Quaternary Science Reviews 29 (2010) 1317–1321

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Viewpoint

Inferring moisture transport across Central America: Can modern analogs of climate variability help reconcile paleosalinity records?

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ARTICLE INFO

Article history:
Received 10 November 2009
Received in revised form
16 February 2010
Accepted 26 February 2010

ABSTRACT

The interpretation of sea-surface paleosalinity reconstructions from the eastern tropical Pacific in terms of Atlantic-to-Pacific moisture transport is revisited. It is argued that the use of modern analogs of interannual climate variability may help to reconcile seemingly contradictory results from paleosalinity reconstructions at different locations in the east Pacific. For the Last Glacial Maximum, the pattern of tropical east Pacific paleosalinity suggests that the Atlantic-to-Pacific moisture export was similar to today's, while the wind field was probably biased towards El Niño-like conditions in that region. A La Niña analog for Heinrich Stadial 1 leads to the conclusion that the Atlantic-to-Pacific vapor transport was reduced during times of thermohaline circulation slowdown. It is further argued that the modern seasonal cycle is not a useful analog for longer-term hydroclimatic variability in the tropical Pacific–Atlantic region.

1. Introduction

The vast amount of rainfall over the tropical eastern Pacific is often attributed to the atmospheric transport of water vapor from tropical Atlantic and Caribbean sources via the northeasterly trade winds that cross Central America (e.g., Weyl, 1968; Benway and Mix, 2004). Today, this net export of freshwater from the Atlantic to the Pacific Ocean is estimated to be on the order of 0.1–0.3 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$; e.g., Zaucker and Broecker, 1992). The Atlantic-to-Pacific moisture flux helps to maintain relatively high salinities within the Atlantic and is therefore an important driving factor for the global thermohaline circulation (THC; e.g., Broecker et al., 1990; Stocker and Wright, 1991; Zaucker et al., 1994; Schmittner et al., 2000; Hasumi, 2002). Modelling studies further suggest that the Atlantic-to-Pacific moisture transport exerts a strong control on the stability of the THC in glacial and deglacial climates (Lohmann, 2003; Romanova et al., 2004) and plays a crucial role in the prediction of future climate change (Latif et al., 2000; Marsh et al., 2007). For a deeper understanding of the mechanisms that stabilize or destabilize the THC, the reconstruction of past changes in the cross-isthmus water vapor transfer is therefore of great importance.

Although the role of moisture transport in maintaining the Atlantic–Pacific interocean salinity contrast is known, variations through time are still poorly constrained. So far, three paleoceanographic studies were devoted to the estimation of past changes in the cross-isthmus vapor transport during the last ice age (Benway et al., 2006; Leduc et al., 2007; Pahnke et al., 2007). In these studies (ice-volume corrected) sea-surface paleosalinity reconstructions from the eastern tropical Pacific (partly in combination with records from the Caribbean) were used to derive changes in the Atlantic-to-Pacific moisture flux during the latest Quaternary. The basic idea of this approach is that Atlantic and Caribbean moisture sources compose a significant portion of the precipitation budget in the eastern tropical Pacific (Benway and Mix, 2004) and, hence, a local salinity increase (decrease) should reflect a decrease (increase) in the cross-isthmus moisture transport. An alternative approach to interpret the paleosalinity data in terms of water vapor fluxes would involve modern analogs of climate variability inferred from instrumental meteorological data. In what follows, we will show that this second approach has the potential to reconcile seemingly contradictory results between the studies of Benway et al. (2006), Leduc et al. (2007), and Pahnke et al. (2007).

2. Modern analogs of climate variability

2.1. Seasonal variability

In present-day boreal summer and autumn (May to late November), the eastern Pacific Intertropical Convergence Zone

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0277-3791/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2010.02.029

(ITCZ) is located at its northernmost position (cf. Fig. 1). During this time of the year, the moisture transport across the Central American isthmus is weak (Liu and Tang, 2005). A strong sea-surface temperature (SST) gradient across the equator related to the eastern Pacific equatorial front and the strong southeast trades enhance the so-called Choco Jet, a low-level jet that transports large amounts of Pacific moisture into the Panama Bight region (Poveda and Mesa, 2000; Hastenrath, 2002). In winter and early spring (December to April) the ITCZ is at its southernmost position close to the equator and strong northeasterly trades cross the Central American isthmus (Fig. 1). Although precipitation is at its minimum during this time of the year, large amounts of water vapor are transported from the Atlantic into the Pacific across Central America via the intense northeast trades (Liu and Tang, 2005). The southeast trade winds and the equatorial front, however, are weak and the Choco Jet ceases, delivering less Pacific moisture to western Colombia (Poveda and Mesa, 2000).

