Potential of Equatorial Atlantic Variability to Enhance El Niño Prediction

N. S. Keenlyside[1], Hui Ding[2], and M. Latif[2,3]

[1]*Geophysical Institute and Bjerknes Centre, University of Bergen, Bergen, Norway*

[2]*GEOMAR | Helmholtz-Zentrum für Ozeanforschung, Kiel, Germany*

[3]*Kiel University, Kiel, Germany*

Corresponding author:

Noel S. Keenlyside
noel.keenlyside@gfi.uib.no
+47 55 58 20 32

Geophysical Institute and Bjerknes Centre, University of Bergen,
Allegaten 70, 5007, Bergen, Norway

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Abstract

Extraordinarily strong El Niño events, such as those of 1982/83 and 1997/98, have been poorly predicted by operational seasonal forecasts made before boreal spring, despite significant advances in understanding, improved models, and enhanced observational networks. The Equatorial Atlantic Zonal Mode – a phenomenon similar to El Niño but much weaker and peaking in boreal summer – impacts winds over the Pacific, and hence affects El Niño, and also potentially its predictability. Here we use a climate model to perform a suite of seasonal predictions with and without SST in the Atlantic restored to observations. We show for the first time that knowledge of Equatorial Atlantic sea surface temperature (SST) significantly improves the prediction across boreal spring of major El Niño events and also weaker variability. This is because Atlantic SST acts to modulate El Niño variability, rather than triggering events. Our results suggest that better prediction of major El Niño events might be achieved through model improvement in the Equatorial Atlantic.

1. Introduction

El Niño is the warm phase of the El Niño/Southern Oscillation (ENSO), a phenomenon with 2–7 year periodicity that originates from large-scale ocean-atmosphere interaction in the Equatorial Pacific [*Zebiak and Cane*, 1987; *Jin*, 1997; *Neelin et al.*, 1998]: a positive (Bjerknes) feedback among SST, surface Trade Winds, and upper ocean heat content anomalies drives the rapid development of ENSO extremes; and the upper ocean heat content response to wind stress produces a delayed negative feedback that causes the phase reversal [*Jin*, 1997; *Meinen and McPhaden*, 2000]. ENSO derives its predictability from the latter *oceanic memory* and is presently the main basis for seasonal forecasting [*Jin et al.*, 2008]. However, non-linear dynamics and stochastic (i.e., random) atmospheric variability cause irregularity in the amplitude, structure, and occurrence of ENSO events [*Neelin et al.*, 1998]. This limits skillful ENSO prediction, which is currently possible to about 6 months in advance [*Jin et al.*, 2008].

Zonal Mode (or Atlantic Niño) events dominate interannual climate variability in the Equatorial Atlantic [*Zebiak*, 1993; *Kushnir et al.*, 2006; *Ding et al.*, 2010], occuring every 2–4 years on average. The Equatorial Atlantic SST variability is strongest during summer and comparable to the variability in the Equatorial Pacific during this season. Zonal Mode SST variations tend to precede opposite signed anomalies in the central and eastern Equatorial Pacific by 2–3 seasons [*Wright*, 1986; *Keenlyside and Latif*, 2007]. During the period 1970 to present this relation was particularly strong (explained variance, r^2, ~15%) [*Keenlyside and Latif*, 2007; *Rodriguez-Fonseca et al.*, 2009]. Observations and climate models indicate diabatic heating over the Equatorial Atlantic associated with a warm (cold) Zonal Mode event strengthens (weakens) the Walker Circulation over the Pacific in boreal summer [*Rodriguez-Fonseca et al.*, 2009; *Ding et al.*, 2012] – a period crucial for ENSO development. The Bjerknes feedback amplifies these anomalies, leading to significant cold (warm) SST anomalies in the eastern Equatorial Pacific in boreal autumn and winter, and thus modulating ENSO variability [*Rodriguez-Fonseca et al.*, 2009; *Ding et al.*, 2012]. An inter-basin feedback may also enhance this link [*Wang*, 2006]. North Tropical Atlantic SST variations may also influence ENSO variability [*Ham et al.*, 2013].

Previous idealized studies indicate that accounting for Atlantic SST variability may enhance ENSO predictability [*Jansen et al.*, 2009; *Frauen and Dommenget*, 2012]. Here we investigate whether Equatorial Atlantic SST variability can enhance actual ENSO predictions initialized prior to boreal spring, by performing experiments with a climate model (section 2). Section 3 presents the results and this is followed by a discussion.

