Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures

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[1] Observations suggest a possible link between the Atlantic Multidecadal Oscillation (AMO) and El Niño–Southern Oscillation (ENSO) variability, with the warm AMO phase being related to weaker ENSO variability. A coupled ocean-atmosphere model is used to investigate this relationship and to elucidate mechanisms responsible for it. Anomalous sea surface temperatures (SSTs) associated with the positive AMO lead to change in the basic state in the tropical Pacific Ocean. This basic state change is associated with a deepened thermocline and reduced vertical stratification of the equatorial Pacific ocean, which in turn leads to weakened ENSO variability. We suggest a role for an atmospheric bridge that rapidly conveys the influence of the Atlantic Ocean to the tropical Pacific. The results suggest a non-local mechanism for changes in ENSO statistics and imply that anomalous Atlantic ocean SSTs can modulate both mean climate and climate variability over the Pacific.
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1. Introduction

[2] Analyses of global SSTs show an inter-hemispheric thermal contrast mode [e.g., *Folland et al.*, 1999] or AMO [e.g., *Kerr*, 2000; *Delworth and Mann*, 2000] as a leading pattern of multidecadal variability. This mode affects North American climate [*Sutton and Hodson*, 2005], and several other aspects of global climate [*Knight et al.*, 2005], and is thought to be related to multidecadal fluctuations of the Atlantic thermohaline circulation (THC) [e.g., *Delworth and Mann*, 2000].

[3] The amplitude of ENSO also varies on decadal-multidecadal time scales, and this variation is believed to be related to interdecadal changes in mean state of the tropical Pacific [e.g., *Wang and An*, 2002]. However, there is no clear consensus about the exact relationship between changes in the mean state and ENSO amplitude modulation, nor about the chief causes of the changes in the mean state [*Timmermann,* 2003; *Rodgers et al.*, 2004; *Yeh and Kirtman*, 2004]. In addition, it is still an open question as to whether the decadal modulation of ENSO amplitude is more than a sampling issue [e.g., *Yeh and Kirtman*, 2004].

[4] In this paper we investigate the hypothesis that changes in Atlantic SST could play a role in ENSO amplitude modulation on multidecadal timescales. Previous studies [e.g., *Dong and Sutton*, 2002; *Zhang and Delworth*, 2005; R. T. Sutton and D. L. R. Hodson, Climate response to Multidecadal warming and cooling of the North Atlantic Ocean, submitted to *Journal of Climate*, 2006, hereinafter referred to as Sutton and Hodson, submitted manuscript, 2006] have already shown that AMO-like SST anomalies in the Atlantic can influence the mean climate of the tropical Pacific. The Atlantic influence appears to be transmitted through the atmosphere primarily by Rossby waves that are excited by latent heating anomalies in the tropical Atlantic (Sutton and Hodson, submitted manuscript, 2006). There are also potential oceanic teleconnections that could link changes in the THC with the thermocline in the tropical Pacific [e.g., *Timmermann et al.*, 2005]. However, the atmospheric teleconnections which are the focus of this study, may well be dominant [*Dong and Sutton*, 2002].

[5] Figure 1a shows the second empirical orthogonal function (EOF2; EOF1 is the trend), and the corresponding principal component (PC), of low frequency Atlantic SST variability based on observations [*Rayner et al.*, 2003]. This mode represents the interhemispheric contrast or AMO [*Folland et al.*, 1999]. It was in a positive phase from the mid 1920s to the late 1960s, and in a negative phase from the 1970s to the 1990s (Figure 1b). Figure 1b also suggests that weak (strong) ENSO variability coincides with the positive (negative) phase of the AMO with a correlation coefficient -0.68 (significant at 95% confidence level by t-test). (Note however that AMO changed to positive phase in the mid 1990s while ENSO did not show a weakening). The monthly Nino 3 SST standard deviation was 22% lower during the AMO warm phase (1930–1960) relative to the cold phase (1965–1995). Whether this apparent association between Atlantic SST and ENSO variance is a coincidence, or is due to a causal link between the Atlantic and tropical Pacific Oceans, is unclear. However, it could imply an impact of Atlantic SST on ENSO variability, or an impact of ENSO variability on the Atlantic Ocean. In this paper, we use a coupled GCM to investigate the possible impact of Atlantic SST on ENSO variability.