2.2. Interannual variability

Fig. 2 shows the leading EOF (Empirical Orthogonal Function) of modern annual-mean precipitation for the northern South American region. It is not surprising that the first EOF is strongly linked to the El Niño/Southern Oscillation (ENSO). The four maxima of the corresponding time amplitude function (not shown) are associated with the El Niño years 1983, 1992, 1997, and 1998, while the four minima are linked to La Niña conditions (1985, 1988, 1989, 1996). On the Pacific side, the EOF exhibits a precipitation dipole between the Panama Bight/Colombian coast and the eastern Pacific west of ~80°W. In most parts of Colombia, El Niño is associated with droughts due to a weakening of the moisture-laden Choco Jet, the strength of which is positively correlated to the north-south SST gradient between the eastern Pacific cold tongue area and western Colombia (Poveda and Mesa, 2000; Vernekar et al., 2003). Over the Atlantic Ocean, a north–south precipitation dipole is visible (Fig. 2). Associated with a northward (southward) shift of the ITCZ, the corresponding surface wind anomalies are directed northward (southward) over the Atlantic (eastern Pacific) during El Niño phases. A northward shift of the Atlantic ITCZ associated with El Niño has also been identified in previous works (Enfield and Mayer, 1997; Chiang et al., 2000). Precipitation over the Caribbean is in phase with Panama Bight/Colombian rainfall. As to the Atlantic-to-Pacific moisture flux, Schmittner et al. (2000) presented evidence that the transport of water vapor out of the tropical Atlantic is enhanced (reduced) during warm (cold) ENSO phases. The difference in moisture export between La Niña and El Niño conditions is on the order of 0.1 Sv for the entire Atlantic. Model results suggest that this amplitude may substantially affect the THC (Schmittner et al., 2000).

The present-day analogs of seasonal and interannual climate variability provide four scenarios which are characterized by the positions of the Atlantic and Pacific ITCZs, the strength of the Choco Jet, the intensity of the Atlantic-to-Pacific moisture transport and the tropical eastern Pacific rainfall pattern (Table 1). Interannual climate variability is ruled by ENSO, whose most distinct feature in the region of interest is the precipitation dipole between the Panama Bight and the open eastern Pacific.

3. Modern analogs applied to the paleosalinity records

3.1. Last Glacial Maximum

Investigations of sediment cores from the eastern Pacific “freshwater pool” off the coast of Costa Rica (~8°N; ODP Site 1242 and MD02-2529; see Fig. 2 for core locations) indicated (ice-volume corrected) Last Glacial Maximum (LGM) paleosalinities

