A coastal upwelling seesaw in the Atlantic Ocean as a result of the closure of the Central American Seaway

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[1] Based on coupled climate model experiments, we suggest an antiphase relationship between the two major coastal upwelling zones in the Atlantic Ocean off northwestern and southwestern Africa. We describe this as an 'upwelling seesaw'. The state of the coastal upwelling seesaw is controlled by variations in the oceanic meridional heat transfer between South and North Atlantic. In particular, we suggest that the Pliocene closure of the Central American Seaway induced a large-scale redistribution of heat in the Atlantic Ocean, leading to an intensification (weakening) of upwelling off southwest (northwest) Africa. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4255 Oceanography: General: Numerical modeling; 4267 Oceanography: General: Paleoceanography; 4279 Oceanography: General: Upwelling and convergences. **Citation:** Prange, M., and M. Schulz (2004), A coastal upwelling seesaw in the Atlantic Ocean as a result of the closure of the Central American Seaway, *Geophys. Res. Lett.*, *31*, L17207, doi:10.1029/2004GL020073.

1. Introduction

[2] Coastal upwelling regions are important areas of investigation for paleoclimatic research, because of their high-resolution sedimentary archives and their sensitivity to environmental changes [e.g., *Berger and Wefer*, 2002]. The two major upwelling regions in the Atlantic Ocean are located along the coasts of northwestern Africa (Mauritanian upwelling zone) and southwestern Africa (Benguela-Namibia upwelling system). In these regions, the intensity of coastal upwelling is a function of the strength of the trade-wind systems.

[3] Records of paleoproductivity from the southwest African upwelling zone indicate a remarkable shift in upwelling intensity during the Pliocene. Utilizing results from Ocean Drilling Program (ODP) Site 1084, situated off the coast of Namibia, *Marlow et al.* [2000] report a significant increase in mass accumulation rates of organic carbon, diatom abundance, and the proportion of upwelling-indicating species in the diatom assemblage, starting around 4 million years ago. Here, we propose that the increase in upwelling off southwestern Africa was directly linked to the formation of the Isthmus of Panama. We present coupled climate model results which suggest that the closure of the Central American Seaway (CAS) induced a large-scale redistribution of heat in the Atlantic Ocean. The resulting effect on the atmospheric pressure system changed the trade-wind strengths such that upwelling was intensified along the southwest African coast, but weakened off northwestern Africa.

2. Experimental Design

[4] We use the global atmosphere-ocean model ECBILT-CLIO version 3. The coupled model derives from the atmosphere model ECBILT [*Opsteegh et al.*, 1998] and the ocean/sea-ice model CLIO [*Goosse and Fichefet*, 1999]. The atmospheric component solves the quasi-geostrophic equations with T21-resolution for three layers. The primitive-equation, free-surface ocean component has a horizontal resolution of 3 degrees and 20 levels in the vertical. It is coupled to a thermodynamic-dynamic sea-ice model with viscous-plastic rheology. There is no local flux correction in ECBILT-CLIO. However, precipitation over the Atlantic and Arctic basins is reduced by 8.5% and 25%, respectively, and homogeneously redistributed over the North Pacific. More information about the model and a complete list of references is available at http://www.knmi.nl/onderzk/CKO/ecbilt-papers.html.

[5] Beside a 5000 years control run (experiment CTL), simulating the present-day climate, we conduct an experiment with open Panama Isthmus (experiment CAS). In this experiment, the CAS is defined on three velocity grid points, corresponding to a width of approximately 1000 km. With a CAS depth of 700 m, the model setup crudely mimics the paleobathymetric conditions of the late Miocene, somewhere between 12 and 6 million years ago [cf. *Duque-Caro*, 1990]. We note that all other boundary conditions are the same as in the control run. Therefore, experiment CAS should be viewed as a sensitivity study rather than as a simulation of late Miocene climate. The model is integrated another 2250 years to reach a new equilibrium, starting from the control run's final state as initial condition. All model results presented below are annual averages determined from the last 50 years of each experiment.

3. Model Results

[6] In the control run, maximum meridional overturning in the North Atlantic amounts to 27 Sv (1 Sv = 10^6 m^3 s^{-1}) (Figure 1). This vigorous circulation is associated with a large northward heat transport in the Atlantic Ocean (Figure 2). Maximum heat fluxes of about 0.9 PW are found between 15°N and 35°N. In the South Atlantic, the northward heat transport is approximately 0.4 PW. These values are within the range of results from inverse and constrained modeling [*Ganachaud and Wunsch*, 2000; *Stammer et al.*, 2003].