2. Model and experiments

Model and experiments are briefly described here; more details are provided in the supplementary information. We use the ECHAM5/MPI-OM coupled general circulation model (IPCC AR4 version) [*Jungclaus et al.*, 2006]. The atmospheric model [*Roeckner et al.*, 2003], is run at T63 (~1.8°) horizontal resolution, and with 31 vertical levels extending to

10hPa (~30km); the oceanic model [*Marsland et al.*, 2003], has 1.5° average horizontal resolution and 40 vertical levels.

We perform five different seasonal prediction experiments that start February 1st and end December 31st and cover the period 1980–2005. In four of the experiments, SST is strongly relaxed to (1) *Observed Atlantic SST* between 30°S–30°N; (2) *Observed Equatorial Atlantic SST* between 15°S–5°N; (3) *Observed Atlantic climatological SST* between 30°S–30°N, and (4) Observed Atlantic SST till May and climatological SST thereafter between 30°S–30°N. The relaxation of model SST to observations reduces linearly to zero in 30° latitudinal bands to the North and South, except in *Observed Equatorial Atlantic SST* where a 5° band is used. These are compared to a fully coupled prediction experiment (*Standard*). All predictions have nine ensemble members, except for the *Observed Atlantic SST climatology* that has five. They are initialised from three coupled simulations with model SST strongly relaxed to observations over the tropics, with a relaxation constant that varies with latitude as in the Observed Atlantic predictions. Strong ocean-atmosphere coupling makes this simple method effective for initialising ENSO forecasts [*Keenlyside et al.*, 2005; *Luo et al.*, 2005; *Luo et al.*, 2010].

A partial-coupled experiment (*Observed Atlantic SST 20C*) [*Ding et al.*, 2012] with SST relaxed to observations as in the Observed Atlantic SST predictions but extending continuously over the period 1950–2005, with five ensemble members that differ only in their initial condition, was also performed.

Radiative forcing in the initialisation and Observed Atlantic SST 20C experiments follows the observations/IPCC A1B scenario (greenhouse gas and sulphate aerosol concentrations, solar cycle variations, and major volcanic eruptions). It is identical in the seasonal predictions, except that solar cycle variations are repeated from the previous eleven years, and major volcanic eruptions that occurred during a forecast are not included, but the impact of any that occurred prior to the forecast is reduced with a one-year e-folding time.

3. Results

Twin seasonal prediction experiments initialized February 1st with and without model SST relaxed to observations [*Kalnay et al.*, 1996], over parts of the Atlantic are performed for the period 1980–2005. Skill of the Standard experiment without SST relaxation results from factors largely independent of Atlantic Zonal Mode, as boreal summer Equatorial Atlantic SST is poorly predicted (Fig. S1), common with other prediction systems [*Stockdale et al.*, 2006]. Whereas, the SST relaxed experiments indicate the potential skill achievable from perfect future knowledge of Atlantic SST (i.e., an upper bound).

Relaxing Tropical (and partly mid-latitude) Atlantic SST to observations during the entire forecast (Observed Atlantic SST) significantly and substantially increases skill in predicting October-December Indo-Pacific SST: anomaly correlation skill of the Standard experiment hardly exceeds 0.6, and is mainly confined to the central Equatorial Pacific (Fig. 1A); whereas skill of the Observed Atlantic SST experiment is mostly above 0.5 in the Equatorial Pacific and extends to the sub-tropics and Indian Ocean (Fig. 1B). Consistent with the previously identified mechanism [*Rodriguez-Fonseca et al.*, 2009], enhanced skill in predicting central and eastern Equatorial Pacific SST anomalies begins in boreal summer and peaks in early winter (Fig. 2A). From 1–6 month lead, prediction skill of both the Standard and Observed Atlantic SST experiments drops rapidly, following persistence skill till month three. This is probably because our initialisation scheme (Suppl. Info.) does not take into account observed atmospheric or subsurface ocean data, leading to a relatively large initialisation shock [*Keenlyside et al.*, 2005].

