Title:

Atlantic Induced Pan-tropical Climate Change over the Past Three Decades

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Summary

During the last three decades, tropical sea surface temperature (SST) has shown dipole-like trends, with warming over the tropical Atlantic and Indo-Western Pacific but cooling over the Eastern Pacific. Competing hypotheses relate this cooling, identified as a driver of the global warming hiatus[1,2], to the warming trends in either the Atlantic[3,4] or Indian Ocean[5]. However, the mechanisms, the relative importance, and the interactions between these teleconnections remain unclear. Using a state-of-the-art climate model, we show that the Atlantic plays a key role in initiating the tropical-wide teleconnection, and the Atlantic-induced anomalies contribute ~55%-75% of the tropical SST and circulation changes during the satellite era. The Atlantic warming drives easterly wind anomalies over the Indo-Western Pacific through the Kelvin wave, and westerly anomalies over the eastern Pacific as Rossby waves. The wind changes induce an Indo-Western Pacific warming via the wind-evaporation-SST effect[6,7], and this warming intensifies the La Niña-type response in the tropical Pacific by enhancing the easterly trade winds and through the Bjerknes ocean-dynamical processes[8]. The teleconnection develops into a tropical-wide SST dipole pattern. This mechanism, supported by observations and a hierarchy of climate models, reveals that the tropical ocean basins are more tightly connected than previously thought.

The tropics have experienced marked climate change since 1979 when the era of global satellite observations began. Sea surface temperature (SST) trends exhibit a pan-tropical dipole-like pattern (**Fig. 1a**), with extensive warming from the tropical Atlantic to the Indo-Western Pacific, and a triangular cooling pattern in the Central-Eastern Pacific. This tropical-wide gradient in the SST trend interacts with the atmospheric and oceanic circulation throughout the tropics (**Fig. 1c, e**), with an enhanced Walker circulation[9-11] and a La-Niña-like Pacific sub-surface response. These changes further contribute to global climate change[1,12,13] via multiple atmospheric teleconnections[8,14].

The tropical ocean basins are connected through atmospheric bridge[15] into an interactive system. On interannual time scales, El Niño-Southern Oscillation (ENSO) dominates the tropical inter-basin teleconnections[15,16], although the Indian[17,18] and Atlantic[19-21] Oceans experience regional effects that can feedback to the Pacific. In this inter-basin teleconnection, El-Niño warming heats the Indian and Atlantic basins[13]. Were the same relationship to hold on multidecadal time scales, the cooling of the Eastern Pacific would be linked to decreased SSTs in the Indian and Atlantic basins (**Supplementary Fig. 1**), contrary to the observed trends. This discrepancy implies that other mechanisms are required to compensate the Eastern Pacific induced tropical cooling.

The north and tropical Atlantic has experienced a continuous warming trend, due to the combined effects of anthropogenic radiative forcing[7,22] and the change in Meridional Overturning Circulation[23,24]. Pioneering work using slab ocean-atmospheric models[3] and reduced-gravity ocean-atmospheric models[4] suggest that this observed Atlantic warming directly contributes to the Eastern Pacific cooling, although the full range of ocean dynamics and atmospheric-ocean interactions may not be well represented by these idealized oceanic models. Here we simulate the global impact of the tropical

Atlantic warming using a fully coupled earth system model, and further investigate the mechanisms of these teleconnections using a hierarchy of climate models. The results from the coupled model show that the Atlantic warming can induce a basin-scale warming over the Indian Ocean and Western Pacific through atmospheric bridge. This secondary Indo-Western Pacific warming, together with the original Atlantic warming, intensifies the easterly wind anomaly over the Pacific, accelerates the Walker circulation, and contributes to the La-Niña-type response over the Pacific (**Fig. 1**). Both surface heat fluxes and ocean dynamics play key roles in this tropical-wide pattern formation.

