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Solar influence on the Indian summer monsoon during the Holocene

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[1] The large (8%) changes in the past seasonal insolation have a well-documented influence on the Indian summer monsoon. However, the effect of the small (<1%) decade to century scale solar variability is less certain. Evidence is emerging that Earth's climate is sensitive to small changes in solar output on centennial time scale during the Holocene. Comparison of a recently published proxy record for sunspot activity with our newly-revised higher-resolution record of the Indian summer monsoon winds reveals multiple intervals of weak summer monsoon during the Holocene at multidecadal to centennial scales. Weak summer monsoon winds correlate with reduced solar output. Our results suggest that small changes in solar irradiance can bring pronounced changes in the tropical monsoon. The multidecade to century scale variations in the monsoon winds were much larger in the early Holocene coincident with increased sunspot numbers. **Citation:** Gupta, A. K., M. Das, and D. M. Anderson (2005), Solar influence on the Indian summer monsoon during the Holocene, *Geophys. Res. Lett.*, *32*, L17703, doi:10.1029/2005GL022685.

1. Introduction

[2] The Indian summer monsoon is critical in understanding global hydrological and carbon cycles, influencing the climate and societies across South Asia. The summer monsoon was stronger with more abrupt changes in the early Holocene (10–8 Kyr) and an intense arid phase beginning at ~4 Kyr [*Overpeck et al.*, 1996; *Gupta et al.*, 2003; *Staubwasser et al.*, 2003]. The changes in the monsoon winds were accompanied by changes in rainfall over India affecting the fluvial systems and thus biota of the region [*Goodbred and Kuehl*, 2000; *Hong et al.*, 2003; *Sharma et al.*, 2004].

[3] Centennial to millennial scale abrupt changes in the summer monsoon are documented in several recent studies from the marine sediment records of the Arabian Sea [*Sirocko et al.*, 1993; *Schulz et al.*, 1998; *Gupta et al.*, 2003], cave deposits from southern Oman [*Fleitmann et al.*, 2003], peat deposits from western Tibetan Plateau [*Hong et al.*, 2003], and sediment load in the Bay of Bengal [*Kudrass et al.*, 2001]. Variations in solar activity might have driven these persistent abrupt changes in the summer monsoon, as has been demonstrated for changes in monsoon precipitation in Oman [*Neff et al.*, 2001; *Fleitmann et al.*, 2003], and climates of the North Atlantic (Bond Cycles) and North Pacific Oceans [*Bond et al.*, 2001; *Hu et al.*, 2003].

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[4] Recent studies indicate that Earth's climate is sensitive to small changes in solar output on centennial time scale during the Holocene [*Rind and Overpeck*, 1993; *Bond et al.*, 2001; *Shindell et al.*, 2001; *Hu et al.*, 2003]. Evidences are also emerging that monsoon could be sensitive to relatively small changes in forcing (0.25% change in solar output) [*Overpeck et al.*, 1996; *Neff et al.*, 2001; *Fleitmann et al.*, 2003]. To test this hypothesis, we examined an important and widely used proxy of the summer monsoon, the record of percentages of fossil shells of planktic foraminifer *Globigerina bulloides* in sediments from the Oman margin where this upwelling-loving species dominates the surface sediments [*Anderson and Prell*, 1993]. A newly published sunspot reconstruction, together with an improved version of our previous [*Gupta et al.*, 2003] *G. bulloides* time series, and ^{14}C and ^{10}Be proxies allow us to test the solar-monsoon link at the multidecade to century scale during the Holocene.

2. Materials, Methods, and Results

[5] We generated an ~11,100 calendar years old record of *G. bulloides* by sampling cores at contiguous 1 cm interval from Ocean Drilling Program (ODP) Hole 723A, Leg 117, off Oman, northwestern Arabian Sea (18°03.079′N, 57°36.561′E; water depth 807.8m) in the centre of an Oxygen Minimum Zone (OMZ), providing a high-resolution sedimentary record of variations in the summer monsoon-induced upwelling. The bioturbation smoothing is minimal at this hole due to the strong OMZ that exists at mid depths in the Arabian Sea [*Hermelin and Shimmield*, 1990]. Near the Oman margin, strong summer or southwest (SW) monsoon winds induce strong upwelling that enhances the primary production and thus high sediment accumulation at Site 723 (~30 cm/Kyr), and strengthens the OMZ [*Hermelin and Shimmield*, 1990]. The average age interval per studied sample is ~30 years based on a linear-interpolation of four new and eleven published AMS ^{14}C calibrated dates [*Gupta et al.*, 2003] (Table 1s). The radiocarbon measurement error (1 s.d.) is less than 50 years, including the uncertainty in reservoir age, but stratigraphic interpolation increases the uncertainty to about (±) 100 years. The percentages of *G. bulloides* were calculated from an aliquot of ~300 specimens of planktic foraminifera from >149 μm size fraction from each sample (Table 2s). The *G. bulloides* time series is compared with sunspot numbers inferred from ^{14}C data [*Solanki et al.*, 2004], with proxies for solar activity including smoothed time series of ^{14}C production rates [*Stuiver et al.*, 1998], ^{10}Be flux data from Greenland [*Finkel and Nishiizumi*, 1997] and percent haematite-stained grains [*Bond et al.*, 2001] (Figure 1). The detrending of the sunspot numbers and *G. bulloides* time series is done by passing a ninth order best-fit polynomial and