2. Coupled Model and Experiments

[6] We use the UK Hadley Centre global coupled ocean atmosphere GCM HadCM3 [*Gordon et al.*, 2000]. The resolution is $2.5° \times 3.75°$ latitude-longitude with 19 vertical levels for the atmospheric component and $1.25° \times 1.25°$ latitude-longitude using an Arakawa B-grid with 20 levels for the oceanic component. The model does not require flux corrections to maintain a stable climate.

[7] Two experiments, each 150 years long, corresponding to AMO positive and negative phases were performed by

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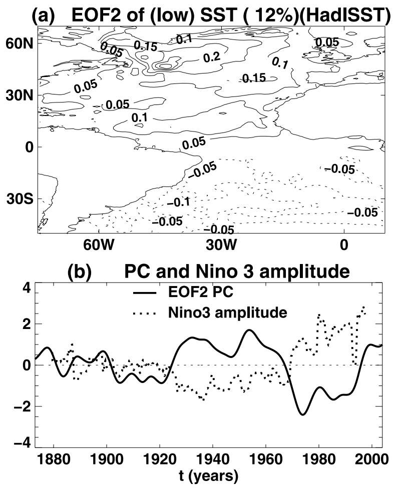

Figure 1. (a) EOF 2 of low frequency (low-pass filter with half power at period of 13.3 years) monthly SST variability (°C) over Atlantic, and (b) corresponding normalized principal component (full) and the normalized anomalous ENSO magnitude (defined as monthly Nino 3 index standard deviation in a running 13 year window) variation (dotted) based on observations [*Rayner et al.*, 2003].

relaxing SSTs over the Atlantic ocean (over the region bounded by coastlines, 70°W–15°E in Arctic, and 70°W–20°E in southern ocean) to prescribed values with a time scale of 2.5 days. The prescribed Atlantic SST consisted of the monthly mean model climatology plus or minus 3 times the AMO pattern shown in Figure 1a. (i.e., $\pm 3\sigma$). This approach allows us to assess the impact of the anomalous Atlantic Ocean state on the mean climate and climate variability. The initial state was taken from the control simulation, and analyses of the early decades of each experiment indicated that any transient adjustment effects were small.

3. Results

[8] Differences in the mean surface temperature between the AMO positive and negative experiments (Figure 2d) show the expected dipolar pattern in the Atlantic and also warm anomalies over Africa, Eurasia, the Indian Ocean, the Maritime Continent and the North Pacific. Over the tropical Pacific, SST anomalies are generally small (~0.1°C), with a band of negative anomalies stretching from the equatorial western Pacific to the subtropical eastern Pacific. The precipitation anomalies (Figure 2a) show a northward shift of the ITCZ over the tropical Atlantic, which is a direct response to the underlying SST. In addition, significantly enhanced precipitation is found over the eastern Indian Ocean, the Maritime Continent, southeast Asia and Australia. The enhanced precipitation in the latter regions is associated with stronger summer monsoons (not shown). Over the tropical Pacific the precipitation pattern closely mirrors the pattern of SST anomalies with suppressed/enhanced precipitation over negative/positive SST anomalies.

[9] In SLP (Figure 2b) there are negative anomalies over the North Atlantic and positive anomalies over the south Atlantic, consistent with a local response to the underlying SST. The atmospheric response extends through the full depth of the troposphere (not shown). In addition, the Atlantic SST anomalies excite a large scale stationary wave pattern featuring positive SLP anomalies and an anomalous anticyclonic circulation over the North Pacific (Figures 2b and 2c). A corresponding centre of high pressure anomalies is found in the South Pacific, with an anomalous ridge extending northward over the central equatorial Pacific. This ridge is associated with anomalous easterly winds over the western equatorial Pacific and anomalous westerly winds over the eastern equatorial Pacific (Figure 2c).