We first test the hypothesis that the tropical Atlantic warming drives the tropical-wide change by nudging the tropical Atlantic SST in a state-of-the-art fully coupled model (**Fig. 1b**), the Community Earth System Model (CESM1, see Method Section). The restoring reproduces the bulk of the observed warming trend over the tropical Atlantic (97%, see gray bars in **Supplementary Fig. 2c**). Forced by this Atlantic warming, the model (**Fig. 1b**) captures the detailed features of the observed tropical-wide SST changes (**Fig. 1a**), i.e., a significant warming anomaly over the Indo-Western Pacific (**Supplementary Fig. 2c** blue bars), and significant cooling anomalies in the off-equatorial Eastern Pacific (purple and green bars). A Mann-Kendall test indicates that the observed equatorial Pacific cooling trend from 1979 to 2013 is only marginally significant (left red bar) due to high internal variability and the short period. With a large sample size, the Pacific cooling is significant in the ensemble simulation with a Student *t*-test. In addition, the 25-year-mean results for each of the 12 ensemble members (**Supplementary Fig. 2c**) show a cooled equatorial eastern Pacific in response to the Atlantic warming, indicating a robust anti-correlated relationship between these two ocean basins. The coupled simulation captures 55% - 75% of the observed trends over the Indian and Pacific Oceans, highlighting the association between the Atlantic warming and pan-tropical SST changes, although additional mechanisms, e.g. anthropogenic radiative forcing for the Indo-Western Pacific warming[7], are likely required to explain the entire observed SST trend.

The Atlantic warming induced tropical-wide SST pattern drives a series of tropical climate changes in the CESM (**Fig. 1** right panels). The enhanced convection forced by the surface warming heats the troposphere, and the deep convection over the Indo-Western Pacific warm pool area intensifies the Indo-Pacific Walker circulation (**Fig. 1c, d**). At the surface, this circulation change manifests itself as a strengthened easterly wind anomaly[11] over the equatorial Pacific (**Fig. 1a**). With the dynamical ocean-atmosphere coupling, this simulated equatorial Pacific easterly wind anomaly captures 68% of the observed trend (**Supplementary Fig. 2c**), albeit with a slight westward shift (**Fig. 1b**). This wind anomaly is accompanied by a La-Niña-like Pacific subsurface anomaly both in observations and in the simulation (**Fig. 1e,f**). The coupled model successfully captures the main features of the observed temperature and circulation changes over the tropical ocean and atmosphere, although some of the detailed characteristics are not fully reproduced. In particular, the observed atmospheric temperature has exhibited a cooling trend over the African continent (**Fig. 1b**), associated with a downwelling flow in the troposphere. This is not well represented by the simulation, indicating that land-air interaction may be important for understanding the changes over that region. Additionally, the simulated atmospheric vertical motion (**Fig. 1d**) is both weaker and more widespread than the observed changes (**Fig. 1c**), which may be related to the convective scheme in the atmospheric model.

To better identify the potential sources of the pan-tropical climate variability (**Fig. 1a**), we also nudge the SST changes over the Indian Ocean and the Pacific Ocean, separately. The Indian Ocean nudging replicates the observed cooling trend in the Eastern

Pacific[1], albeit with a smaller amplitude, but it erroneously cools the Atlantic (**Supplementary Fig. 3**). The Pacific nudging, on the other hand, cools the Indian Ocean. Both simulations produce an SST response that is partially inconsistent with observations, indicating that the Atlantic is the most consistent driver of the pan-tropical dipole-like SST variability.

While our Atlantic nudging simulations successfully reproduce the observed trends, the coupled model alone does not reveal the mechanisms underlying these pan-tropical inter-basin teleconnections. Next, we use an idealized atmospheric model and a comprehensive atmospheric model to identify the dynamical pathways by which the tropical Atlantic warming forces the tropical-wide climate changes.

CESM simulations involve both atmospheric dynamics and atmosphere-ocean interactions. To single out the immediate atmospheric responses to the Atlantic SST forcing, we introduce a tropical Atlantic heating to an idealized atmospheric model – the dry-dynamical-core of the GFDL atmospheric model (Methods). The atmospheric deep convection generated by the Atlantic warming (**Supplementary Fig. 4**) excites an equatorial Kelvin-wave, inducing strong easterly wind anomalies to the east of the SST forcing (**Supplementary Fig. 5b**), as well as two Rossby wave packets with equatorial westerly wind anomalies and two off-equatorial cyclonic flows, west of the heat source. This circulation pattern closely resembles the classic Gill-model[25]. Within one week, the Kelvin-wave induced easterly wind anomalies extend from the Atlantic Ocean to the international-date-line (**Supplementary Fig. 5c**), traversing the entire Indian Ocean and Western Pacific, while the Rossby-wave equatorial westerly wind anomalies occupy the Eastern Pacific and Central America.