A five ensemble-member coupled model simulation starting in 1950 and ending in 2005 with model SST relaxed to observations over the Atlantic provides another estimate of skill arising from Atlantic SST variability (Observed Atlantic SST 20C) [*Ding et al.*, 2012]. Again, we only consider the period 1980–2005. Observed eastern Equatorial Pacific SST anomalies are predicted best in boreal spring and summer (r ~0.6) and worst in winter (r ~0.4) (Fig. 2A). This skill results from both contemporaneous Atlantic forcing of the Pacific, primarily in boreal spring and summer, and a delayed response to this forcing, primarily in autumn and winter [*Rodriguez-Fonseca et al.*, 2009; *Ding et al.*, 2012]. In boreal autumn and early winter the SST variance explained by the Observed Atlantic SST 20C and Standard experiments approximately sum to that of the Observed Atlantic SST experiment (Fig. 2A, Fig. S2). This is consistent with Atlantic SST variations providing an independent source of predictability for Indo-Pacific SST in these two seasons.

Further analysis shows that Atlantic SST variations enhance ENSO prediction via improved prediction of western Equatorial Pacific wind stress variations. Relaxation to observed Atlantic SST increases seasonal prediction skill of wind stress anomalies over this region from June to December, preceding the increase in SST prediction skill by 1–2 months (Fig. 2A & B, Fig. S3A & B), which is approximately the time required for eastward propagating equatorial Kelvin waves excited in the west to influence eastern Pacific SST. In addition, from June to December the variance explained in western Pacific wind stress by the Observed Atlantic SST 20C and Standard experiments approximately sum to that of the Observed Atlantic SST experiment (Fig. 2B, Fig. S3). Atlantic SSTs are apparently not instrumental in the ENSO cycle [*Jin*, 1997; *Burgers et al.*, 2005], as they do not strongly enhance skill in predicting Equatorial Pacific averaged upper ocean heat content, as expressed by the warm water volume (WWV) [*Meinen and McPhaden*, 2000], nor is there a similar partition of explained variance (Fig. 2C). In contrast to SST and wind stress, skill in predicting WWV does not show an initial rapid decline, but starts at much lower values (Fig. 2C). This reflects deficiencies in our simple initialization scheme, and is partly indicative of imperfect initial conditions that contribute to the initial shock.

Several additional prediction experiments confirm that Equatorial Atlantic SST variability in boreal spring and summer are key to enhancing skill in predicting Indo-Pacific SST and zonal wind stress anomalies. First, the increase in skill is very similar when SST is strongly relaxed only over the Equatorial Atlantic (5°N–15°S)

(Observed Equatorial Atlantic SST), as opposed to the whole Atlantic (Fig. 2A & B, Fig. S4A & B). Second, there is no substantial increase in skill when SST is relaxed to observations only from February to May and observed monthly climatological SST from June to December (Fig. 2A & B, Fig. S4C & D), clearly showing the importance of Atlantic SST in boreal summer. Third, the skill increase does not simply result from an improved Atlantic climatology, but is further degraded when SST over the Atlantic is relaxed to the observed monthly climatology during the entire forecast (Fig. 2A & B, Fig. S4E & F; Observed Atlantic SST climatology).

Most notably, near perfect knowledge of Atlantic SST improves the prediction of the 1982/1983 and 1997/1998 major El Niño events (Fig. 3, Fig. S5). The Standard experiment (Fig. 3B) fails to predict either event, whereas the Observed Atlantic SST experiments capture both robustly (Fig. 3A). However, their strength is somewhat underestimated (Fig. S5), suggesting other process are also important. In particular, for the 1997/1998 event the observed extreme westerly wind bursts in late boreal winter over the far western Pacific were not predicted by our model (Fig. S5). The improved prediction of the 1982/1983 and 1997/1998 events alone accounts for approximately half of the skill enhancement in predicting eastern Equatorial Pacific SST for October–December, as shown by computing the anomaly correlations excluding these events (Fig. 2A). Furthermore, the increase in skill is consistent with western Equatorial Atlantic SST modulating (rather than triggering) ENSO, through impacting western Equatorial Pacific wind stress variations mainly in boreal summer, and not only for strong events (Fig. S6).

Remote forcing from the Atlantic adds important physics during the development of ENSO, as shown by the lag-regression of October–December eastern Equatorial Pacific SST anomalies with Equatorial Pacific/Atlantic SST, zonal wind stress, and thermocline depth anomalies (Fig. 4). Observed El Niño events begin with westerly wind stress anomalies over the western and central Equatorial Pacific and thermocline depth anomalies in the central Pacific (Fig. 4A). The thermocline anomalies propagate eastward, causing anomalous warm

SST, which enhance the westerly wind stress anomalies, further deepening the thermocline. This positive ‘Bjerknes’ feedback leads to the El Niño event in boreal winter.

