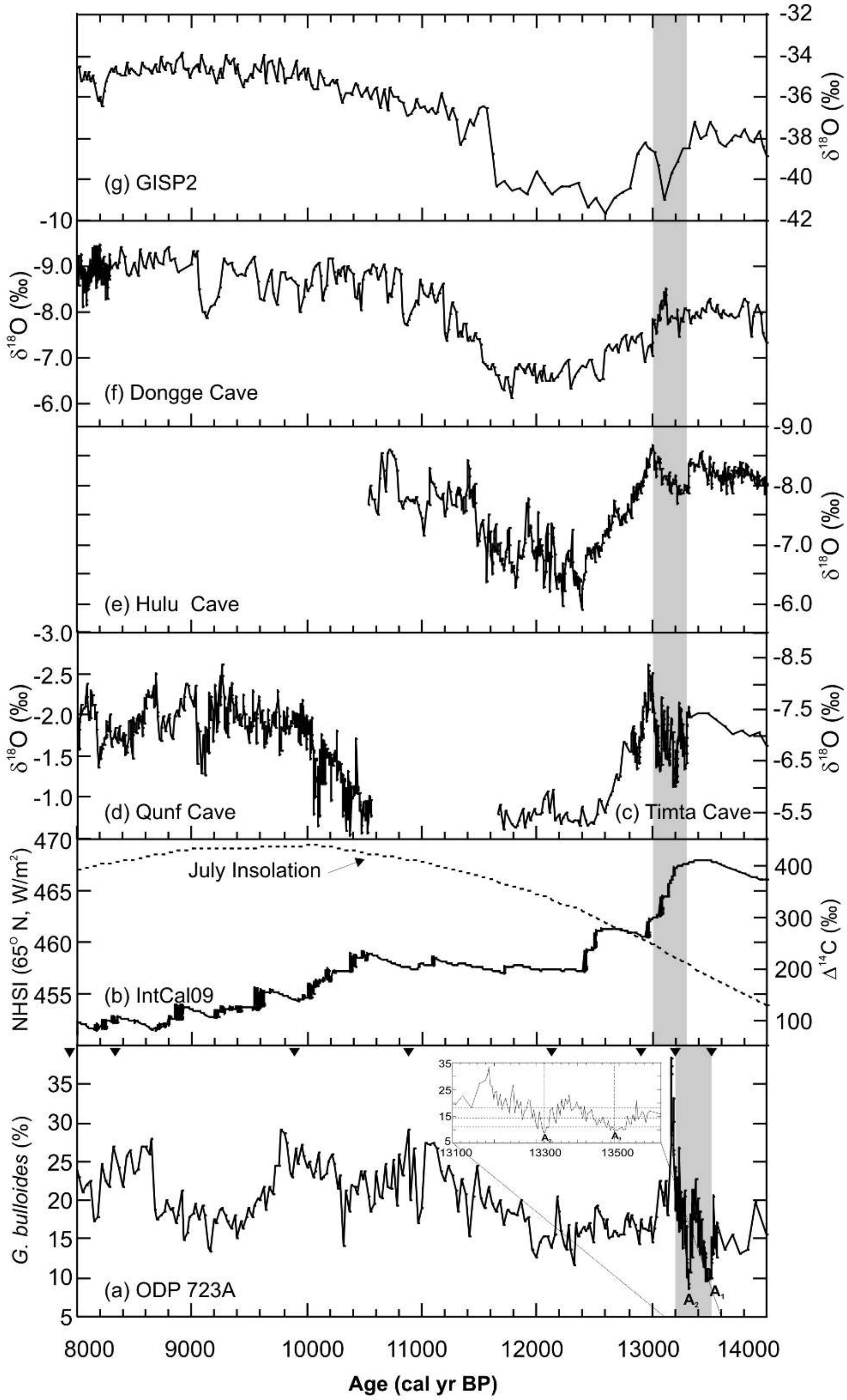

Figure 2 | Southwest monsoon proxy record from the Arabian Sea ODP Hole 723A combined with cave records from India, China and Oman, and GISP2 record from Greenland. Time series of (a) *G. bulloides* percentage in Hole 723A off Oman Margin, Arabian Sea, the inset figure shows expanded 13.6–13.1 cal kyr BP interval; the calibrated AMS ^{14}C dated intervals are shown by inverted solid triangles, (b) 65° N July insolation[26] (NHSI) and IntCal09 $\Delta^{14}C_{atm}$ values[27], $\delta^{18}O$ values of (c) Timta cave[9], (d) Qunf cave[11], (e) Hulu cave[7] and (f) Dongge cave[8], and (g) GISP2 record from Greenland[6]. The vertical grey bar indicates an interval of weak Indian summer monsoon winds aligned with Intra-Ållerød Cold Periods (IACPs) A1 and A2 when solar insolation was less[26].