Moisture processes are important in the tropics but are absent in the GFDL-dry-dynamical-core. The Community Atmospheric Model (CAM4, Methods) is the atmospheric component of CESM1 and includes interactive moist processes. The CAM4 response agrees well with that of the idealized simulation (**Supplementary Fig. 5c,d)**, again showing an easterly wind anomaly extending from the Atlantic to the Indo-Western Pacific and a westerly wind anomaly over the Eastern Pacific. The Kelvin-wave induced easterly wind anomalies favor a La-Niña-type ocean dynamical response[8], consistent with the coupled model results. In contrast, the Rossby-wave induced westerly wind anomalies favor an El-Niño-type response.

To investigate the direct ocean response to these atmospheric circulation anomalies, we use the anomalies to force an ocean-only model (POP2, see **Supplementary Fig. 6**). In the absence of ocean-atmosphere feedbacks, the ocean model response is different from the La-Niña-type responses simulated in the fully-coupled model. This discrepancy highlights the importance of atmosphere-ocean interactions in the pan-tropical teleconnections. The remainder of this work investigates atmosphere-ocean interactions that further enhance the equatorial Pacific easterly wind anomalies and the Walker circulation, thus contributing to a La-Niña-like Pacific response.

Atmospheric forcing may influence regional SST by changing surface heat flux and oceanic dynamical effects[6, 7]. In CAM4, the surface energy-exchanges over the Indo-Pacific oceans are dominated by the wind-induced latent heat flux (**Fig. 2b**), whose contribution is ~3 times greater than that of all the other components of surface heat flux combined (**Supplementary Fig. 7**). The Kelvin-wave induced easterly wind anomaly over the Indian Ocean reduces surface wind speed (blue contours in **Fig. 2b**) and suppresses evaporation, which warms the Equatorial-Northern Indian Ocean (red color in **Fig. 2b**) via the wind-evaporation-SST effect[6] (WES, Methods). Note that in the atmosphere-only simulation (**Fig. 2b**), the SSTs are fixed and cannot feed back to the atmospheric circulation. The simulated regional-mean latent heat flux anomaly is ~4.35 W/m^2, corresponding to an initial heating rate of the ocean mixed layer of ~0.05 K/month, which implies a fast response of Indo-Western Pacific with a time scale of ~1 year. This fast response is well reproduced in the coupled model and is supported by the statistical analyses of the observational data and the CMIP5 simulations (**Supplementary Fig. 8**)

To the west of the Atlantic warming, the Rossby-wave-induced circulation changes strengthen the trade winds and cool the off-equatorial Eastern Pacific in both hemispheres (blue color in **Fig. 2b**). This cooling signal may propagate equatorward and westward to the central-equatorial Pacific via the WES seasonal footprinting mechanism[26]. The Kelvin-wave-induced easterly wind anomaly also cools the central equatorial Pacific around the international dateline. These WES cooling effects contribute to an SST decrease over the Central-Eastern Pacific, which has been well simulated by a recent study using a slab ocean-atmosphere coupled model[3].

The Atlantic-induced Indo-Western Pacific warming generates a secondary atmospheric deep convection (**Fig. 2c**, also see **Supplementary Fig. 9**) with westerly wind anomalies over the Indian Ocean, and an easterly wind anomaly across the Pacific basin. This secondary circulation change, representing an enhanced Indo-Pacific Walker circulation, explains the different atmospheric circulation responses between the CAM4 and CESM results. It reinforces the Atlantic-induced easterly wind anomalies over the western equatorial Pacific, overwhelming the Atlantic-induced westerly wind anomalies over the eastern equatorial Pacific. Atmospheric circulation changes further interact with Pacific Ocean dynamics through the Bjerknes feedback[4,8]. This feedback is at work in the coupled model (**Fig. 2d**): over the equatorial Pacific strong easterly winds drive an enhanced SST gradient, which further intensify the winds, ultimately giving rise to a La-Niña-like subsurface anomaly in the Pacific Ocean. In contrast, the ocean dynamical response is comparatively weak in the Indian Ocean, which experiences an overall warming in the upper 300m with a cooling at ~100m (**Fig. 1e**). The Indian Ocean temperature change is primarily a direct response to the surface heat fluxes, while the Indonesian Throughflow may also contribute to these upper layer changes[27].

