Quaternary Science Reviews 180 (2018) 214–228

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Hemispherically asymmetric trade wind changes as signatures of past ITCZ shifts

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A R T I C L E I N F O

Article history:
Received 11 July 2017
Received in revised form
15 November 2017
Accepted 15 November 2017

Keywords:
ITCZ
Hadley circulation
Tropics
Heinrich stadials
Quaternary
Climate dynamics
Global

A B S T R A C T

The atmospheric Hadley cells, which meet at the Intertropical Convergence Zone (ITCZ), play critical roles in transporting heat, driving ocean circulation and supplying precipitation to the most heavily populated regions of the globe. Paleo-reconstructions can provide concrete evidence of how these major features of the atmospheric circulation can change in response to climate perturbations. While most such reconstructions have focused on ITCZ-related rainfall, here we show that trade wind proxies can document dynamical aspects of meridional ITCZ shifts. Theoretical expectations based on angular momentum constraints and results from freshwater hosing simulations with two different climate models predict that ITCZ shifts due to anomalous cooling of one hemisphere would be accompanied by a strengthening of the Hadley cell and trade winds in the colder hemisphere, with an opposite response in the warmer hemisphere. This expectation of hemispherically asymmetric trade wind changes is confirmed by proxy data of coastal upwelling and windblown dust from the Atlantic basin during Heinrich stadials, showing trade wind strengthening in the Northern Hemisphere and weakening in the Southern Hemisphere subtropics in concert with southward ITCZ shifts. Data from other basins show broadly similar patterns, though improved constraints on past trade wind changes are needed outside the Atlantic Basin. The asymmetric trade wind changes identified here suggest that ITCZ shifts are also marked by intensification of the ocean's wind-driven subtropical cells in the cooler hemisphere and a weakening in the warmer hemisphere, which induces cross-equatorial oceanic heat transport into the colder hemisphere. This response would be expected to prevent extreme meridional ITCZ shifts in response to asymmetric heating or cooling. Understanding trade wind changes and their coupling to cross-equatorial ocean cells is key to better constraining ITCZ shifts and ocean and atmosphere dynamical changes in the past, especially for regions and time periods for which few paleodata exist, and also improves our understanding of what changes may occur in the future.

1. Introduction

The paleoclimate record contains abundant evidence of past perturbations of the balance of surface temperatures between the two hemispheres, and as such it provides unique insights into the climate system's response to hemispherically asymmetric heating (Broecker and Putnam, 2013; Harrison et al., 1983; Schneider et al., 2014). The clearest examples of such perturbations are millennial-scale coolings of the Northern Hemisphere (stadials) that occurred during the last glacial period (Dansgaard et al., 1982; Alley et al., 1993; Bond et al., 1993; Taylor et al., 1993; Blunier et al., 1998; Blunier and Brook, 2001; Barbante et al., 2006; Clement and Peterson, 2008). During these events, expansions of sea ice in the North Atlantic and reduction of cross-equatorial ocean heat transport associated with the Atlantic Meridional Overturning Circulation (AMOC) are thought to have cooled the Northern Hemisphere

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https://doi.org/10.1016/j.quascirev.2017.11.020
0277-3791/

(NH) (Boyle and Keigwin, 1987; Clement and Peterson, 2008; Henry et al., 2016; Li et al., 2005) and warmed the Southern Hemisphere (SH) (Barker et al., 2009; Blunier et al., 1998; Broecker, 1998; Buizert et al., 2015). The most prolonged of these stadials were also marked by iceberg discharge into the North Atlantic and are known as Heinrich stadials (Hemming, 2004). Stadials have been connected with shifts in the tropical rain belt associated with the Intertropical Convergence Zone (ITCZ) and changes in monsoon strength. A broad range of evidence indicates a southward shift of the ITCZ, a weakening of NH monsoons, and a strengthening of at least the South American summer monsoon in the SH in response to NH cooling (Arbuszewski et al., 2013; Baker, 2001; Collins et al., 2013; McGee et al., 2014; Peterson, 2000; Placzek et al., 2006; Stager et al., 2011; Wang et al., 2007, 2004; Wang, 2001).

A variety of modeling experiments have found a qualitatively similar southward shift of the ITCZ in response to NH cooling. In these studies, ITCZ shifts are accompanied by a pronounced intensification of the annual-mean Hadley cell in the NH and a weakening in the SH, with each hemisphere's trade winds — the surface expression of the Hadley circulation — changing in kind (Figs. 1 and 2) (Broccoli et al., 2006; Chiang, 2003; Chiang and Bitz, 2005; Dahl et al., 2005; Timmermann et al., 2005; Vellinga and Wood, 2002; Zhang and Delworth, 2005). As we review below, this asymmetric Hadley cell and trade wind response is a fundamental expectation of the atmosphere's response to asymmetric cooling of one hemisphere and a shift of the ITCZ toward the warmer hemisphere.