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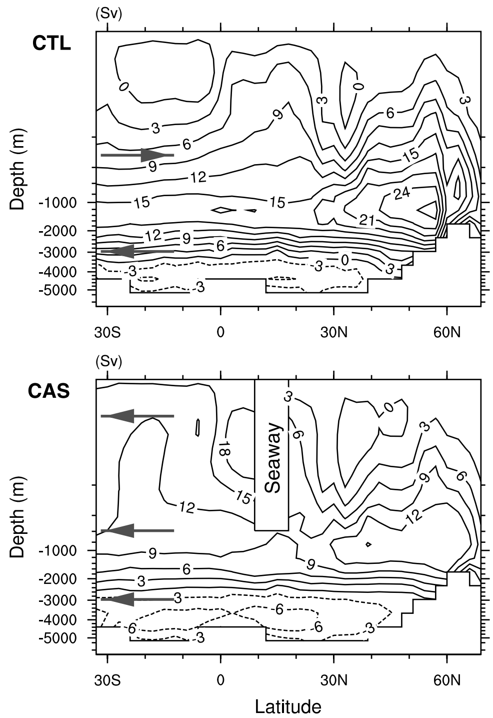

Figure 1. Meridional streamfunction in the Atlantic Ocean (contour interval is 3 Sv) in experiments CTL (top) and CAS (bottom). Dashed (solid) contour lines indicate negative (positive) values. The streamfunction has been calculated by integrating the net meridional flow from the bottom to the top. The arrows indicate the direction of the net (i.e., zonally integrated) meridional flow above the layer of Antarctic Bottom Water.

[7] Introducing a Panama Seaway in experiment CAS results in a transport of tropical water masses from the Pacific into the Atlantic Ocean. The mean total volume transport through the passage is ~14 Sv and the flow is directed from the Pacific to the Atlantic over the entire depth of the strait. Intensity and vertical profile of the throughflow are very similar to the results from a recent study with an ocean-only model (see *Nisancioglu et al.* [2003] and their experiment CAS1000). The inflow of relatively fresh water masses into the Atlantic reduces the salinity contrast between the two oceans. As a result, deep-water formation and meridional heat transport in the North Atlantic are decreased by 12 Sv (compare Figure 1) and ~0.2 PW (compare Figure 2), respectively, compared to CTL.

[8] The volume flux through the CAS into the Atlantic Ocean is balanced by a southward transport of warm water masses in the upper 1000 m of the South Atlantic (Figure 1). Comparing the upper-ocean circulation of experiment CAS with the control run, we find the most salient differences in the North Brazil Current (not shown). This current reverses below 100 m; that is, the subsurface flow is directed southward when the Isthmus of Panama is open. The southward flow of warm upper-ocean waters is associated with a southward heat transport in the South Atlantic (Figure 2).

[9] In experiment CTL, a northward cross-equatorial heat transfer in the Atlantic Ocean (Figure 2) results in relatively warm conditions in the North Atlantic and low temperatures in the South Atlantic. Figure 3 shows sea-surface temperature (SST) differences between experiment CTL and experiment CAS. The altered SST pattern influences atmosphere dynamics: Higher temperatures in the North Atlantic weaken the northern hemispheric subtropical high in experiment CTL. In contrast, over the South Atlantic, the subtropical high pressure cell is intensified by the oceanic cooling. Decreasing (northwestern Africa) and increasing (southwestern Africa) alongshore wind stresses clearly affect the coastal upwelling systems in the Atlantic Ocean (Figure 3).

[10] Even though the resolution of the model is too coarse to resolve coastal upwelling dynamics explicitly, it is instructive to look at the changes in Ekman vertical velocities. Ekman pumping velocities are given by the divergence of horizontal Ekman transports [e.g., *Pedlosky*, 1996]. Setting Ekman transports to zero on continental grid points, Ekman pumping can be calculated over the entire domain of the ocean model, except for the equatorial region where Ekman pumping is not defined. Figure 3 shows a significant increase (decrease) in wind-driven upwelling off southwestern (northwestern) Africa in response to the closed Isthmus of Panama in experiment CTL. This antiphase relationship between the two major coastal upwelling zones in the Atlantic Ocean can be described as an 'upwelling seesaw'.