In summary, we have shown that the tropical Atlantic warming over the past three decades, aided by coupled ocean-atmosphere processes, caused a tropical-wide response that included the Indo-Western Pacific warming and eastern Pacific cooling. The direct atmospheric response to the tropical Atlantic warming includes easterly wind anomalies over the Indo-Western Pacific in the form of Kelvin waves, and westerly wind anomalies over the eastern equatorial Pacific as Rossby waves (**Fig. 3a**), in line with Gill's solution. The easterly wind anomalies cause the Indo-Western Pacific to warm and the central equatorial Pacific to cool through the WES effect, while the Rossby wave gyres intensify the easterly trade winds in the off-equatorial Eastern Pacific, contributing to the equatorial Pacific cooling via the WES foot-printing mechanism (**Fig. 3a**). This surface atmospheric-ocean interaction generates a temperature gradient over the Indo-Pacific basins, which further enhances the Walker circulation and induces easterly wind anomalies across the equatorial Pacific, and drives it into a La-Niña state (**Fig. 3b**). The Bjerknes feedback helps amplify the coupling of the equatorial Pacific cooling and easterly intensification.

A global SST pattern characterized by the eastern Pacific cooling and warming over the rest of oceans is identified as the most predictable mode at multi-year lead times[28]. Pacific decadal variability may be partly tied to Atlantic multidecadal oscillation[29,30]. The tropical Atlantic warming trend is likely due to radiative forcing[7,22] and Atlantic Multi-decadal Oscillation[23,24], the latter possibly tied to the Atlantic meridional overturning circulation (AMOC). The mechanism revealed by this study suggests that the AMOC may force the pan-tropical decadal variability, and the slow time scales of the AMOC may explain the decadal predictability[19,28] of the tropical-wide SST pattern.

The Indo-Western Pacific SST response to the tropical Atlantic warming is almost immediate, with a timescale of ~1 year. In contrast, there exists a ~10 year phase lag between the Atlantic warming and the cooling phase of the Pacific Decadal Oscillation[30]. This decadal-scale phase lag may be related to shorter-term variability such as ENSO, which serves as a stochastic forcing to the long-term variability. In this study we mainly focus on explaining the observed trend during the satellite era, but we plan to address this phase-lag problem in future work. Additionally, our coupled simulations are forced by a fixed radiative forcing. The radiative forcing changes caused by increased greenhouse gases could further warm the Atlantic Ocean and the Indo-Western Pacific, although its impact on the Eastern Pacific requires further investigations.

While recent studies of the global warming hiatus have focused on the Pacific effect[1], consistent with earlier studies[2-4] our results suggest that the hiatus may ultimately be traced back to the warming in tropical Atlantic. This teleconnection is aided by Indo-Western Pacific adjustments as revealed in this study. Together, these studies show that the three tropical ocean basins are linked more closely than previously thought, and on decadal time scales the tropical oceans should be considered as a single entity. In addition to the well-known ENSO-induced tropical-wide response that is dominant on inter-annual time scales, this study highlights the role of the tropical Atlantic in initiating a different pan-tropical dipole pattern that is important on decadal timescales.

Online Methods

Data sets. The UK Met Office Hadley Centre's SST dataset HadISST[31] was employed in this study to estimate the trend of the Tropical SST from 1979 to 2012 (**Fig. 1a**), and the SST trend over the Tropical Atlantic estimated by this dataset was used to force the CESM and CAM4 models. The Kaplan Extended SST version2[32], and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST version 3b[33], were also used together with the HadISST to reveal the decadal relationship between the Tropical Atlantic and the Indo-Western Pacific.

The Ishii Subsurface Ocean Temperature Analysis[34] was used to calculate the subsurface ocean temperature trends from 1979 to 2012 (**Fig. 1e**). The Global Precipitation Climatology Project[35] (GPCP) data were used to estimate the trend in the tropical precipitation for the same period. The European Centre for Medium Range Weather Forecasts (ECMWF) Interim Re-Analysis[36] (ERA-Interim) data were used to estimate the trend in the atmospheric circulation (**Fig. 1a,c**).