Trade wind changes are central to the dynamics of stadials and other perturbations of interhemispheric temperature differences. By regulating upwelling along eastern boundaries, trade winds determine surface productivity and air-sea heat and carbon dioxide fluxes over large areas of the world's oceans. Trade winds also have a pronounced influence on the ocean circulation, helping drive the circulation of the subtropical gyres and subtropical cells. Attempts to model ocean circulation in the Atlantic during the Last Glacial Maximum (LGM) have demonstrated that even small changes in surface trade winds can alter ocean circulation and improve data-model agreement (Amrhein et al., 2015; Dail and Wunsch, 2014); as such, accurate characterization of trade wind responses during stadials may be essential to modeling of the ocean's response to these events. Trade winds modulate evaporative fluxes from subtropical oceans, leading to sea surface temperature (SST) cooling in the hemisphere in which trade winds intensify; this wind-evaporation-SST feedback may play a central role in communicating high-latitude cooling to the low latitudes (Chiang and Bitz, 2005), and may warm tropical SSTs in the opposite hemisphere, where trade winds are expected to weaken. Perhaps most importantly for the dynamics of abrupt climate change, trade wind-driven changes in the ocean's subtropical cells may increase ocean heat transport into the cooler hemisphere, limiting the magnitude of ITCZ shifts (Green and Marshall, 2017; Yang et al., 2017, 2013).

It is thus clear that trade winds are more than passive tracers of atmospheric circulation changes during NH cooling events; rather, they actively modulate the atmosphere-ocean system's response to asymmetric warming/cooling. Reconstructions of trade wind changes during NH cooling events thus have the potential to provide unique insights into the dynamics of the atmosphere and ocean's response to asymmetric warming or cooling. Proxy-based constraints on trade wind changes are particularly valuable in light of models' long-standing biases in simulating the ITCZ (Oueslati and Bellon, 2015), which raise questions about the accuracy of simulated responses to forcing.

Despite this potential, few studies have focused on reconstructing trade wind responses to changes in the balance of heating between the hemispheres. Most observational studies of the tropical atmosphere's response to NH cooling events have employed precipitation proxies (Arbuszewski et al., 2013; Baker, 2001; Collins et al., 2013; Peterson, 2000; Sachs et al., 2009; Schneider et al., 2014; Wang et al., 2004) and have focused on the behavior of the tropical rain belt and monsoons, leaving changes in the broader Hadley circulation relatively unexplored. Previous investigations of trade winds in Late Pleistocene climates have primarily focused on single regions and on glacial-interglacial changes. Studies in the eastern subtropical Atlantic (Sarnthein et al., 1981), the southeastern Atlantic Ocean (Little et al., 1997; Stuut et al., 2002), the southeastern Indian Ocean (Stuut et al., 2014), and the southeastern Pacific Ocean (Saukel, 2011) have concluded that trade winds in each of these regions were more intense during the last glacial period than today, with little indication of hemispheric asymmetry. A study of past changes in thermocline depth in the western tropical Pacific, which reflects the surface wind field, found evidence for an anomalous thermocline ridge centered at ~6-7°S during the LGM, consistent either with a southward shift of the ITCZ or a more zonal orientation of the South Pacific Convergence Zone (Leech et al., 2013).

Here we present a compilation of trade wind proxies during Heinrich stadials, the longest and largest-amplitude NH cooling events of the last glacial period and deglaciation, and explore the implications of trade wind changes for the dynamics of these events. This compilation offers an important complement to existing precipitation-based reconstructions, as precipitation proxies are not available everywhere and are particularly sparse over oceans, which underlie the majority of the tropical rain belt. Further, interpretation of precipitation proxies is not always straightforward; each proxy is sensitive to multiple variables, including precipitation amount, evapotranspiration, water vapor source, and convective processes, and the relationship between these variables and the broader Hadley circulation can sometimes be unclear. Trade wind-sensitive proxy data provide additional leverage in testing interpretations of past atmospheric changes, as they directly reflect the tropical atmospheric circulation.

We begin, in Section 2, with a description of the dynamics and observations of the trade winds and their response to Northern Hemisphere cooling in models. In Section 3, we summarize and evaluate proxies for trade wind intensity. In Section 4, we review evidence for trade wind changes associated with Heinrich stadials. We discuss the implications of these results in Section 5, including the role trade winds play in damping the ITCZ response to interhemispheric temperature differences, and close with a summary of key findings and a discussion of directions for future research in Section 6.

2. Dynamics of wind responses to ITCZ shifts

2.1. *Dynamics of the Hadley circulation and trade wind changes accompanying ITCZ shifts*

Before describing the paleoclimate evidence, we introduce the physical mechanisms underlying the response of the tropical atmospheric circulation and trade winds to an interhemispheric heating contrast, as reconstructed during stadials. We start by considering an idealized state without any heating contrast between the Northern and Southern hemispheres, and without cross-equatorial energy transport. In this idealized configuration, the zonally averaged tropical atmospheric circulation is symmetric about the Equator in the annual mean; the Hadley cells and the surface zonal winds are of equal strength in both hemispheres (Fig. 1A). The ascending branch of the Hadley circulation and the ITCZ are therefore situated at the Equator.