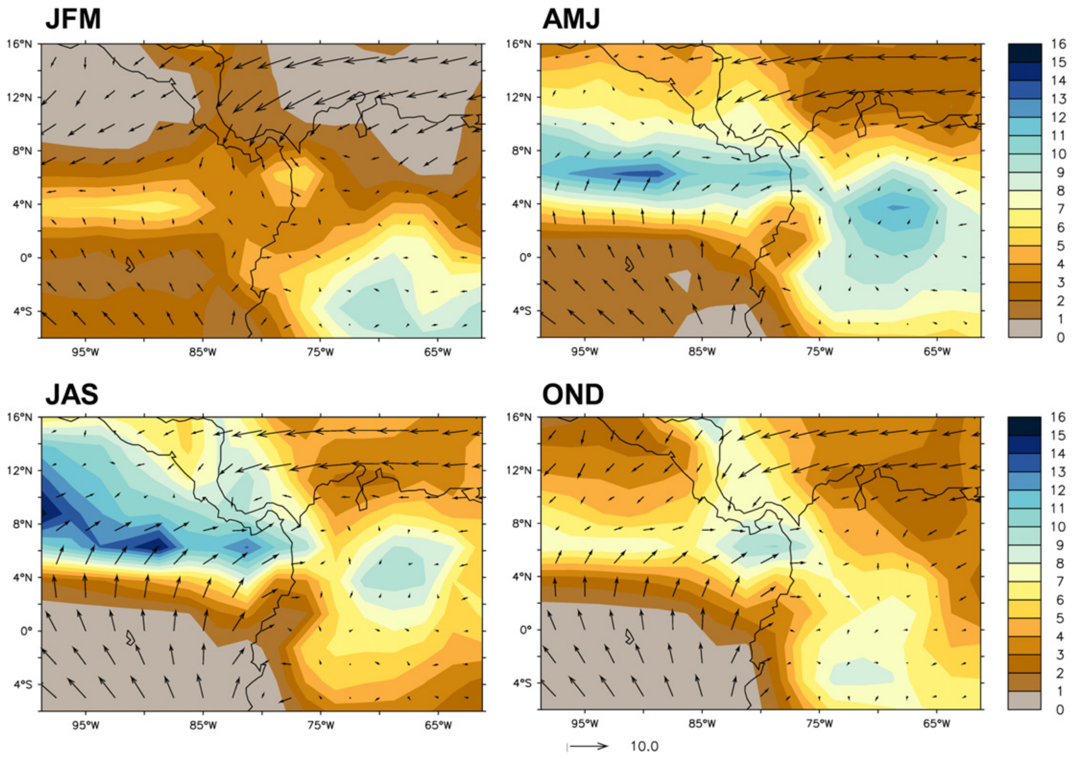

Fig. 1. Climatological (1979–2007) precipitation (mm/day) and surface winds (m/s) for different seasons (January–March, April–June, July–September, October–December), 2.5° resolution. Data sources: CPC Merged Analysis of Precipitation (Xie and Arkin, 1997), NCEP/NCAR reanalysis (Kalnay et al., 1996).

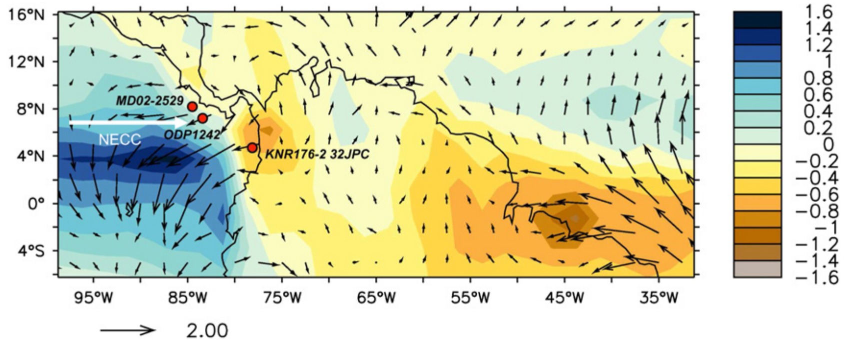

Fig. 2. First EOF of annual-mean precipitation (mm/day) for the region displayed (32% variance explained). Detrended precipitation data (gridded, 2.5° resolution) for the period 1979–2007 were used. Overlaid is the associated surface wind field (m/s) computed as the composite difference of annual-mean surface wind constructed from the years where the first time amplitude function of annual precipitation is at maximum (El Niño-dominated years 1983, 1992, 1997, 1998) or minimum (La Niña-dominated years 1985, 1988, 1989, 1996). Note that an almost identical pattern emerges from the regression of annual-mean precipitation upon the Multivariate (or any other) ENSO Index (Garreaud et al., 2009). The red dots indicate the locations of sediment core MD02-2529 (Leduc et al., 2007), ODP Site 1242 (Benway et al., 2006), and sediment core KNR176-2 32JPC (Pahnke et al., 2007). Unlike KNR176-2 32JPC, which is a sensitive recorder of continental runoff due to its proximity to the mouth of Rio San Juan (Pahnke et al., 2007), MD02-2529 and ODP 1242 are hardly affected by river runoff (cf. Benway and Mix, 2004). Instead, these sites are under the influence of the broad eastward flowing North Equatorial Counter Current (NECC; white arrow) which transports surface salinity anomalies from the open Pacific to the core locations (Chaigneau et al., 2006). Therefore, even though the Costa Rica sites are located close to the zero anomaly contour, they are suitable recorders of rainfall anomalies over the open eastern Pacific. Data sources: CPC Merged Analysis of Precipitation (Xie and Arkin, 1997), NCEP/NCAR reanalysis (Kalnay et al., 1996).

