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Changes in equatorial Pacific thermocline depth in response to Panamanian seaway closure: Insights from a multi-model study

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ABSTRACT

The early Pliocene warm phase was characterized by high sea surface temperatures and a deep thermocline in the eastern equatorial Pacific. A new hypothesis suggests that the progressive closure of the Panamanian seaway contributed substantially to the termination of this zonally symmetric state in the equatorial Pacific. According to this hypothesis, intensification of the Atlantic meridional overturning circulation (AMOC) – induced by the closure of the gateway – was the principal cause of equatorial Pacific thermocline shoaling during the Pliocene. In this study, twelve Panama seaway sensitivity experiments from eight ocean/climate models of different complexity are analyzed to examine the effect of an open gateway on AMOC strength and thermocline depth. All models show an eastward Panamanian net throughflow, leading to a reduction in AMOC strength compared to the corresponding closed-Panama case. In those models that do not include a dynamic atmosphere, deepening of the equatorial Pacific thermocline appears to scale almost linearly with the throughflow-induced reduction in AMOC strength. Models with dynamic atmosphere do not follow this simple relation. There are indications that in four out of five models equatorial wind-stress anomalies amplify the tropical Pacific thermocline deepening. In summary, the models provide strong support for the hypothesized relationship between Panama closure and equatorial Pacific thermocline shoaling.

1. Introduction

During the warm early Pliocene, ~5.5 to 4 Ma ago, sea surface temperatures in the eastern equatorial Pacific were similar to those of the western tropical Pacific warm pool (Fedorov et al., 2006; Lawrence et al., 2006; Ravelo et al., 2004; Wara et al., 2005). The absence of the eastern equatorial Pacific cold tongue was linked to a weak Walker Circulation, a deep thermocline and low biogenic productivity in the tropical region (Barreiro et al., 2006; Dekens et al., 2007; Fedorov et al., 2006). It has been suggested that this warm equatorial state was responsible for a 3–4 °C warmer-than-present global mean surface temperature and the absence of major ice sheets in the northern hemisphere via processes and teleconnections similar to those that are at work during El Niño states (e.g. Barreiro et al., 2006; Cane and Molnar, 2001; Chiang, 2009; Huybers and Molnar, 2007; Molnar and Cane, 2002; Vizcaíno et al., 2010), although other studies have disputed this (Haywood et al., 2007; Lunt et al., 2008b). Recent studies suggested mechanisms that might have contributed to maintaining the "permanent El Niño-like" climate state, involving a higher frequency of tropical cyclones in the early Pliocene (Fedorov et al., 2010) or a dynamical state approaching "equatorial superrotation" with westerly surface wind anomalies over the equatorial Pacific (Tziperman and Farrell, 2009). However, causes or preconditions for the termination of the equatorial Pacific zonally symmetric state remain obscure. In particular, the original hypothesis by Cane and Molnar (2001), which suggests a key role for the northward displacement and uplift of New Guinea and Halmahera in triggering the climatic switch in the equatorial Pacific, could not be corroborated by climate model experiments thus far (Jochum et al., 2009; Krebs et al., 2011).

A new hypothesis brings the Pliocene closure of the Panamanian seaway into play. Analyzing oxygen isotope and Mg/Ca temperature records from shallow- and deep-dwelling planktonic foraminifers, Steph et al. (2010) reconstructed the Pliocene evolution of the thermocline in the eastern equatorial Pacific and found that gradual shoaling of the thermocline between 4.8 and 4 Ma ago occurred

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synchronously with the progressive closure of the Panamanian seaway and an increase in the Atlantic meridional overturning circulation (AMOC). Based on these findings along with simulation results from the coupled climate model ECBILT-CLIO, Steph et al. (2010) suggested the following chain of events: The early Pliocene shoaling of the Panamanian seaway caused an intensification of the AMOC driven by enhanced North Atlantic Deepwater (NADW) formation. Enhanced NADW production resulted in an increased volume of the "cold water sphere" and hence to upward thermocline shifts in the global ocean transmitted by baroclinic oceanic adjustment processes (Cessi et al., 2004; Clement and Peterson, 2008; Goodman, 2001; Haarsma et al., 2008; Huang et al., 2000; Lopes dos Santos et al., 2010; Timmermann et al., 2005). In the eastern tropical Pacific, the thermocline shoaling preconditioned the equatorial cold tongue state, before intensified trade winds (probably related to high-latitude glaciation) could bring cold waters to the surface after ~3.6 Ma.

In this study, we shall further test the hypothesized relationship between Panama closure, AMOC strength and equatorial Pacific thermocline depth. How robust are the model results presented by Steph et al. (2010) among different models? How strong is the influence of changes in AMOC strength on tropical Pacific thermocline depth? How may wind-stress feedbacks affect the Pacific thermocline? To address these questions, we analyze and compare climate model results from twelve different Panamanian seaway-closure simulations.