reduced summer monsoon precipitation during ca. 13.3–13 kyr BP[9], which also appear (within dating uncertainties) to be present in Hulu[7] and Dongge[8] cave records of China. The Timta cave and Hole 723A records show close similarity with Timta events occurring 200 yrs later than those at Hole 723A, which may be reconciled in the context of the relative chronological uncertainties. These abrupt, high amplitude events across the Ållerød period indicate that the Indian monsoon underwent rapid centennial changes similar to those observed in the North Atlantic[25], representing intervals of weak summer monsoon wind and perhaps low precipitation. The summer monsoon winds were also weak during the Younger Dryas (12.9–11.6 kyr BP), 9.7–8.7 kyr BP and 8.2 kyr cold event (Fig. 2; supplementary information), agreeing with the earlier observations that the summer monsoon weakened during cold intervals[5].

The frequency spectrum of ISM wind strength during the Ållerød period at Hole 723A is similar to that of the $\Delta^{14}C$ spectrum and other

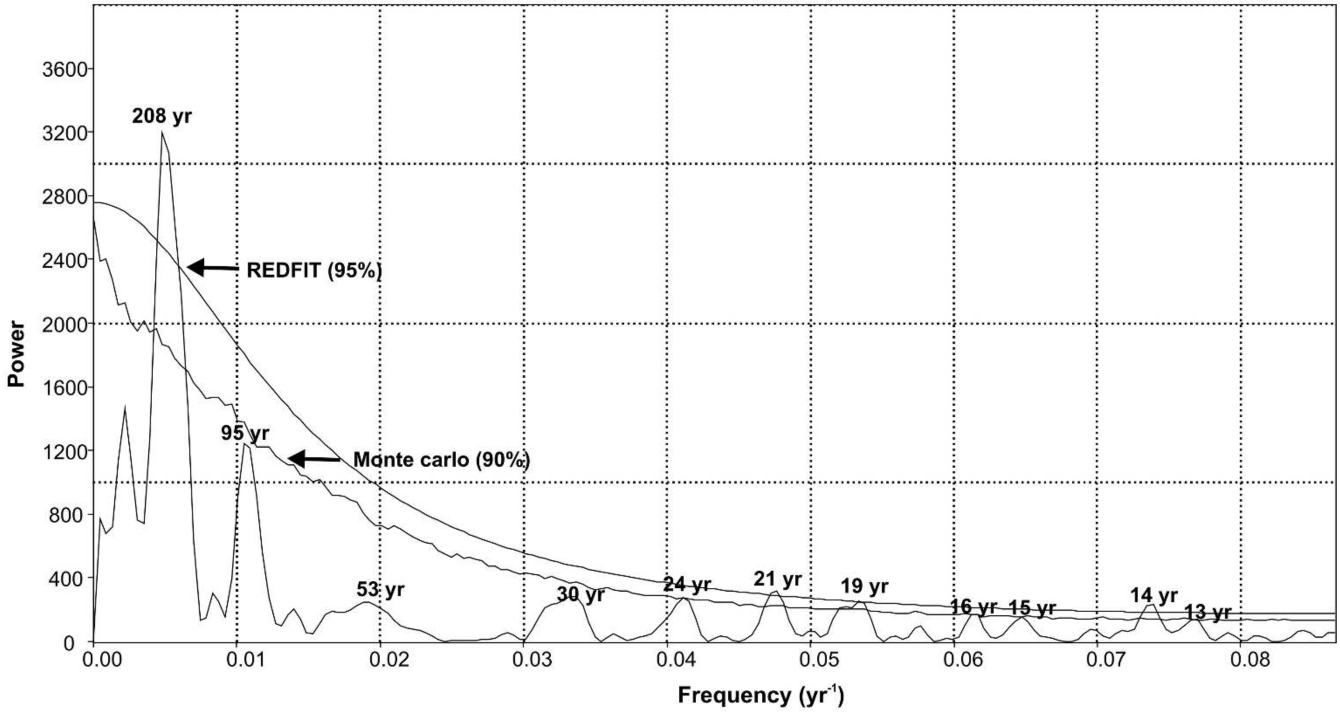

Figure 3 | The spectral analysis of *G. bulloides* time series for the period 13.6–13.1 cal kyr BP showing statistically most significant (strongest) periodicity centered at 208 year (solar de Vries cycle