[10] To understand these remote responses we compared the results shown in Figure 2 with responses found when the atmospheric component of the coupled model was forced with a warm North Atlantic pattern similar to that shown in Figure 1 (Sutton and Hodson, submitted manuscript, 2006). The pattern of wind anomalies over the central and eastern tropical Pacific is similar in both the uncoupled and coupled experiments, suggesting that these wind anomalies are a direct response to the Atlantic SST. By contrast, the pattern of wind anomalies over the far western tropical Pacific and Indian Ocean differs considerably between the two experiments, suggesting that coupled ocean-atmosphere feedbacks play a critical role in these regions. The positive SST and enhanced precipitation anomalies in the Indian Ocean and Maritime continent region, and the associated anomalous convergence of low level winds, are evidence of these feedbacks. The pattern of negative and positive SST anomalies in the tropical Pacific is substantially shaped by wind-forced anomalous Ekman currents, with anomalous surface fluxes acting to damp the SST anomalies (not shown). Note finally that many features of the mean climate changes found in our experiments are in agreement (allowing for a sign change) with the changes induced by a weakening of the Atlantic THC [*Dong and Sutton*, 2002; *Zhang and Delworth*, 2005].

[11] What then is the effect on ENSO of the changes to the mean state? Relative to the negative AMO experiment, the amplitude of SST variability over the tropical Pacific is reduced in the positive AMO experiment (Figure 3a). The largest decrease (~20%) occurs over the eastern tropical Pacific, while in the warm pool the decrease is ~10%. The standard deviation of monthly Nino 3 SST index (Figures 3b and 3c) shows a 23% decrease (similar to observed reduction of 22%). However, the observed change in the AMO index between the two periods was about 40% of the change imposed in our experiments. This comparison there-

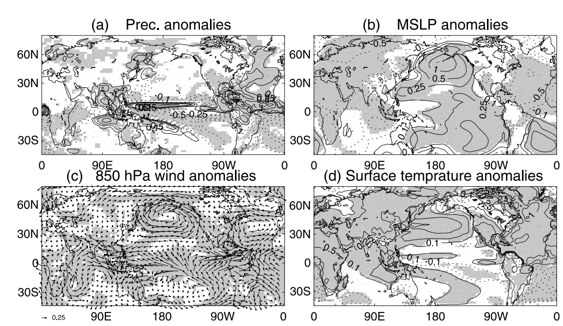

Figure 2. The climatological annual mean anomalies between positive and negative AMO experiments. (a) Precipitation (mm d^{-1}), (b) MSLP (hPa), (c) 850 hPa wind (m s^{-1}), and (d) surface temperature (°C). Shading indicates significant anomalies at 95% confidence level using t-test.

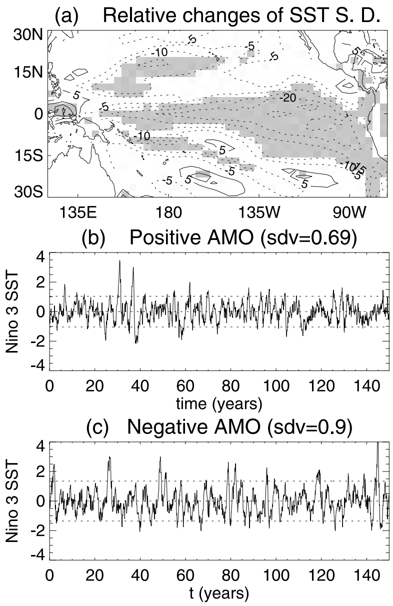

Figure 3. (a) Percentage changes of monthly SST standard deviation between positive and negative AMO experiments. Shading indicates significant changes at 95% confidence level using F-test. (b) and (c) Monthly Nino 3 SST anomalies with thin dotted lines being 1.5 standard deviation limits. The error of Nino 3 standard deviation for 150 year sections based on an 1800 year HadCM3 simulation is 0.053°C.

fore suggests either that the simulated response of ENSO variance to the AMO change is too weak in the model or that other factors also affected ENSO variance in the real world. Nevertheless, Figure 3 clearly demonstrates that changes in Atlantic SST have an impact on ENSO variance in the HadCM3 model.