2. Model simulations and analysis

A total of twelve experiments with eight different models are analyzed in this study. In contrast to coordinated model intercomparison projects, the model experiments were set up independently, such that differences in boundary conditions, Panama seaway depth, etc. exist. Table 1 provides an overview of the different models and setups. Five models include a dynamic atmosphere, thus allowing for, e.g., wind-stress feedbacks (HadCM3, CCSM2, CCSM3, KCM and ECBILT-CLIO). The other three models (UVIC, BREMIC/LSG, MIT) apply prescribed modern wind fields to force the ocean. All models use present-day or pre-industrial boundary conditions, except for the HadCM3 experiment in which mid-Pliocene boundary conditions are applied. The mid-Pliocene boundary conditions include reduced ice-sheet sizes, Pliocene vegetation distribution and enhanced atmospheric CO_2 concentration (400 ppmv). As a result, the global mean surface temperature is ca. 3 °C warmer compared to pre-industrial conditions (Lunt et al., 2008a).

Applying different seaway depths and ocean vertical diffusivities, Schneider and Schmittner (2006) performed a series of sensitivity experiments with the UVIC model. These experiments are referred to as UVIC3sh, UVIC3in, UVIC6sh and UVIC6in, where "3", "6", "sh" and "in" stand for low vertical diffusivity (0.3 $cm^2\ s^{-1}$ in the upper ocean), high vertical diffusivity (0.6 $cm^2\ s^{-1}$ in the upper ocean), shallow seaway (130 m) and intermediate-depth seaway (700 m). This allows us to examine the effects of both vertical mixing and Panamanian sill depth on the behavior of the Pacific equatorial thermocline in one and the same model. We note that the UVIC simulations with a 2000 m deep Panamanian gateway performed by Schneider and Schmittner (2006) were not included in this paper, as the results of these simulations are nearly identical to the UVIC runs with a 700 m deep seaway.

Four previously unpublished Panama experiments have been conducted and are included in this study. ECBILT-CLIO was used in the first new experiment. Apart from a shallower Panamanian sill depth (415 m), the experimental design is identical to that described by Prange and Schulz (2004) who applied a 700 m deep seaway in their original study. In the second previously unpublished experiment, we employed the global ocean model BREMIC/LSG coupled to a simplified energy balance model. The closed-Panama control run with modern boundary conditions is described in Butzin et al. (2005, 2011). In the corresponding open-Panama experiment, the model has been integrated into a new equilibrium after implementing a 500 m deep seaway by replacing three land grid cells by ocean cells. The third new experiment employed the comprehensive Community Climate System Model version 3 (CCSM3) in its low-resolution version (Collins et al., 2006; Yeager et al., 2006). The

Table 1
Overview of the model simulations analyzed in this paper. "AMOC" refers to the North Atlantic overturning streamfunction maximum. Four different experiments were performed with the UVIC model which differs in Panamanian seaway depth and vertical mixing. These experiments are denoted by "3", "6", "sh" and "in" which stands for low vertical diffusivity (0.3 $cm^2\ s^{-1}$ in the upper ocean), high vertical diffusivity (0.6 $cm^2\ s^{-1}$ in the upper ocean), shallow seaway (130 m) and intermediate depth seaway (700 m). With ECBILT-CLIO, two experiments with different seaway depths were carried out, denoted by EC415 and EC700, which stands for 415 m and 700 m depth, respectively.

Model name	Atmosphere component	AMOC (Sv); closed/open seaway	Seaway depth (m)	Net eastward flow through seaway (Sv)	Remark	Reference for model	Reference for open-Panama experiment
UVIC 3sh	Energy-moisture balance model	13/11	130	5	Vert. diffusivity: 0.3–1.3 $cm^2\ s^{-1}$	Weaver et al. (2001)	Schneider and Schmittner (2006)
UVIC 3in	Energy-moisture balance model	13/5	700	10	Vert. diffusivity: 0.3–1.3 $cm^2\ s^{-1}$	Weaver et al. (2001)	Schneider and Schmittner (2006)
UVIC 6sh	Energy-moisture balance model	18/17	130	7	Vert. diffusivity: 0.6–1.6 $cm^2\ s^{-1}$	Weaver et al. (2001)	Schneider and Schmittner (2006)
UVIC 6in	Energy-moisture balance model	18/13	700	16	Vert. diffusivity: 0.6–1.6 $cm^2\ s^{-1}$	Weaver et al. (2001)	Schneider and Schmittner (2006)
BREMIC/LSG	Simplified energy balance model	18/10	500	14		Maier-Reimer et al. (1993), Prange et al. (2003)	This study
MIT (OGCM)	Mixed boundary conditions	31/28	1000	16	No Arctic Ocean	Marshall et al. (1997)	Nisancioglu et al. (2003)
HadCM3	General circulation model	20/10	370	8	Mid-Pliocene boundary conditions	Gordon et al. (2000)	Lunt et al. (2008a)
CCSM2	General circulation model	14/12	800	12		Kiehl and Gent (2004), Prange (2008)	Steph et al. (2006a)
CCSM3	General circulation model	16/8	1475	11		Collins et al. (2006), Yeager et al., (2006)	This study
KCM	General circulation model	14/11	1200	13		Park et al. (2009)	This study
EC415 (ECBILT-CLIO)	Quasi-geostrophic circulation model	27/19	415	11		Goosse and Fichefet (1999), Opsteegh et al. (1998)	This study
EC700 (ECBILT-CLIO)	Quasi-geostrophic circulation model	27/15	700	14		Goosse and Fichefet (1999), Opsteegh et al. (1998)	Prange and Schulz (2004)