4. The Coastal Upwelling Seesaw in a Paleoclimatic Context

[11] Our model results suggest that the Pliocene closure of the CAS caused an intensification of upwelling off southwest Africa, which may elucidate the paleoceanographic records presented by *Marlow et al.* [2000]. Unequivocal paleoceanographic reconstructions for upwelling off northwest Africa during the Pliocene, which could corroborate or negate our seesaw-hypothesis, do not exist to our knowledge [cf. *Tiedemann*, 1991]. The proposed coastal upwelling seesaw, however, would not operate as an isolated mechanism in the real climate system. Other processes may affect upwelling and primary productivity as well. The intensification of northern hemisphere glaciation in the Pliocene would have possibly counteracted

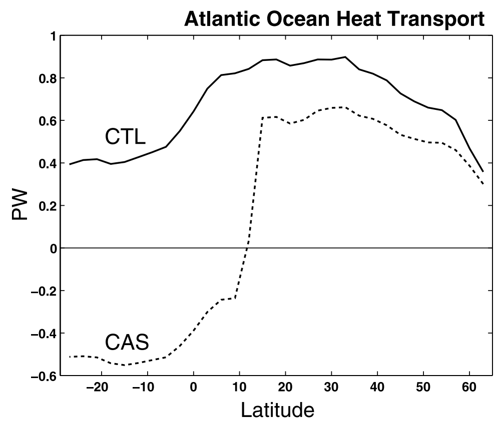

Figure 2. Northward heat transport in the Atlantic Ocean in experiments CTL (solid) and CAS (dashed). A reference temperature of 1.3°C has been used for the calculations.

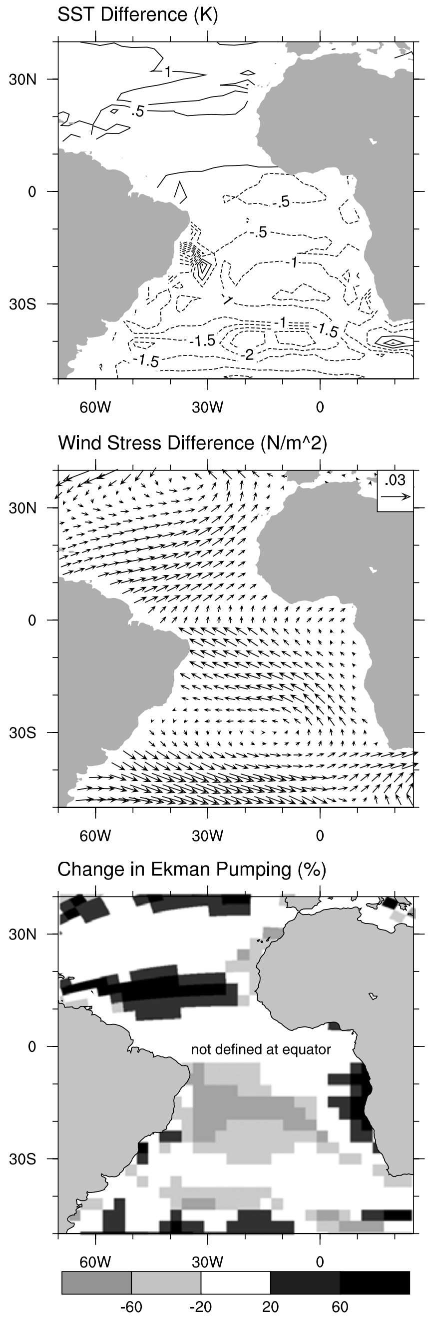

Figure 3. Annual mean differences between experiment CTL and experiment CAS in the Atlantic Ocean: Sea-surface temperature (contour interval is 0.5°C; dashed contour lines indicate negative values), surface wind stress (N/m^2) and Ekman vertical velocity *w* (Ekman pumping). Changes in Ekman pumping are given in percent, calculated as $100 \cdot (w_{\mathrm{CTL}} - w_{\mathrm{CAS}})/|w_{\mathrm{CAS}}|$. Positive values indicate stronger upwelling or weaker downwelling in experiment CTL compared to experiment CAS.

the effect of an upwelling seesaw off northwestern Africa. A strengthening of northern hemisphere trade winds owing to a steeper pole-to-equator temperature gradient would have tended to increase Mauritanian upwelling [e.g., *Flohn*, 1984]. On the other hand, recent marine ecosystem modeling (A. Schmittner, manuscript in preparation, 2004) suggests that the closure of the CAS had the effect of decreasing (increasing) nutrient contents off northwestern (southwestern) Africa [see also *Berger et al.*, 2002]. Thus, upwelling seesaw and large-scale redistribution of nutrients would have acted in the same direction as far as Pliocene changes in biological productivity in the Atlantic coastal upwelling zones are concerned.

