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Global seiching of thermocline waters between the Atlantic and the Indian-Pacific Ocean Basins

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[1] Proxy climate data from the Greenland icecap and marine deposits in the Pacific indicate that warm conditions in the North Atlantic are linked to cool conditions in the Eastern Equatorial Pacific, and vice versa. Our ocean models show that the surface branch of the overturning circulation connecting the North Atlantic to the Equatorial Pacific adjusts by exchanging thermocline water between ocean basins in response to changes in deep water formation in the northern North Atlantic. Planetary ocean waves give rise to a global oceanic seiche, such that the volume of thermocline water decreases in the Pacific-Indian Ocean while increasing in the Atlantic Ocean. We conjecture that the remotely forced changes in the thermocline of the Eastern Equatorial Pacific may trigger El Niño events. These global seiches have been previously overlooked due to the difficulty of integrating high-resolution climate models for very long time-scales. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4532 Oceanography: Physical: General circulation; 1620 Global Change: Climate dynamics (3309). **Citation:** Cessi, P., K. Bryan, and R. Zhang (2004), Global seiching of thermocline waters between the Atlantic and the Indian-Pacific Ocean Basins, *Geophys. Res. Lett.*, *31*, L04302, doi:10.1029/2003GL019091.

1. Introduction

[2] It has been somewhat puzzling that climate records taken near the equator reflect many of the events recorded in the proxy temperatures of the Greenland icecap. For example, *Behl and Kennett* [1996] have found evidence of anoxia events in the Santa Barbara Basin that correspond in time to cold periods recorded in the Greenland icecap over the past 60,000 years. Anoxic events have low surface density, higher rainfall and warmer conditions along the coast of California under present climatic conditions. Using Greenland icecap data *Stott et al.* [2002] found that a cold North Atlantic is associated with a shift of rainfall towards the eastern tropical Pacific, consistent with more frequent El Niño activity, while warm North Atlantic conditions are correlated with dry, cooler eastern tropical Pacific. They interpreted the anoxic conditions in the Santa Barbara basin reported by *Behl and Kennett* [1996] as evidence in support for these events, which they call “Super ENSOs”. Further indications of opposite temperature conditions in the equatorial Pacific and North Atlantic come from the analysis by *Cobb et al.* [2003] of a new proxy temperature record in the Central Pacific. *Cobb et al.* [2003] conclude that conditions were relatively cold along the equator in the Pacific during the medieval warm period, about 1000 A.D., and that there were warm conditions and frequent El Niños at the height of the Little Ice Age in the 17th century. Although *Cobb et al.* [2003] do not provide a continuous record over the past 1000 years, their findings are consistent with ‘Super ENSOs’.

[3] Of the possible mechanisms for low frequency changes in the Equatorial Pacific, a prime candidate is the surface branch of the conveyor belt which presently takes up heat in the tropical Pacific and transports it to the North Atlantic through the Cape of Good Hope and the Indonesian Passage [*Gordon*, 1986; *Ganachaud and Wunsch*, 2000]. An increase of the overturning circulation implies greater upwelling in the Pacific and cooler surface temperatures. Increased advection of warm tropical waters into the North Atlantic implies a warming of the surface. Therefore variations of conveyor-belt strength produce sea surface temperature anomalies of opposite sign in the North Atlantic and Tropical Pacific.

[4] As *Gu and Philander* [1997] point out the oceans at high latitudes act as a decadal filter of anomalous potential energy injected at all frequencies by the atmospheric thermal and mechanical forcing. This potential energy is expressed by a displacement of the thermocline caused by the fluctuating winds and by the unsteady convection at high latitudes where the deep branches of the global thermohaline circulation are formed. The North Atlantic is a particularly important source, because of low frequency changes in the formation of deep water in the Greenland and Labrador Seas. Periodic changes in convection are best documented in the Labrador Sea [*Dickson et al.*, 1996]. Convection appeared to cease for a period of years in the late 1960s and early 1970s. Other important decadal variations since that time have been observed [*Schlosser et al.*, 1991].

