Quaternary Science Reviews 59 (2013) 1–4

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Viewpoint

Bi-hemispheric forcing for Indo-Asian monsoon during glacial terminations

Thibaut Caley[a,b,*], Bruno Malaizé[a], Masa Kageyama[c], Amaelle Landais[c], Valérie Masson-Delmotte[c]

[a] *Section Climate Change and Landscape Dynamics, Dept. of Earth Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*
[b] *Univ. Bordeaux, EPOC, UMR 5805, F-33400 Talence, France*
[c] *Institut Pierre-Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ – UMR8212, 91191 Gif-sur-Yvette, France*

ARTICLE INFO

Article history:
Received 20 July 2012
Received in revised form
2 October 2012
Accepted 8 October 2012
Available online 19 November 2012

Keywords:
Paleoclimatology
Quaternary
Monsoon
Terminations

ABSTRACT

The drivers of the Indo-Asian monsoon dynamics during terminations have recently emerged as a controversial issue. Cheng et al. (2009. Ice Age Terminations. Science 326, 248–252), using East-Asian speleothem records, proposed a strict northern hemisphere insolation control at the orbital timescale with weak monsoon intervals occurring at terminations. On the contrary, An et al. (2011. Glacial–Interglacial Indian Summer Monsoon Dynamics. Science 333, 719–723), using a record from the Hequing paleolake basin, highlight the importance of the southern hemisphere climate forcings on Indian summer monsoon dynamics at glacial–interglacial timescale. The purpose of this note is to propose an explanation of the weak monsoon intervals at terminations, using a deep sea sediment stack monsoon record. The mechanism involved is linked to interhemispheric interactions, as proposed by An et al. (2011), superimposed to the role of orbital forcing (precession and obliquity parameters). This explanation clarifies the combination of complex drivers acting on the Indo-Asian monsoon dynamic at terminations.

Indo-Asian summer monsoons act on the interhemispheric exchange of moisture and energy (Denton et al., 2010; Chiang and Friedman, 2012). They interact with the global climate system and strongly affect the economical prosperity of vast, heavily populated regions. Large uncertainties are associated with projections of potential future monsoon changes (IPCC, 2007). Past climates allow an exploration of the response of monsoons to a variety of natural perturbations, including the well known glacial–interglacial variability (Guo et al., 2000, 2009; Sun et al., 2006; An et al., 2011), the orbital forcing (Clemens and Prell, 2003; Wang et al., 2008; Cheng et al., 2009; Ziegler et al., 2010; Caley et al., 2011a) but also major bipolar reorganisations during millennial abrupt events (Altabet et al., 1995; Schulz et al., 1998; An et al., 2000; Wang et al., 2001; Rohling et al., 2009) (Fig. 1).

A diversity of monsoon records have been established based in proxies sensitive to winds (e.g. upwelling, transport capacity) (Altabet et al., 1995, 1999; Reichart et al., 1998; Schulz et al., 1998; Chen et al., 2003; Clemens and Prell, 2003; Schmiedl and Leuschner, 2005; Clemens et al., 2008; Sun et al., 2008; Caley et al., 2011a), to precipitation (e.g. pollen, runoff, soil weathering) (Morley and Heusser, 1997; Guo et al., 2000, 2009; Igarashi and Oba, 2006; Sun et al., 2006; Caley et al., 2011a), or to precipitation isotopic composition (e.g. speleothem calcite) (Wang et al., 2001, 2004, 2008; Fleitmann et al., 2003; Yuan et al., 2004; Sinha et al., 2005; Cheng et al., 2009). From these records, a variety of mechanisms driving the evolution of the Indo-Asian monsoon have been proposed. Among these, two recently published records illustrate the diversity of these mechanisms.

Cheng et al. (2009), using East-Asian speleothem records covering the last 400 ka, proposed a strict northern hemisphere (NH) insolation control for summer monsoon dynamics, with periods of intense monsoon occurring simultaneously to periods of high northern hemisphere summer insolation. They suggest that this relationship breaks down during glacial terminations, which are marked by periods of weak monsoon. These weak monsoon intervals (hereafter WMI) were attributed to InterTropical Convergence Zone (ITCZ) shifts driven by northern hemisphere cold anomalies caused by North Atlantic Meridional Overturning Circulation (AMOC) changes, themselves driven by NH ice sheet disintegration.