Beyond this classical picture, anomalous cold SST appear in the eastern Equatorial Atlantic early in the year and peak in boreal summer, when easterly wind stress anomalies are found to the west; these anomalies are associated with a negative Zonal Mode event. A very similar picture is found in the Observed Atlantic SST predictions (Fig. 4B), whereas in the Standard predictions, anomalies in the Equatorial Atlantic are absent and those in the Equatorial Pacific are weaker (Fig. 4C). Early in the year both experiments show a build up of equatorial heat content and zonal wind stress anomalies that are not observed, reflecting errors in the model’s ENSO dynamics and initialization (Fig. 2C). The regressions computed from the difference of the two experiments highlights the influence of the Atlantic (Fig. 4D), with significant impacts starting to develop in spring.

4. Discussion and conclusions

We performed a suite of prediction experiments to assess the impact of observed Atlantic SST on ENSO prediction. Our results show remote forcing from the Equatorial Atlantic may considerably improve ENSO forecasts initialized before boreal spring, particularly of major events such as those of 1982/83 and 1997/98, and hence may help alleviate the spring predictability barrier. The skill improvement arises from the modulation of ENSO, rather than from triggering of ENSO extremes.

Several considerations apply to our results. Firstly, here we do not discriminate between locally generated and remotely forced Tropical Atlantic SST variations, and so skill improvements may partly result from better representation of ENSO teleconnections. However, isolating ENSO’s impact on Equatorial Atlantic SST is complex [*Chang et al.*, 2006; *Lübbecke and McPhaden*, 2012]. Secondly, although simulated tropical atmospheric circulation patterns agree well with observations from boreal summer to winter

[*Ding et al.*, 2012], restoring SST strongly to observations may compromise our results [e.g., *Krishna Kumar et al.*, 2005]. Thirdly, the skill improvement reported here could be inflated, as we use a simple initialization scheme – only restoring coupled model SST to observations. Nevertheless, forecast systems initialized with similar as well as more complete schemes still have difficulty predicting major El Niño events before boreal spring [*Barnston et al.*, 1999; *Luo et al.*, 2005; *Jin et al.*, 2008].

Our results indicate that some of the deficiencies of state-of-the-art climate models in simulating and predicting ENSO variability could be related to the strong systematic model error in the Tropical Atlantic [*Richter and Xie*, 2008; *Wahl et al.*, 2011]. In many climate models, the SST gradient across the Equatorial Atlantic is too weak or even reversed, inhibiting realistic simulation and prediction of Zonal Mode variability. Lastly, accounting for other remote influences may also enhance ENSO skill [e.g., *Vimont et al.*, 2001; *Izumo et al.*, 2010; *Terray*, 2011], and deserves further investigation.

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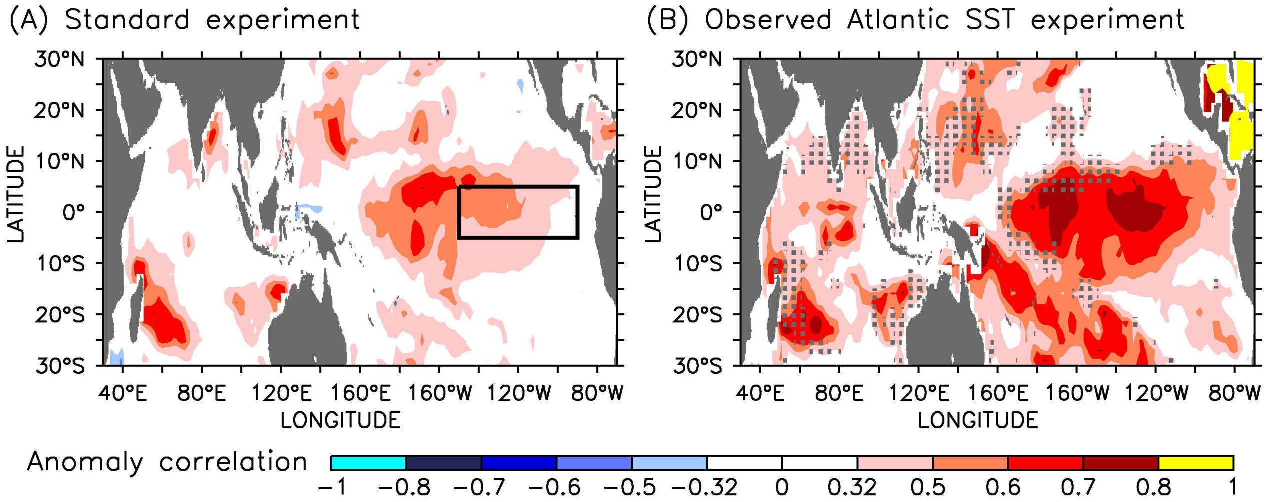