[5] In the following, we show how signals from the North Atlantic to the Pacific Ocean are transmitted via the Indian Ocean.

2. Adjustment to North Atlantic Changes

[6] The study of large scale adjustment of ocean circulation in response to imposed forcing was investigated extensively by *Gill* [1982] and more recently by *Hsieh and Bryan* [1996], *Huang et al.* [2000], *Goodman* [2001], *Cessi and Otheguy* [2003]. The initial adjustment of the thermocline

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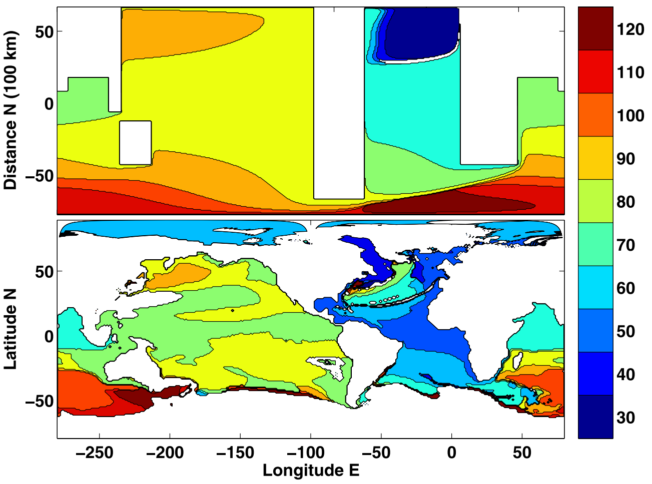

Figure 1. The time of arrival of the first maximum in SSH in response to a change in the northern North Atlantic is contoured in years. The corresponding amplitudes are given in Figure 2. (Top) A solution of a reduced-gravity shallow water model of the World Ocean in simplified geometry, forced in the northernmost quarter of the North Atlantic by a dipolar thickness source with zero spatial average. The forcing is a 'switch on' sinusoid with a period of 100 years. (Bottom) Corresponding results for the SSH anomalies in a three-dimensional ocean model forced by wind and buoyancy gradients. The SSH anomalies are the difference between a perturbed and a control experiment: in the perturbed experiment deep convection is interrupted in the Labrador Sea by adding an anomalous freshwater flux near the Greenland coast; in the control experiment freshwater flux is calculated by the coupled model itself (similar to modern observation). The anomalous freshwater flux is a sinusoid in time with a period of 100 years. In both panels the white areas are either continents or values outside the contoured range.

takes place through the propagation of Kelvin waves that are confined to thin regions near the coasts and the equator. These waves are familiar because of their role in the El Niño/La Niña phenomenon. An El Niño, for example, is initiated by the rapid eastward propagation of an equatorially trapped Kelvin wave on the thermocline from the western Pacific to the Eastern Pacific. However, it takes decades for basin-wide changes in sea-surface height (SSH) to take place. This global adjustment is achieved through Rossby waves that are continuously spawned at the eastern boundary of each ocean basin and then propagate westward. Since Rossby waves move more rapidly near the equator than at higher latitudes, the equatorial oceans adjust relatively quickly. Indeed, the seiching of thermocline waters in an El Niño/La Niña event has a period of only 3 to 7 years, which approximately corresponds to the transit time of a Rossby wave in the equatorial Pacific (modified by the air-sea coupling). In contrast, the transit time across the North Pacific of a Rossby wave is of the order of 10 to 15 years.

[7] To illustrate the global response to low-frequency changes in the North Atlantic branch of the thermohaline circulation we used two models: a high-resolution shallow water model and a low-resolution global three-dimensional ocean general circulation model (OGCM) coupled to an energy balance model and a sea ice model.

[8] Our high-resolution model is the reduced-gravity shallow water equations (gravity is reduced by a factor of 500 to account for the small density difference between the thermocline waters and the deep water below). The resolution is 60km in both directions.