An et al. (2011), using a 2.6-million year long record from Heqing paleolake basin, have documented glacial–interglacial Indian Summer Monsoon (ISM) dynamics with an apparent absence of WMIs during terminations. The WMIs seem to be recorded in the

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[*] Corresponding author. Section Climate Change and Landscape Dynamics, Dept. of Earth Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands. Tel.: +31 20 59 87144.
E-mail address: t.caley@vu.nl (T. Caley).

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http://dx.doi.org/10.1016/j.quascirev.2012.10.008

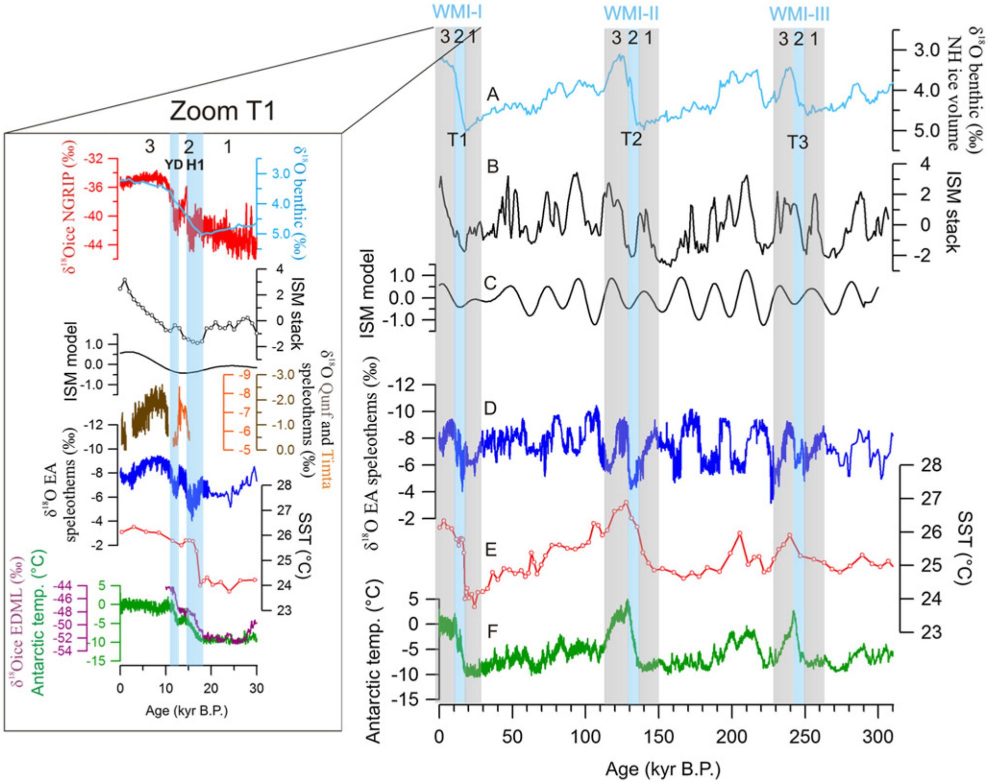

Fig. 1. The Indo-Asian monsoon at terminations in a bipolar context. (A) NH ice volume (Lisiecki and Raymo, 2005). (B) ISM stack (Caley et al., 2011a). (C) Orbital ISM model constructed using (B) with the method developed in Caley et al. (2011c). (D) Compilation of East-Asian speleothem records (Cheng et al., 2009 and references therein). (E) Sea surface temperature (SST) in the south-west Indian Ocean (Caley et al., 2011b). (F) Surface air temperature at Dome Concordia, Antarctica (Jouzel et al., 2007). WMI refers to weak monsoon interval (blue frame) and numbers 1, 2, 3 to the different phases of the Indo-Asian monsoon dynamics at terminations described in the text. T refers to terminations. A zoom is inserted for termination 1, where the age uncertainties for marine, ice and continental records are weaker. Compared to the last 300 ka, we added the high-resolution δ^{18}O ice record from Greenland (NGRIP, NGRIP Members, 2004), the EPICA Dronning Maud Land (EDML, EPICA Community Members, 2006) record and Indian monsoon records from Qunf and Timta caves (Fleitmann et al., 2003; Sinha et al., 2005) on the termination 1 zoom. H1 and YD denote Henrich event 1 and the Younger Dryas event respectively. The GICC05 timescale (NGRIP, transferred to EDML) is layer-counted with uncertainty limits which increase with age (errors are cumulative), amounting to about 0.9% at around 12 ka BP to about 3.5% at around 32 ka BP (Andersen et al., 2006; Rasmussen et al., 2006). The U–Th age uncertainties for the Dongge and Hulu cave records remain around 1.5% (Wang et al., 2001, 2004; Yuan et al., 2004). The U–Th age uncertainties for the Kunf and Timta records are better than 300 years and 600 years respectively. ^{14}C dating has a precision better than 70 years for the ISM stack during termination 1 (Caley et al., 2011a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ISM record from Marine Isotopic Stage (MIS) 12–22 but are not clearly expressed in the most recent terminations (since MIS12), possibly due to low signal to noise levels. These authors highlight the important role of the southern hemisphere (SH) on glacial–interglacial ISM dynamics in