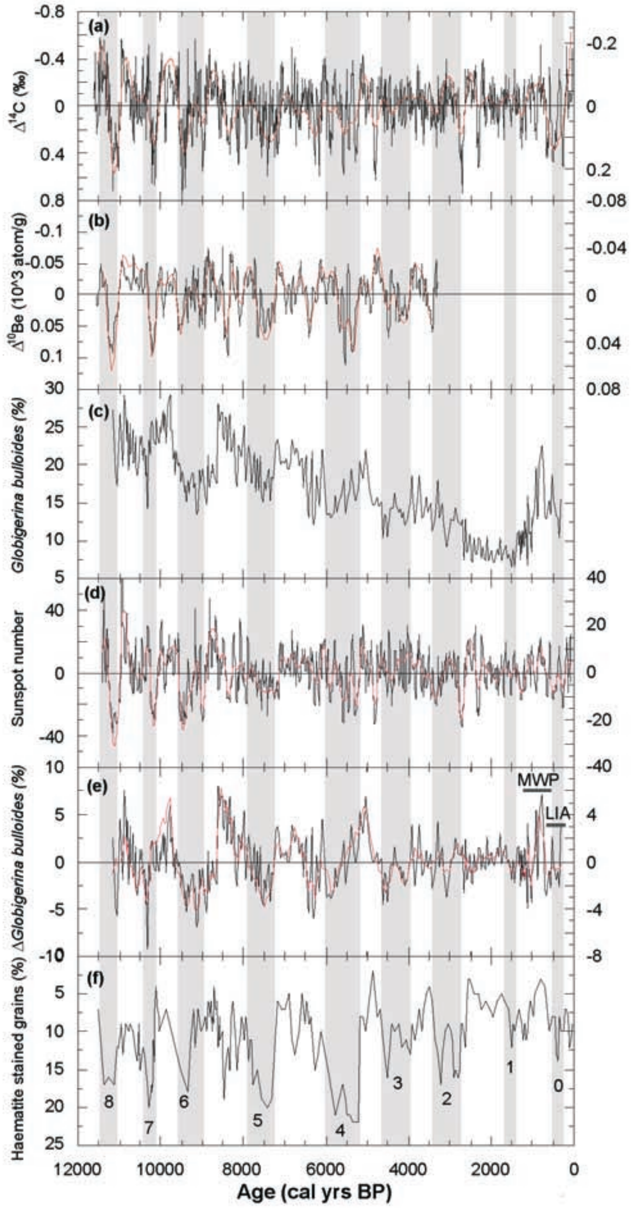

Figure 1. Southwest monsoon record from the Oman Margin combined with sunspot numbers, ^{14}C and ^{10}Be, and North Atlantic haematite percentages. Time series of **a**, ^{14}C values from Greenland [*Stuiver et al.*, 1998], **b**, ^{10}Be values from Greenland [*Finkel and Nishiizumi*, 1997], **c**, *G. bulloides* percentage in Hole 723A, **d**, sunspot numbers based on ^{14}C model [*Solanki et al.*, 2004], **e**, detrended *G. bulloides* time series, **f**, haematite % in core MC52 in the North Atlantic, and events labelled 0–8 by *Bond et al.* [2001]. Black curves are raw detrended (left side scale) and red curves are detrended smoothed (right side scale) values in panels **a**, **b**, **d** and **e**.

smoothed taking 5-point average, whereas that of ^{14}C and ^{10}Be was done by *Bond et al.* [2001].

[6] We performed spectral analysis of the *G. bulloides* and sunspot numbers using SPECTRUM program [*Schulz and Stattegger*, 1997] and calculated the rednoise using REDFIT [*Schulz and Mudelsee*, 2002] (Figure 2). Statistically significant periodicities for the *G. bulloides* time series are centred at 1550, 152, 137, 114, 101, 89, 83, and 79 years. Except the 1550 year cycle, all cycles of the *G. bulloides* time series closely match the periodicities of sunspot numbers (226, 209, 150, 132, 117, 104, 87, 82, 75 years) (Figure 2), indicating a century-scale relation between solar and summer monsoon variability. The cross-spectral analysis of these two time series further confirms the strong correspondence of the periodicities during the Holocene (Figure 2). It is remarkable to observe the 1550 year cycle in the summer monsoon record, which has been noted in numerous climate records during the last glacial as well as the present interglacial [*Mayewski et al.*, 1997; *Bond et al.*, 2001]. The presence of this periodicity, a part of Dansgaard/Oeschger cycles, in the North Atlantic [*Mayewski et al.*, 1997] as well as the summer monsoon record strengthens the sun-monsoon-North Atlantic link.