Figure 1. Impact of observed Atlantic SST on seasonal prediction in the Indo-Pacific Sector. Anomaly correlation skill for October–December (9–11 month lead) average SST for nine-member ensemble predictions starting 1st of February each year during the period 1980–2005 and performed with a state-of-the-art climate model. Atlantic SST in (A) are predicted by the model (i.e., standard case) and (B) are prescribed from observations. Shaded positive values are significantly different from zero at 5% level according to a 1-sided Student's t-test. Shaded non-stippled regions in (B) indicate where prescribed Atlantic SST leads to a significant increase in skill at the 5% level, according to a one-sided t-test applied to Fisher-Z transformed values. Box in (A) delineates the Niño 3 (150–90°W, 5°S–5N) region. Observed SST are from HadISST [*Rayner et al.*, 2003].

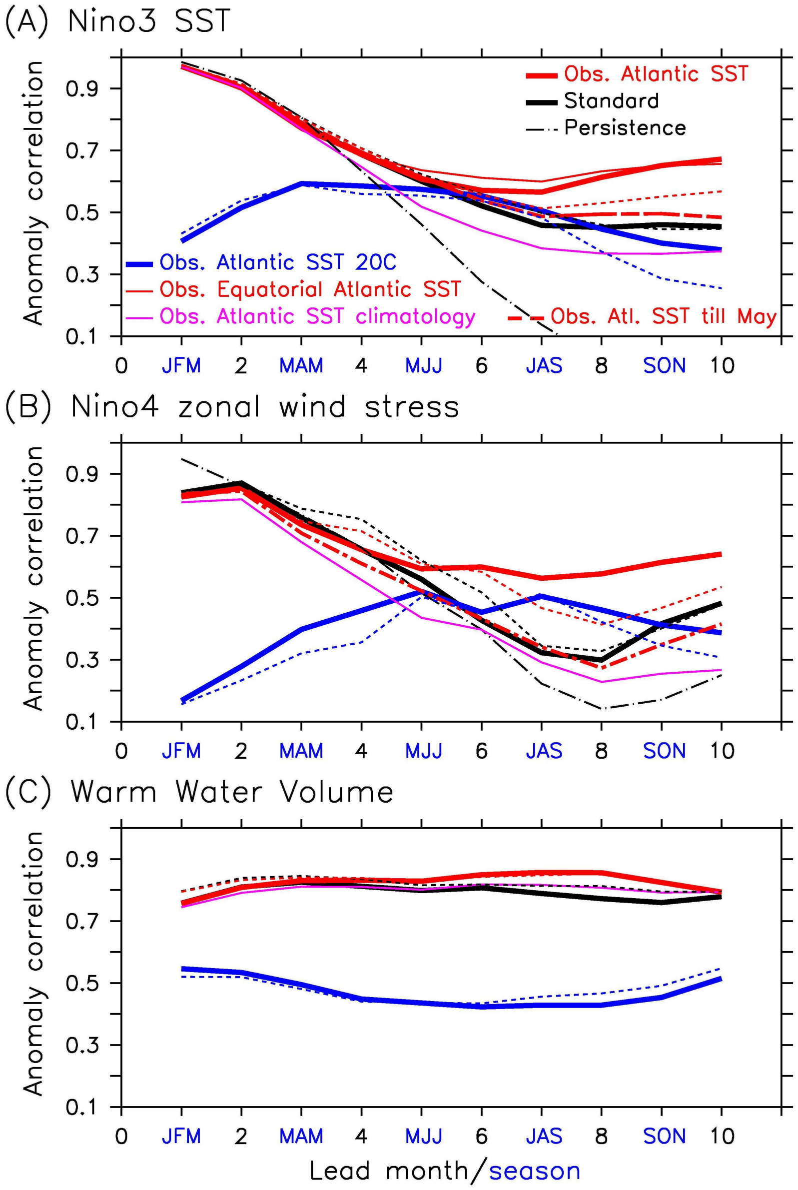

Figure 2. Equatorial Atlantic SST improves prediction skill in the Pacific. (A) Anomaly correlation skill for three-month mean Niño3 (box in Fig. 1B) averaged SST for Observed Atlantic SST and Standard predictions as function of forecast lead-time. Also shown are skill of analogous predictions with either observed SST prescribed only over the Equatorial Atlantic (10°N–20°S), or observed SST monthly climatology prescribed over the Atlantic (60°S–60°N); skill of a five-member 20th century climate simulations with observed SST prescribed over the Atlantic (60°S–60°N); and persistence skill (i.e., assuming initial anomaly persists). Thin dashed lines show forecast skill computed excluding predictions of major 82/83 and 97/98 El Nino events for Observed Atlantic SST, Standard, and 20th century experiments. Thick dash-dotted red line indicates skill of predictions with Atlantic SST as observed from February-May and climatology from June–December. (B) & (C) as in (A), except for Niño 4 (160°E–150°W, 5°S–5N; box in Fig. S3A) averaged surface zonal wind stress, and Equatorial Pacific (120°E–80°W, 5°S–5°N) warm water volume. The latter, a measure of upper-ocean heat content, is defined as the volume of water warmer than 20°C. Observed SST are from HadISST [*Rayner et al.*, 2003], wind stress from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] and thermocline depth from Smith (1995) [*Smith*, 1995]. Values greater than 0.32 are significant at the 5% level according to a 1-sided Student's t-test.