[9] Our global three-dimensional OGCM is the Geophysical Fluid Dynamics Laboratory Modular Ocean Model coupled to a 2-dimensional atmospheric Energy Balance Model (EBM) with a hydrological cycle and to a slab sea-ice model *Winton* [2000]. The horizontal resolution is 1° × 1° latitude-longitude, about four times higher than that used in published global calculations [*Manabe and Stouffer*, 1995; *Goodman*, 2001], and there are 20 levels in the vertical. The coupled model can simulate reasonable modern climate without the use of flux correction.

[10] The global propagation of a disturbance from the North Atlantic is illustrated in Figure 1, where the arrival times of the first maximum of SSH are shown. The top panel illustrates that propagation in the shallow water model is counterclockwise around ocean basins in the Northern Hemisphere and clockwise in the Southern Hemisphere. From the source region in the North Atlantic the wave propagates equatorward along the western boundary. At the equator it moves eastward and then splits into two waves moving north and south along the eastern boundary of the Atlantic. At the southern tip of Africa the wave turns eastward and eventually finds its way to the equator in the Indian Ocean. At the equator eastward propagation by equatorially trapped Kelvin waves is relatively rapid in spite of the barrier imposed by Indonesia. In the Pacific the wave acts like the El Niño, travelling eastward along the equator except that its low frequency allows it to penetrate all the way poleward along the eastern boundary. From there, the disturbance is radiated westward in the form of much slower Rossby waves that eventually fill the entire basin. The Southern Ocean region to the south and east of Cape Horn is the last to adjust, since very slow Rossby waves reach the Southern Ocean only by radiating energy westward from the eastern South Pacific.

[11] The bottom panel of Figure 1 shows a similar propagation pattern in the OGCM, with the notable exception that communication from the Atlantic to the Pacific occurs both through the Indian Ocean and through Drake Passage. The Indian Ocean to South Pacific route implicates transport by the Antarctic Circumpolar Current (ACC), a flow which is absent in the simplified model, which has no wind-forcing. In summary, many decades are required for forced changes in SSH in the Atlantic to reach the Pacific and even longer to reach the Southern Ocean. In the three-dimensional model the Southern Ocean is not adjusted by the end of the 140 years calculation.

[12] The SSH amplitudes corresponding to the arrival times of Figure 1 are shown in Figure 2. Outside of the directly forced region in the northern North Atlantic, the sea-level anomaly is several centimeters high in both the simplified and in the three-dimensional model. Note that the amplitude along the Pacific equator is about a third of that along the Atlantic equator for this low frequency event, which is remarkable considering the great difference in distance from the perturbation source.

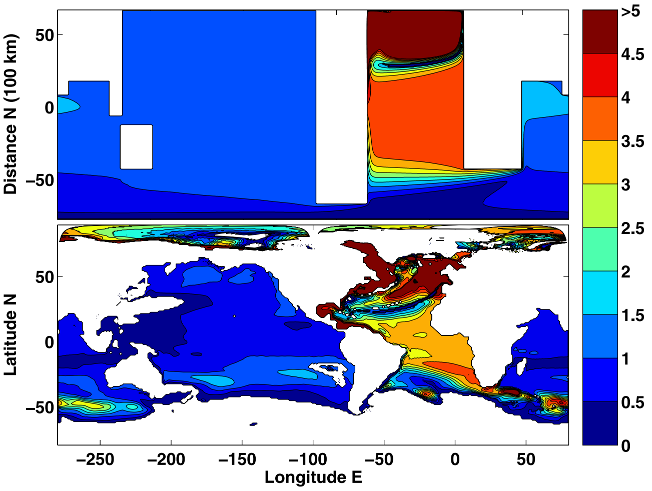

Figure 2. The amplitude of sea surface height (SSH) anomalies at the time of the passage of the first maximum of the wave emanating from the North Atlantic. The time of the passage of the first maximum is given in Figure 1. The amplitude is over 3.5 cm over a broad area of the tropical Atlantic and between 0.5 and 1.5 cm over the equatorial Pacific. Values above 5 cm are all indicated with dark red. The actual maxima in the northern North Atlantic are 39 cm for the shallow water (top panel) and 32 cm for the OGCM (bottom panel).