3. Discussion and Conclusions

[7] The intervals of monsoon minima (low *G. bulloides* percent) coincide with increased production rates of cosmogenic nuclides ^{14}C [*Stuiver et al.*, 1998] and ^{10}Be [*Finkel and Nishiizumi*, 1997], low sunspot numbers [*Solanki et al.*,

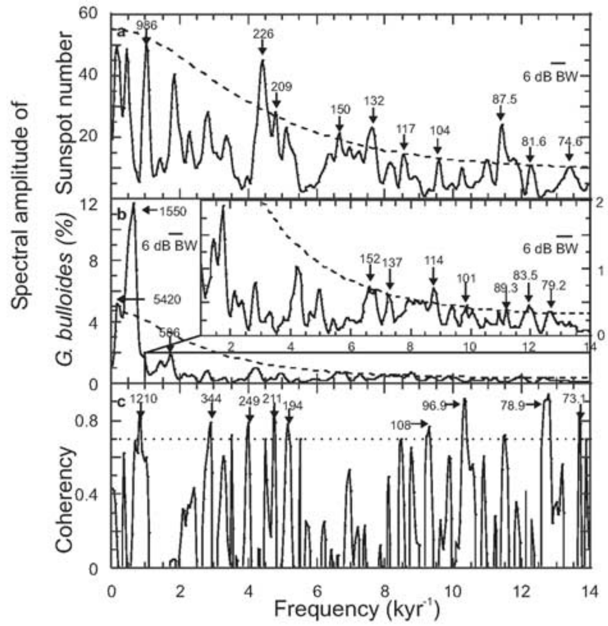

Figure 2. Frequency analysis of sunspot numbers (n = 328, panel **a**) and *G. bulloides* (n = 320, panel **b**) time series combined with coherency spectrum of the two time series (panel **c**). The enclosed portion in panel **b** is magnified to larger scales in inset. Bivariate spectral analysis was done using the SPECTRUM program [*Schulz and Stattegger*, 1997], which uses the Lomb-Scargle periodogram for unevenly spaced data. Three segments with 50% overlapping were used with Welch type window and 6 dB bandwidth [(Kyr^{-1}) 0.293 for *G. bulloides* and 0.285 for sunspot numbers]. Significant peaks, above the 90% χ^2 bound red noise background (broken line), in both the time series are labeled with their period (in years). The broken line in panel **c** is the 5% false alarm level.

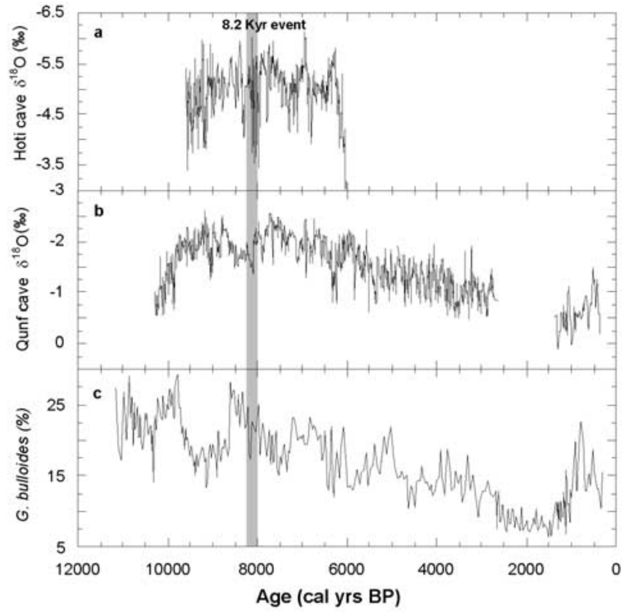

Figure 3. Visual correlation between southwest monsoon proxy records of, **a**, Hoti cave $\delta^{18}O$ [*Neff et al.*, 2001], **b**, Qunf cave $\delta^{18}O$ [*Fleitmann et al.*, 2003], and **c**, *G. bulloides* percent from ODP Hole 723A. Grey bar highlights the 8.2 Kyr event [*Alley et al.*, 1997].