[12] To explain the ENSO changes we examined annual mean temperature anomalies in the equatorial Pacific between the AMO positive and negative experiments (not shown). Consistent with Figure 2d, surface anomalies are very small except on the far western and far eastern sides of the basin. But there are larger changes (0.6°C) at depth, and in particular positive anomalies extend across the basin at and below the depth of the mean thermocline. This warming of the thermocline will tend to weaken the vertical stratification of upper ocean in the tropical Pacific thus tending to weaken the coupled instability through which ENSO events grow [e.g., *Zebiak and Cane*, 1987].

[13] What is the cause of the warming of the thermocline in the AMO positive experiment? The anomalous equatorial winds (Figure 2c) are likely to play a key role. The anomalously strong easterlies over the western and central tropical Pacific will cause an accumulation of warm thermocline waters on the western side of the basin and a deepening of the thermocline. The anomalous westerly winds on the eastern side of the basin may also reduce the upwelling of the thermocline that is forced by surface Ekman divergence. Changes in the shallow meridional overturning circulation [e.g., *Yang et al.*, 2005] are small in our experiments (not shown), suggesting they do not play a primary role.

[14] Further insight into mechanisms by which the Atlantic SST anomalies influence the interannual variability of the tropical Pacific is obtained by analyzing the seasonal cycle of anomalies along the equator. Figure 4 shows that the response of zonal wind stress and precipitation is strongest in the boreal summer and autumn seasons. These are the seasons in which the direct impact of Atlantic SST anomalies on the Pacific is greatest (Sutton and Hodson, submitted manuscript, 2006), because the latent heating anomalies are largest and furthest north, and so more effective at exciting Rossby waves that propagate into the Pacific. As discussed in connection with Figure 2, the direct impact appears to be amplified by a coupled feedback: Figure 4 shows an association in summer and autumn between easterly wind stress anomalies, negative SST anomalies and negative precipitation anomalies over the western tropical Pacific.

[15] Associated with the stronger easterly stress, the 20°C isotherm is 8–10 metres deeper in the western tropical Pacific in the positive AMO experiment (Figure 4b). This change in thermocline depth is roughly similar to the difference reported by *Wang and An* [2002] associated with the 1970s climate shift. The seasonal variation of the thermocline depth is consistent with it responding to the seasonal variation of zonal wind stress. Thus, following the onset of stronger easterly stress in summer, the thermocline deepens in the west Pacific until midwinter when the wind stress weakens. In spring, a positive thermocline depth anomaly propagates eastward into the central and eastern Pacific. The deep thermocline in the western and central tropical Pacific and weakened vertical stratification in the winter and spring seasons could lead to a reduction of ‘‘thermocline feedback’’ [*Jin and An*, 1999], and therefore play a role for weakened ENSO variance. In addition, the westward shift [*Wang and An*, 2002] of climatological zonal stress (Figure 2b) in the positive AMO experiment could also lead ENSO structure changes (for example, westward shift of zonal stress anomalies associated with El Niño, not shown), which weakens local ‘‘upwelling feedback’’ in the central and eastern tropical Pacific. This mechanism may also contribute to the reduced ENSO variance.