similar to modern values (Benway et al., 2006; Leduc et al., 2007). The lack of a significant glacial–interglacial salinity contrast was interpreted such that the cross-isthmus moisture transport was hardly affected by LGM boundary conditions. It has been argued that the effect of stronger glacial trade winds – favoring enhanced westward moisture transport – was offset by a generally lower glacial atmospheric moisture content (Benway et al., 2006).

By contrast, a recent study on sediment core KNR176-2 32JPC from the western Colombian margin (see Fig. 2 for core location) indicated reduced precipitation and river discharge into the Panama Bight during the LGM as compared to the Holocene (Pahnke et al., 2007). At first glance, this finding seems to be in conflict with Benway et al. (2006) and Leduc et al. (2007). However, the sediment core off western Colombia is situated in a different hydrologic regime, mainly recording changes in the amount of Pacific moisture transport towards South America delivered by the Choco Jet (Poveda and Mesa, 2000). Hence, the glacial salinity increase found in core KNR176-2 32JPC is most likely attributable to a weakening of this westerly jet. Such a weakening would be consistent with both a winter-like and an El Niño-like scenario (see Table 1). The winter-like scenario, however, would require drier conditions also over the eastern Pacific off Costa Rica (Fig. 1) which is not supported by the proxy data (Benway et al., 2006; Leduc et al., 2007). By contrast, the El Niño-related precipitation dipole in the eastern tropical Pacific would be consistent with the proxy records, if we further assume that the El Niño-related rainfall increase over the eastern Pacific (Fig. 2) was compensated by a general weakening of the glacial hydrologic cycle due to a reduced moisture-holding capacity of the colder air and an associated reduction in evaporation.

The combination of an El Niño-like wind pattern (favoring Atlantic moisture export; see Table 1) with reduced atmospheric vapor content (compensating for enhanced Atlantic moisture export) would be consistent with the model result of an Atlantic-to-Pacific moisture flux during the LGM that was similar to the present one (Lohmann and Lorenz, 2000; their experiment “LGM.N”). Indeed, some paleoceanographic studies considered the ice-age climate in the tropical Pacific as similar to an El Niño-like state (e.g., Koutavas et al., 2002; Stott et al., 2002; Koutavas and Lynch-Stieglitz, 2003). Other studies, however, proposed that glacial Pacific climate was biased towards La Niña (e.g., Lea et al., 2000; Andreasen et al., 2001; Beaufort et al., 2001; Martínez et al., 2003). A recent study by Dubois et al. (2009) suggested a southward displacement of the Pacific ITCZ along with colder SST in the eastern equatorial Pacific cold tongue compared to sites further north in the equatorial front and eastern Pacific warm pool. The authors, however, also pointed out that SST proxies are affected by various biases, which may lead to controversial results regarding the history of the eastern equatorial Pacific.

3.2. Heinrich Stadial 1

Proxy records (e.g., Peterson et al., 2000; Jaeschke et al., 2007) and climate model studies (Stouffer et al., 2006) indicate that THC-related millenial-scale North Atlantic cold events, like Heinrich Stadial 1 (H1), were accompanied by a southern position of the Atlantic ITCZ. It has further been suggested that this may also hold true for the Pacific ITCZ (Benway et al., 2006; Kienast et al., 2006; Leduc et al., 2007, 2009).

Based on eastern tropical Pacific paleosalinity maxima, Benway et al. (2006) and Leduc et al. (2007) suggested that the cross-isthmus atmospheric freshwater export from the Atlantic/Caribbean into the Pacific was reduced during North Atlantic cold events

Table 1
Modern analogs of seasonal and interannual climate variability.