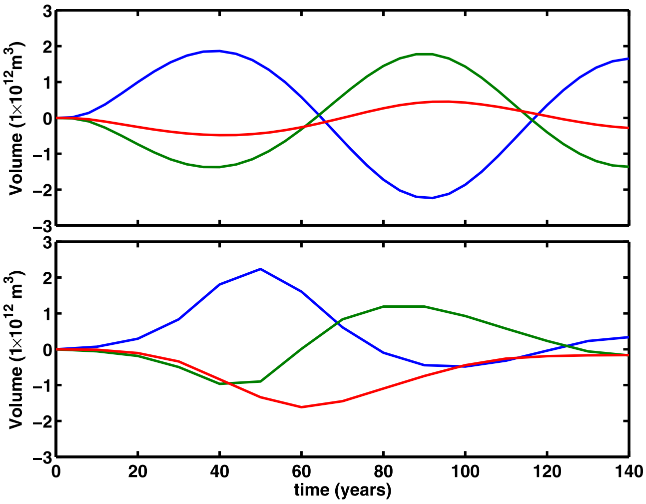

Figure 3. The SSH integrated over the Atlantic Basin down to the latitude of the Cape Good Hope is indicated in blue. The same quantity over the combined Indian-Pacific Basin is indicated in green. The SSH integrated over the area south of the Cape Good Hope, that is in the Southern Ocean, is in red. The shallow water model results are in the top panel and the OGCM results are in the lower panel. To estimate the total volume change of thermocline waters in each basin the ordinate should be multiplied by the ratio of anomalous thermocline displacements to SSH. For very low frequencies this ratio is approximately 500.

[13] In summary, there is a remarkable agreement between the results of the two models, despite many differences in the geography and the steady ocean currents (the simple model has no wind forcing and buoyancy forcing is confined to the northern North Atlantic). In both models the propagation is such that the northwest sector of the Pacific lags the signal in the Equatorial Pacific by about twenty years with a similar lag between the Equatorial Pacific and the Atlantic. Thus, exchange between the Atlantic and Indo-Pacific basins can take place on centennial time-scales as suggested by *Behl and Kennett* [1996].

[14] The seiching character of the global oceanic adjustment is illustrated in Figure 3 where the SSH integrated over the three major sub-basin areas is shown. For slow changes of the ocean circulation the SSH is a measure of the changing thickness of the thermocline resting on deeper waters of greater and more uniform density. Thus the changes in basin-averaged SSH anomalies are approximately equivalent to exchanges of thermocline waters from one basin to another.

[15] Figure 3 shows that in the OGCM the shutdown of the conveyor belt leads to an initial gain in volume for the Atlantic compensated by a loss in the Indian-Pacific and in the Southern Ocean. In both models, the inter-basin transfer amounts to about 2 megatons per second of thermocline water (obtained by multiplying the volume of thermocline water in Figure 3 by the frequency of the oscillation, $2\pi/100$ years^{-1}). This is about 15% of the current Indo-Pacific to Atlantic surface branch of the global conveyor belt [*Ganachaud and Wunsch*, 2000]. The partition of this compensation differs in the two models: the OGCM favors the Southern Ocean and the simple model favors the Indo-Pacific. This difference arises from the already noted ACC connection between the Atlantic and Pacific, which is absent in the simple model. The volume changes of in the second half of the cycle are weaker in the OGCM because the recovery of the conveyor belt in the North Atlantic does not resume when the freshwater flux changes sign. The thermohaline circulation is well known to exhibit hysteresis, which is very sensitive to the details of the freshwater fluxes [*Rahmstorf and Ganopolski*, 1999; *Tziperman*, 2000].