or Suess cycle). The other significant periodicities lie at 95, 21, 19 and 14 years. The presence of 208-yr cycle suggests strong solar forcing of Indian summer monsoon during the Ållerød period.

ISM precipitation records. The presence of statistically strong solar de Vries cycle (208-yr cycle) in the *G. bulloides* time series at Hole 723A indicates a strong link between monsoon wind and solar variability during the Ållerød period. Our data provides robust evidence that minor oscillations as observed in the North Atlantic-Greenland region are also found in the low latitude climatic (Indian monsoon) records, and that the footprints of solar impact on climate can be seen from the poles to the tropics. Northern Hemisphere summer radiation was ~3% less during the Ållerød period than the early Holocene[26] coinciding with increased IntCal09 $\Delta^{14}C_{atm}$ values[27]

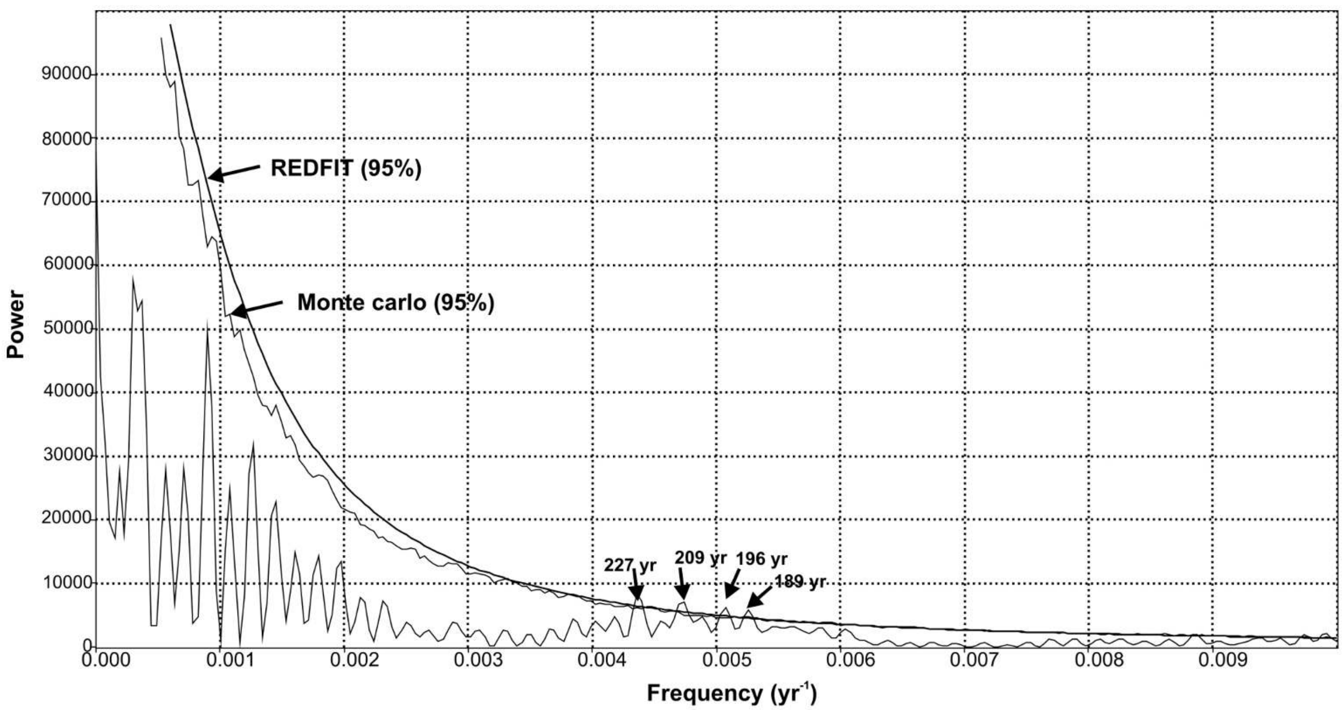

Figure 4 | The spectral analysis of *G. bulloides* time series for the period 14–8 cal kyr BP also shows statistically significant but low amplitude peaks at 227, 209, 196 and 189 years. The presence of 209-yr solar cycle during the late glacial to Holocene transition suggests that sun plays an important role in deriving small scale variability in Indian summer monsoon wind.