Modern analog	ITCZ position	Choco Jet	Atlantic–Pacific moisture flux	Rainfall pattern
Boreal winter-like scenario	Southern position over Atlantic and Pacific	Weak	Enhanced	Dry over Panama Bight and to the west of it
Boreal summer-like scenario	Northern position over Atlantic and Pacific	Strong	Reduced	Wet over Panama Bight and to the west of it
El Niño-like scenario	Southern/northern position over Pacific/Atlantic	Weak	Enhanced	Wet over tropical east Pacific except over dry Panama Bight
La Niña-like scenario	Northern/southern position over Pacific/Atlantic	Strong	Reduced	Dry over tropical east Pacific except over wet Panama Bight

when the ITCZ was further south. This connection, however, is not in line with modern observations of vapor flux across the Central American isthmus (see Table 1, winter-like scenario with southern position of the ITCZ and enhanced moisture flux). By contrast, the paleosalinity record from core KNR176-2 32JPC off western Colombia (Pahnke et al., 2007) suggests rising rainfall and river runoff – relative to the LGM – during a cold interval correlated to H1 (although we note that maximum values in humidity occur after H1, possibly due to a generally enhanced atmospheric moisture-holding capacity and hence intensified hydrologic cycle under globally warmer post-glacial conditions, favoring low salinities at all three sites). The authors interpreted increased freshwater supply to the Panama Bight as a result of enhanced water vapor transfer from the Atlantic/Caribbean to the Pacific. The conflicting observations may be reconciled in view of the ENSO-related precipitation dipole (Fig. 2). Increasing precipitation and river runoff in western Colombia during H1 would rather point to a strengthening of the Choco Jet, a strong equatorial front, and more La Niña-like climate during H1, which in turn would be corroborated by saltier conditions at the core locations off Costa Rica (Benway et al., 2006; Leduc et al., 2007). Such La Niña-like conditions would be associated with reduced Atlantic freshwater export (Table 1). A recent study indeed challenged the notion of a warm ENSO phase in the Pacific during H1 (Koutavas and Sachs, 2008). The authors pointed out that low alkenone-derived SSTs in the Pacific cold tongue area and high productivity near Galapagos (e.g., Kienast et al., 2006; Koutavas and Sachs, 2008) are inconsistent with a southern position of the Pacific ITCZ and/or with a mean El Niño-like state during stadials. This argues for contrasting ITCZ movements in the Atlantic and Pacific during Heinrich Stadials, as observed today associated with ENSO.

4. Conclusions

The assumption of an ENSO-like precipitation dipole may reconcile seemingly contradictory paleosalinity reconstructions from the eastern tropical Pacific. By contrast, the modern seasonal cycle is not a useful analog for longer-term hydroclimatic variability in that region, as already pointed out by Benway et al. (2006). The pattern of tropical east Pacific paleosalinity suggests an El Niño-like wind field for the LGM. In combination with a reduced moisture-holding capacity of the glacial atmosphere, this probably resulted in an Atlantic-to-Pacific moisture transport similar to the modern one.

Assuming the La Niña analog for H1 leads to the conclusion that the Atlantic-to-Pacific vapor transport was reduced during times of THC slowdown. This would imply further freshening of the Atlantic and, hence, a positive feedback on abrupt climate change – in contrast to the reasoning of Pahnke et al. (2007) who argued in favor of a negative feedback (i.e. increased cross-isthmus vapor flux during H1). Interestingly, Leduc et al. (2007) also inferred a positive feedback, although for different reasons. They proposed a winter-like scenario with a southern position of the Atlantic–Pacific ITCZ during Heinrich Stadials, assuming that the modern vapor transport across Central America mainly takes place during the summer season when the ITCZ is at a northerly position, in contrast to observational evidence (Liu and Tang, 2005). The notion of a reduced cross-isthmus vapor flux in response to meltwater-induced THC slowdown is in contrast to numerical freshwater hosing experiments (carried out under modern boundary conditions) which suggest an enhanced Atlantic-to-Pacific moisture transport (Lohmann, 2003; Xie et al., 2008). Whether this finding also holds when glacial boundary conditions are applied to the models has still to be shown. We finally note that, even though ENSO analogs for H1 and the LGM may be appropriate for the tropics, they should not be overinterpreted in terms of their global impact. Low- to high-latitude ENSO teleconnections during those intervals were very different from today (Merkel et al., 2010). Taken together, there is an urgent need for more high-resolution paleosalinity records from the equatorial regions to better understand the role of the tropical hydrologic cycle in shaping abrupt climate change.

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