[16] An additional feature in Figure 4 is the positive SST anomaly, and associated positive precipitation anomaly, in

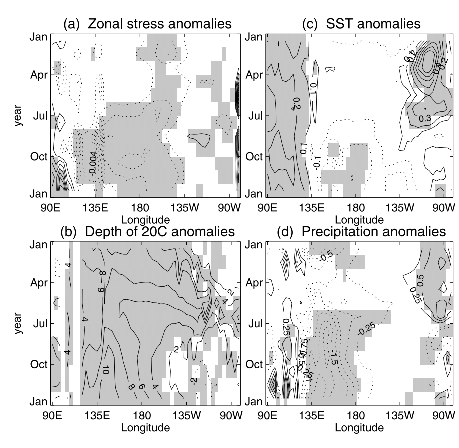

Figure 4. Seasonal cycle of the equatorial (2.5°S–2.5°N) climatological anomalies between positive and negative AMO experiments. (a) Zonal stress (N m^{-2}), (b) depth of 20°C thermocline (m), (c) surface temperature (°C), and (d) precipitation (mm d^{-1}). Shading indicates significant anomalies at 95% confidence level using t-test.

the eastern Pacific in late winter and spring. This temperature anomaly is shallow and is primarily generated by anomalous wind stress driven Ekman currents (not shown). The strong westerly wind anomalies in this region can be seen in Figure 2c, and arise as part of the direct response to the Atlantic SST anomalies [*Wu et al.*, 2005; Sutton and Hodson, submitted manuscript, 2006]. The fact that this SST feature has only a minor effect on the zonal windstress (Figure 4a) suggests its role is not fundamental.

4. Concluding Remarks

[17] Using a coupled GCM, we have shown that warming of the North Atlantic and cooling of the south Atlantic leads to a reduction in ENSO variability. This influence offers a potential explanation for the observation that ENSO variance was lower during the mid twentieth century and higher in the later twentieth century. In quantitative terms our results suggest that Atlantic SST change can account for up to half of the observed change in ENSO amplitude. This finding may indicate that the Atlantic influence is too weak in our simulations or, perhaps more likely, that other factors also play a role.

[18] The major elements of the mechanism via which Atlantic SST influences ENSO variance in HadCM3 are as follows:

[19] 1. Positive latent heating anomalies over the tropical North Atlantic are generated in response to a warm phase of the AMO.

[20] 2. The remote response to 1 involves suppressed convection and anomalous easterly winds over the central and western equatorial Pacific, primarily in boreal summer and autumn. This remote response is amplified by coupled feedbacks.

[21] 3. The easterly wind anomalies deepen the thermocline in the west Pacific, and thermocline deepening propagates eastward into the central and eastern Pacific in boreal winter and spring.

[22] 4. The deeper equatorial thermocline weakens the coupled instability through which ENSO events grow [e.g., *Zebiak and Cane*, 1987], and reduces ENSO variance.

[23] This work suggests that anomalous Atlantic SSTs, which may occur for example in response to a THC change, can modulate ENSO properties on multi-decadal timescales, as conjectured by *Timmermann* [2003]. This hypothesis is further supported by an analysis of ''water hosing'' experiments with HadCM3 (to be reported in a separate study), which shows that a weakened THC leads to an enhancement of ENSO variance. Our results are also consistent with some paleoclimate evidence [*Stott et al.*, 2002]. Interestingly, the association we find is *opposite* to that suggested by *Timmermann et al.* [2005]. However, Timmermann et al. focused exclusively on the role of oceanic teleconnections between the North Atlantic and tropical Pacific, whereas we have focused on the role of atmospheric teleconnections. The timescales associated with these teleconnections are very different. An atmospheric influence can propagate from the tropical Atlantic into the tropical Pacific in a matter of days or weeks, whereas the results of Timmermann et al. suggest the oceanic teleconnection is associated with a timescale of many decades or longer. Understanding possible interactions between these two mechanisms is an important challenge for future work. Part of this work should investigate whether the Atlantic impact on ENSO found in HadCM3 is also found in other coupled models. Future work must also take into account possible influences of the tropical Pacific on the Atlantic [e.g., *Latif*, 2001].

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