[16] Although our models focus on the link between the Atlantic and Pacific at centennial time scales, the analytic calculations of *Cessi and Otheguy* [2003] suggest that the out-of-phase storage of SSH illustrated in Figure 3 exists at even longer time-scales. Indeed, a calculation with the reduced-gravity model analogous to that of Figure 1, but forced by a thickness perturbation with a period of 500 years (not shown) has the same antiphase storage as in Figure 3. Both models conserve total volume and the latter is in exact linear proportion to the *thermocline* volume in the simple model, but not in the OGCM. The agreement between the two models suggests that the global volume average of thermocline water is approximately conserved at low-frequency in the OGCM as well, so that any increase in the Atlantic basin must be compensated by a decrease in the rest of the world ocean. This interbasin compensation is reminescent of the interhemispheric seesaw proposed by *Broecker* [1998], *Stocker* [1998], whereby signals are in antiphase in the northern and southern high latitudes of the Atlantic.

3. Discussion

[17] The model experiments of this study illustrate the response of the Pacific to forcing in the North Atlantic. But the global thermocline seiche could be driven by forcing in

other locations. For instance, low-frequency variability within the mid-latitude North Pacific, as described by *Francis and Hare* [1994] could lead to a local build up of anomalies of potential energy in the thermocline, which eventually return to equilibrium by global seiching. In this case correspondence from the Pacific to the Atlantic may be caused by an ocean connection around the tip of South America. Thus global seiching of thermocline might be the cause of changes in high-latitude water mass formation, rather than the result of it. Future studies of proxy data may be able to constrain these possibilities by determining the leads and lags of anomalous events.

[18] A direct comparision of our model results with proxy climate data is not possible. Our models provide the most reliable information on global SSH variations, while the proxy data are mostly correlated with temperature and rainfall. In the eastern equatorial Pacific, fluctuations in SSH due to changes in the thermocline depth, are tightly correlated with sea-surface temperature (SST) anomalies through the linear relation SST = aSSH. Using modern data (directly measured SST anomalies at the TOGA-TAO array and remotely sensed SSH anomaly from the TOPEX altimetric satellite for the last 10 years) we find that $a \approx 0.14°\mathrm{C}\ \mathrm{cm}^{-1}$: a positive (negative) displacement in SSH of 2 centimeters as shown in Figure 3 corresponds to a warming (cooling) of 0.3 degrees centigrade. No such relation between SSH and SST exists in the western equatorial Pacific [*Chambers et al.*, 1998]. Thus an increase in the equatorial SSH, induced by the reduction of deep water formation in the North Atlantic, leads to an anomaly in the equatorial east-west temperature gradient that can initiate the weakening (strengthening) of the trade winds that triggers an El Niño (La Niña) event. The equatorial Pacific SST anomalies are unrealistically small in our coupled model, and the fixed surface wind forcing does not allow the positive feedback between temperature and wind connected with the El Niño/La Niña cycle. Coupled models with a more accurate atmosphere show that perturbations originating in the North Atlantic ocean are indeed able to trigger an El Niño a few years after the collapse of the thermohaline circulation [*Dong and Sutton*, 2002]. On interannual time-scales, an atmospheric connection between the North Atlantic and the equatorial Pacific is arguably most effective [*Dong and Sutton*, 2002]. However, on multidecadal to century time scales, our models' results support the conclusion that oceanic wave-transmission between the Atlantic and Indo-Pacific basins can substantially modify the SST of the eastern equatorial Pacific and thus varying the frequency of El Niño events.

[19] The conclusions of this study are based almost entirely on ocean models. In our coupled model, the atmospheric component is too simplified to play more than a passive role. Future studies are needed with more complete atmosphere-ocean models, in which the ocean component is detailed enough to resolve planetary waves globally, and the atmospheric component detailed enough to allow realistic air-sea interaction over centennial time scales.

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