2004], and increased advection of drift ice in the North Atlantic [*Bond et al.*, 2001]. Higher production rates of cosmogenic nuclides are associated with weaker solar winds and reduced irradiance [*Masarik and Beer*, 1999]. We identified nine major intervals of summer monsoon minima over the past ~11,100 cal years, which are aligned within the radiocarbon age uncertainties to intervals of cold spells in the North Atlantic (Bond events 0–8, grey bars in Figure 1). The well-documented 8.2 Kyr cold event [*Alley et al.*, 1997] is also visible in our monsoon record (Figure 3). Our record shows that the summer monsoon, in general, was strongest in the early Holocene marked by high amplitude shifts between dry and wet phases (Figure 1). The summer monsoon shows a gradual weakening over the past 8 Kyr with a more or less stable dry phase beginning ~5 Kyr B.P. that coincides with the onset of an arid phase in India [*Sharma et al.*, 2004] and termination of the Indus Valley civilization [*Staubwasser et al.*, 2003; *Gupta*, 2004]. Our record also shows that the SW monsoon winds were stronger (high solar activity) during the Medieval Warm Period (MWP) and weak (low solar activity) during the Little Ice Age (LIA). The record shows a bimodal peak during the LIA, suggesting a two-phase weakening of the SW monsoon during this most recent climatic event (Figure 1).

[8] Our correlations indicate, therefore, that over the past 11,100 years almost every multi-decadal to centennial scale decrease in summer monsoon strength is tied to a distinct interval of reduced solar output (Figures 1 and 2). Conversely, the increase in summer monsoon strength coincides with elevated solar output. The finer resolution (~30 years) of the new *G. bulloides* record reveals a strong and statistically significant correlation with the solar proxies when both records are filtered to remove the long term trend, supporting the hypothesis that solar influence on the monsoon is direct (Figure 1s, auxiliary material[1]). We are convinced by the strong correlation with the solar proxies that there is no need to hypothesize an indirect link, as we did in our earlier paper [*Gupta et al.*, 2003]. The sun-monsoon link can be explained by a direct solar influence on the Intertropical Convergence Zone (ITCZ) that controls the monsoonal precipitation [*Kodera*, 2004]. It is argued by *Kodera* [2004] that a north-south seesaw of convective activity driven by a tropical convergence zone (TCZ) tends to form over land and over the equatorial Indian Ocean ~8° south of the equator during summer [*Waliser and Gautier*, 1993]. Numerical simulation suggests that external forcing can increase the north-south seesaw of convective activity over the Indian region [*Chandrasekar and Kitoh*, 1998; *Kodera*, 2004]. During the solar maximum, temperatures in the lower stratosphere of the equatorial region are higher and equatorial activity is suppressed, which gives rise to enhanced convective activity off equatorial region. This seesaw of the activity between the equatorial and off equatorial region is strong in the Indian Ocean region where two convergence zones exist (K. Kodera, personal communication). Thus in boreal summer increased equatorial convection during high solar activity brings higher precipitation over southern Arabia as well as South Asia [*Kodera*, 2004], as seen in the paleomonsoon records [*Neff et al.*, 2001; *Fleitmann et al.*, 2003; *Gupta et al.*, 2003].

[9] The monsoon record from Oman margin is very similar to the Holocene changes in Arolik Lake, North Pacific in which increases in temperature and moisture corresponded to intervals of increased solar output, and vice versa [*Hu et al.*, 2003]. Previous studies correlated reduced solar irradiance to Holocene glacial advances in Scandinavia [*Denton and Karlén*, 1973], an early Holocene cooling event in lacustrine records from the Faroe Islands [*Björck et al.*, 2001], drift ice record from the North Atlantic [*Bond et al.*, 2001] and lake records from the North Pacific [*Hu et al.*, 2003]. *Neff et al.* [2001] found five episodes of reduced monsoon rainfall at times of intense solar minima in the 10,000–6,000 years record of cave deposits from Oman (Figure 3). The low temperature cycles in the Sargasso Sea [*Keigwin*, 1996], increases in upwelling in the Cariaco Basin [*Black et al.*, 1999], distinct episodes of drought in Yucatan Peninsula [*Hodell et al.*, 2001] all have been linked to episodes of reduced solar irradiance, indicating that the footprints of solar impact on climate can be seen across tropics to poles.

[10] The novelty of our work lies in that we have significantly demonstrated a direct link between solar activity and SW monsoon variability during the past 11,100 years in the longest continuous marine record of the SW monsoon from the Arabian Sea. Our results suggest that small changes in solar output can bring pronounced changes in the tropical climate, indicating the importance of sun-monsoon connection. An important observation of our study, which deserves further investigation, is that changes in the monsoon are more rapid when climate was warm and sun activity was high. Our results highlight the need to improve our understanding of abrupt shifts in the Indian summer monsoon that could accompany abrupt changes in

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL022685.

global climate in the future, because of its wide reach and economic importance to billions of people.

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