Model results from the Coupled Model Intercomparison Project[37] (CMIP5) historical experiments were used to identify the relationship between the Tropical Atlantic and the Indo-Western Pacific decadal-mean SST.

Analyses methods. Sen's slope[38] method is used to calculate the observed trends, with the confidence intervals estimated using the Mann-Kendall test[39]. We used Student's *t*-test to calculate the confidence interval of the model responses.

CESM model experiments. The National Center for Atmospheric Research (NCAR) coupled climate model, the Community Earth System Model[40] (CESM1.06) was used in this study to investigate the response of the tropical climate system to an observed Tropical Atlantic warming. We used F19_G16[40] horizontal resolution, with ~2 degree resolution in the atmospheric component, and ~1 degree in the ocean component. We restored the Tropical Atlantic temperature in the coupled model with an external heating within the mixed layer as follows:

$$F = cD(T_r - T_m) / \tau$$

Where c is the heat content of sea water, D is the mixed layer depth, T_r is the restoring target temperature, T_m is the model temperature at each time step, and τ is the restoring time scale, which was set as 20 days in this study.

The CESM response to the Tropical Atlantic warming was calculated as the ensemble mean of 12 sensitivity experiments. In each experiment, we estimate the difference between a control run and a perturbed run. In the control run, the ocean temperature in the mixed layer of the tropical Atlantic (defined as the Atlantic Ocean between 20°S and 20°N, with linear buffer zones extending from 20°S to 30°S and from 20°N to 30°N) was restored to the model climatology. In the perturbed run, the Tropical Atlantic SST was restored to the model climatology plus the observed 1979-2012 SST trend. We generated 12 ensemble members by slightly perturbing the external forcing around the observed SST trend (±0.1%, ±0.2%, ±0.6%, ±1%, ±1.4%, ±1.8% from the observed trend.) Each simulation starts from the year-2000 initial condition of the CESM system and lasts for 30 model years. The first 5 years serve as a spin up simulation while the results from year 6 to year 30 are used in the calculation. The ensemble mean of these simulations is then considered to be the CESM response to the observed trend of the Tropical Atlantic SST.

CAM4 model simulations. The NCAR atmospheric model, the Community Atmosphere Model version 4 (CAM4), was used in this study to identify the tropical atmospheric responses to the Atlantic SST trend from 1979 to 2012. CAM4 is the atmospheric component of CESM and is run with the same resolution. As we do with the CESM simulation, we estimate the CAM4 response by differencing the control runs (with the climatological SST forcing) from the perturbed runs (forced by the Tropical Atlantic SST trend).

GFDL dry-dynamical-core simulations. The spectral dry-dynamical-core of an atmospheric general circulation model[41], developed at the Geophysical Fluid Dynamics Laboratory (GFDL), was used to investigate the evolution of the atmospheric response to a tropical Atlantic warming, in a primitive-equation dynamical-system. The idealized model is initialized with the climatological background flow from the ERA-interim reanalysis, averaged from 1979 to 2012. At each time step, an additional forcing that balances the model's initial tendency associated with the climatological background flow was added to keep the model steady[42,43]. This external forcing ensures that the model response at each time step is due only to the initial tropical perturbation. In the forced cases, a convective heating is added as an initial impulse over the tropical Atlantic. The model results at each snapshot could be interpreted as the evolution of the primitive - equation - dynamics in response to the tropical heating (see Yoo et al. 2012 for details).

Surface heat flux and WES effect. The change of SST $\partial T'/\partial t$ satisfies a balance[5,6] between the oceanic dynamics D_o and four surface heat flux components: solar radiation Q_S, long wave radiation Q_L, sensitive heat flux Q_H, and latent heat flux Q_E, which can be expressed as:

$$C\frac{\partial T'}{\partial t} = D_O + Q_S + Q_L + Q_H + Q_E ,$$

where C is the heat capacity of the upper ocean, up to the depth of interest.

The latent heat flux Q_E can be further decomposed into an atmospheric forcing term Q_E^a and an oceanic response term Q_E^o,

$$Q_E = Q_E^a + Q_E^o = \frac{\partial Q_E}{\partial W}W' + Q_E^r + \frac{\partial Q_E}{\partial T}T' .$$

The former is mostly sensitive to the surface wind anomaly (W'), and the latter serves as a Newtonian damping with respect to the ocean temperature change (T'). Q_E^r refers to the residuals of the atmospheric forcing related to the relative humidity and stability effect and serves as a second-order factor[6] in this study.