addition to traditionally considered NH dynamics. This relies on role of the cross-equatorial pressure gradient between the Indian low pressure system (over the Asian continent) and the Mascarene high pressure system (in the south-west Indian Ocean) which they see as an important driver for ISM. They identify an increase of the Indian monsoon prior glacial maxima followed by a second phase of enhances ISM when global ice volume decreases into an interglacial state.

Modelled trajectory analysis of air-flow for summer precipitation at Heqing paleolake basin indicates that 90% of total moisture comes from the Indian Ocean (An et al., 2011). Another recent modelling work suggests that East-Asian speleothems δ^{18}O signal may record remote climate changes over India and the Indian Ocean, during periods of reduced AMOC (Pausata et al., 2011). As the Indian Ocean is the primary moisture source for the Indian and East-Asian summer monsoons (Ding et al., 2004; Clemens et al., 2010), both, An et al. (2011) and Cheng et al. (2009) works, should have recorded the same monsoonal dynamics.

In this note, we will focus on Indo-Asian monsoon dynamics during the last three terminations. We are proposing an alternative explanation regarding the hypothesis of Cheng et al. (2009) to explain the WMIs at terminations. The mechanism involved is linked to the bi-hemispheric system, as proposed by An et al. (2011) but also incorporates the role of orbital forcing.

To document the Indo-Asian monsoon over the past 300 ka, we use the recent ISM marine stack of Caley et al. (2011a) located in the northern Arabian Sea. This stack combines three independent proxies which are sensitive to the humidity balance of the regional continental climate and/or winds strength (grain size, foraminiferal assemblage and XRF bromine signal). In addition, this record presents three major advantages: 1) an age model constructed independently from orbital tuning, 2) consistency within ~2 ka with eighteen other Indo-Asian summer monsoon records (Clemens et al., 2010) which represent a variety of chemical, physical, faunal, and isotopic proxies and 3) good age constraints during terminations (^{14}C ages for termination 1 with a precision better than 70 years and U/Th speleothems age constraints for terminations 2 and 3 with a precision better than 2 ka) (Clemens et al., 2010; Caley et al., 2011a).

The complexity of the interpretation of speleothem records has recently been demonstrated (LeGrande and Schmidt, 2009; Clemens et al., 2010; Pausata et al., 2011; Maher and Thompson, 2012), pointing to seasonality as well as large scale circulation effects in addition to local precipitation amounts. Despite significant differences amongst the Indo-Asian monsoon records and speleothem records at orbital timescales (Clemens et al., 2010;