[12] The coastal upwelling seesaw responds directly to the intensity of the cross-equatorial heat transport in the Atlantic Ocean. Hence, *any* process that alters the large-scale oceanic heat transport should have an effect on coastal upwelling. In an additional experiment with closed CAS, we shut down the present-day North Atlantic Deep Water formation by an anomalous freshwater input to the North Atlantic (0.5 Sv between 50°N and 70°N), thereby reducing the oceanic heat transport [cf. e.g., *Stocker et al.*, 1992; *Rind et al.*, 2001]. In the new circulation state, meridional heat transport drops below 0.2 PW in the North Atlantic, and becomes southward in the South Atlantic (not shown). The altered SST pattern (cooling in the North Atlantic, warming in the South Atlantic) has an effect on the strength of the trade winds, thus influencing coastal upwelling in the Atlantic Ocean (more upwelling off northwest Africa, less upwelling off southwest Africa).

[13] The reorganization of the oceanic thermohaline circulation in this freshwater perturbation experiment resembles the processes which occurred during Heinrich events [e.g., *Sarnthein et al.*, 2001; *Prange et al.*, 2004]. Paleoceanographic evidence suggests that the coastal upwelling seesaw indeed responded to the North Atlantic meltwater inputs: Relative abundances of the planktonic foraminifer *Neogloboquadrina pachyderma* (left coiling) in sediment cores from the Benguela-Namibia upwelling indicate reduced coastal upwelling during Heinrich events, particularly during Heinrich 2 and 4 [*Little et al.*, 1997]. For the Mauritanian upwelling zone, high-resolution proxy records for the last 35 kyr were presented by *Zhao et al.* [2000]. A low percentage of the coccolithophorid

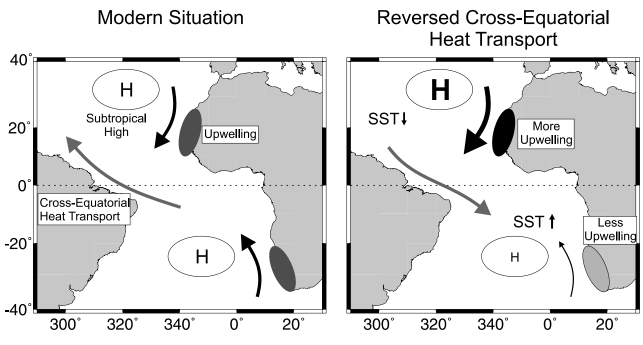

Figure 4. Schematic of the coastal upwelling seesaw in the Atlantic Ocean. Today, the subtropical highs over the North and South Atlantic are associated with a trade-wind system that promotes upwelling along the coasts of northwestern and southwestern Africa (left panel). A reduced or reversed cross-equatorial oceanic heat transport causes sea-surface temperatures to drop in the North Atlantic, and to increase in the South Atlantic. The resulting effect on the atmospheric pressure system changes the trade-wind strengths such that upwelling is intensified along the northwest African coast, and weakened off southwestern Africa (right panel).

Florisphaera profunda during Heinrich 2 suggests a weak surface water stratification due to enhanced upwelling intensity. Moreover, *Kiefer* [1998] estimated primary productivity over the last glacial period from a core located southwest of the Canary Islands. Peaks in paleoproductivity coincide with Heinrich 2–5. A possible explanation for these peaks is that an increased amount of nutrient-rich upwelling water was advected away from the coast towards the core location.

5. Conclusions

[14] We suggest the existence of a coastal upwelling seesaw in the Atlantic Ocean. The antiphase relationship between the two major Atlantic coastal upwelling zones is connected to variations in the meridional (cross-equatorial) oceanic heat transport (Figure 4). In particular, we suggest that an increase in upwelling intensity off Namibia during the Pliocene [*Marlow et al.*, 2000] is attributable to the closure of the CAS and the working of the Atlantic coastal upwelling seesaw. For an improved understanding of Pliocene climatic processes, future studies should focus on upwelling reconstruction of the Mauritanian upwelling zone.

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