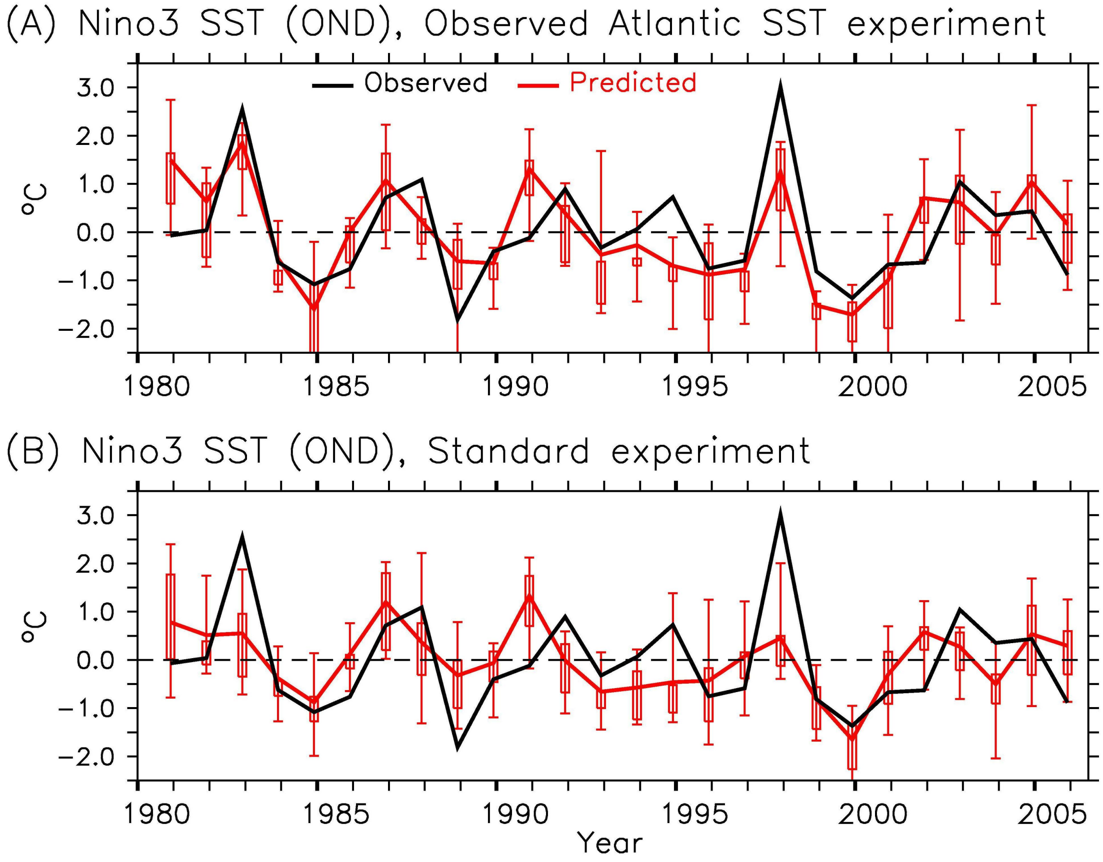

Figure 3. Better prediction of the two major El Niños of 1982/1983 and 1997/1998 mostly enhances El Niño Southern Oscillation prediction skill. Observed [*Rayner et al.*, 2003], and predicted October–December Niño 3 SST anomalies for predictions initialised 1st of February with Atlantic SST (A) as observed and (B) predicted by the model. The ensemble mean (solid line), upper and lower quartiles (box), and ensemble maximum and minimum (error bars) are shown for the predictions.

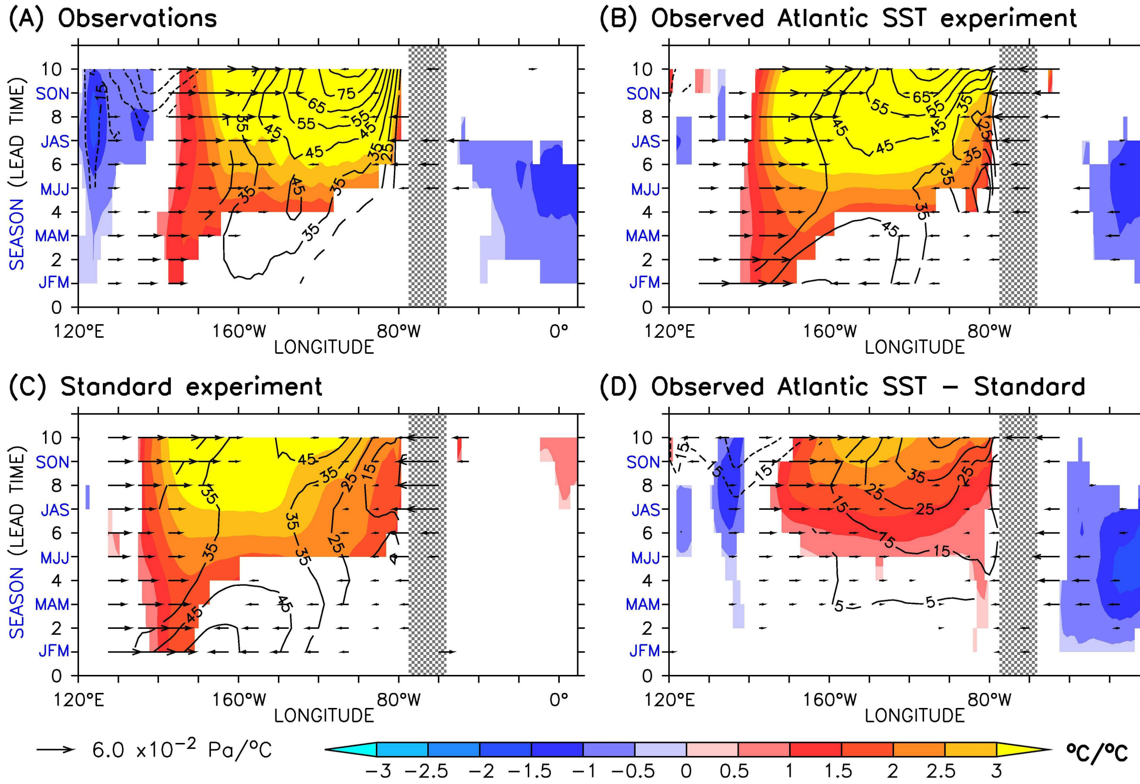

Figure 4. Atlantic Zonal Modes influence on the Pacific in observations and prediction experiments. (A) Observed linear-regression of the boreal autumn/early winter (OND) Niño 3 SST index on 5°S–5°N average SST [*Rayner et al.*, 2003], (shaded), thermocline depth [*Smith*, 1995], (contours, m/°C) and zonal wind stress [*Kalnay et al.*, 1996], (vectors) for seasons JFM to OND. (B-D) as in (A), but for Observed Atlantic SST and Standard prediction and difference of anomalies predicted in Observed Atlantic SST minus Standard experiments. Values shown are significantly different from zero at the 5% level (2-sided t-test), and the linear trend was removed prior to computation. Grey shading shows land.