(Fig. 2). Increases in atmospheric ^{14}C generally coincide with a reduced solar activity[24].

The close correlation between North Atlantic climate and Indian monsoon records suggests that the solar influence acted in the same manner in both the North Atlantic and the South Asian regions. Recent studies suggest that ISM precipitation was coupled to variations in the East Asian monsoon and North Atlantic climate on multicentennial to millennial time scales, and both the monsoons strengthened simultaneously at the onset of B-A interstadials[9,28]. In contrast, during cold intervals the increased latitudinal thermal gradient drove stronger westerly winds and southward shift of ITCZ that led to the weakening of the Indian and East Asian summer monsoons[28]. This perhaps was the case during the two cold IACP events. The changes in atmospheric circulation and precipitation at the end of the Ållerød period may have had a significant impact on global and regional climates.

The novelty of our study lies in the fact that we have found for the first time strong solar de Vries cycle (208-yr cycle) and two cold events (IACPs) in the summer monsoon wind record during the Ållerød period indicating a strong solar forcing of summer monsoon variability through amplification of solar signal by stratospheric-tropospheric interaction. This study also corroborates that monsoon variability intensifies during warmer intervals[12]. The present study highlights the importance of solar variability in driving changes in Indian summer monsoon wind strength that will have a pronounced impact on precipitation and thus on food security of the agrarian economies of the South Asian region. Changes in solar output have a direct bearing on climate and much of the preindustrial natural temperature variability may have been caused by the sun[29].

Methods

The *G. bulloides* percentages were calculated from an aliquot of 300 specimens from 149 μm+ size fraction. Based on our earlier observations, we speculate ±5% error in our *G. bulloides* counts. This new data is combined with published values of *G. bulloides* from Hole 723A during 11–8 kyr interval[12] to extend the record back to the 8.2 kyr cold event (Fig. 2). The *G. bulloides* time series from Hole 723A was compared with Timta[9], Hulu[7], Dongge[8], and Qunf[11] caves for a regional comparison, and combined with 65°N July insolation[26], IntCal09 $\Delta^{14}C_{atm}$ values[27] and GISP2 record from Greenland[6] to understand North Atlantic climate-Indian monsoon-solar connection (Fig. 2). The *G. bulloides* and GISP2 time series were detrended using PAST software available at http://palaeo-electronica.org/2001_1/past/issue1_01.htm, Software link: http://nhm2.uio.no/norlex/past/30 in which 3-points polynomial line fit value was removed from the original data, to understand centennial scale patterns (supplementary information). We carried out spectral analysis of the *G. bulloides* time series using PAST program[30] and calculated the rednoise using REDFIT[22] for the 13.6–13.1 kyr segment owing to very high sediment accumulation in this interval (Fig. 3). Since the time series is not very long only one number of segments was selected to obtain the spectra. The window parameter was selected to "Rectangle" which causes analysis to be carried out on the original series. The Monte Carlo simulation option allows the spectrum to be bias-corrected[31].

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Acknowledgments

Ocean Drilling Program (ODP) is thankfully acknowledged for providing core samples to carry out the present study. This study was supported by DST, New Delhi (SR/S4/ES-46/2003 and J.C. Bose fellowship) to A.K.G. and CSIR, New Delhi, through an independent fellowship to M.D. K.M. was supported by a fellowship from I.I.T., Kharagpur.

Author contributions

A.K.G. interpreted the results and wrote the manuscript. K.M., M.D. and R.K.S. generated the data and performed the analysis.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Gupta, A.K., Mohan, K., Das, M. & Singh, R.K. Solar forcing of the Indian summer monsoon variability during the Ållerød period. *Sci. Rep.* **3**, 2753; DOI:10.1038/srep02753 (2013).