When the surface wind is reduced, according to the bulk formula, the evaporation will be suppressed. This effect thus increases the latent heat flux from the atmosphere to the ocean, warming the sea surface[5].

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Author Contributions

X.L., S.-P.X. and S.T.G. designed the experiments; X.L. performed the data analysis and numerical simulations, and prepared all figures; X.L. and C.Y. ran the CESM and GFDL simulations; all authors wrote and reviewed the manuscript.

Competing Financial Interest:

The authors declare no competing financial interests.

Figures

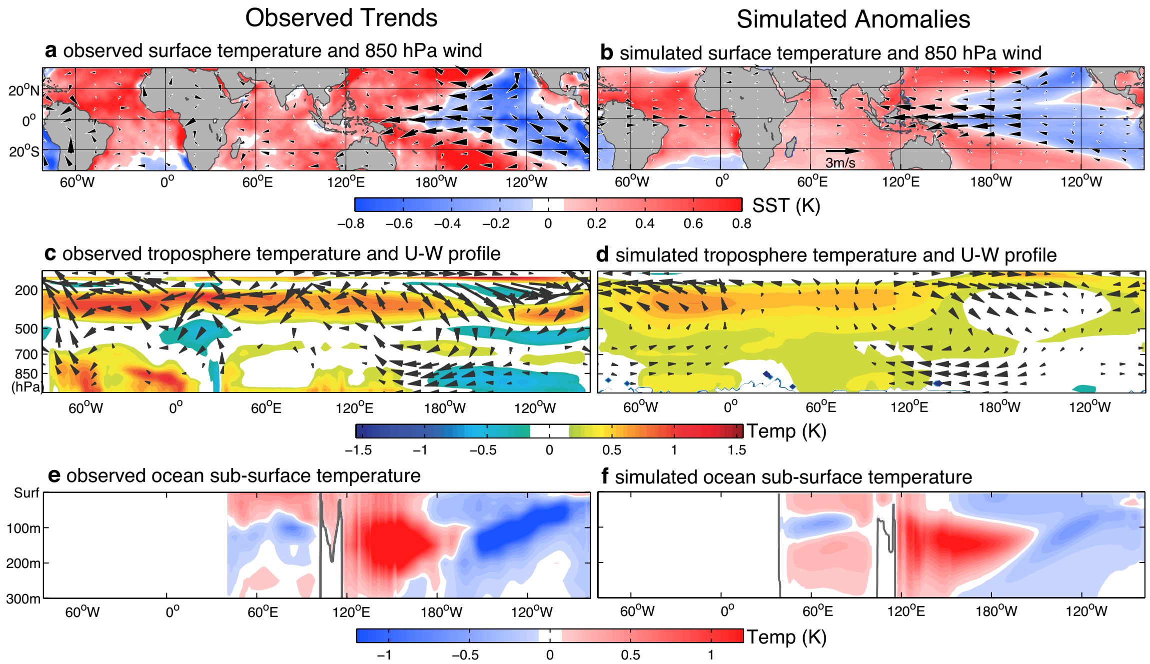


Figure 1 | Observed tropical climate changes (a, c, e) can be well reproduced by the CESM coupled model simulation (b, d, f), forced by the observed tropical-Atlantic-only SST changes. The (**a**) observed and (**b**) simulated sea surface temperature (SST) changes (background color) and 850hPa wind anomaly (arrows) both exhibit a pan-tropical dipole SST change, with warming extending from the Tropical Atlantic to the Indian Ocean and the Western Pacific, and cooling over the Central-Eastern Pacific. The observed trends (**a**) are estimated using the Sen's slope method, from 1979 to 2012. **c** and **d** show the Walker circulation changes (arrows) and troposphere temperature anomalies (color shading): the Indo-Pacific Walker circulation is enhanced. The vertical velocity is magnified by a factor of 750 to make its scale comparable to that of zonal wind. The (**e**) observed and (**f**) simulated ocean subsurface temperature anomalies (color shading) are shown for the tropical cross section between 5°S – 5°N.

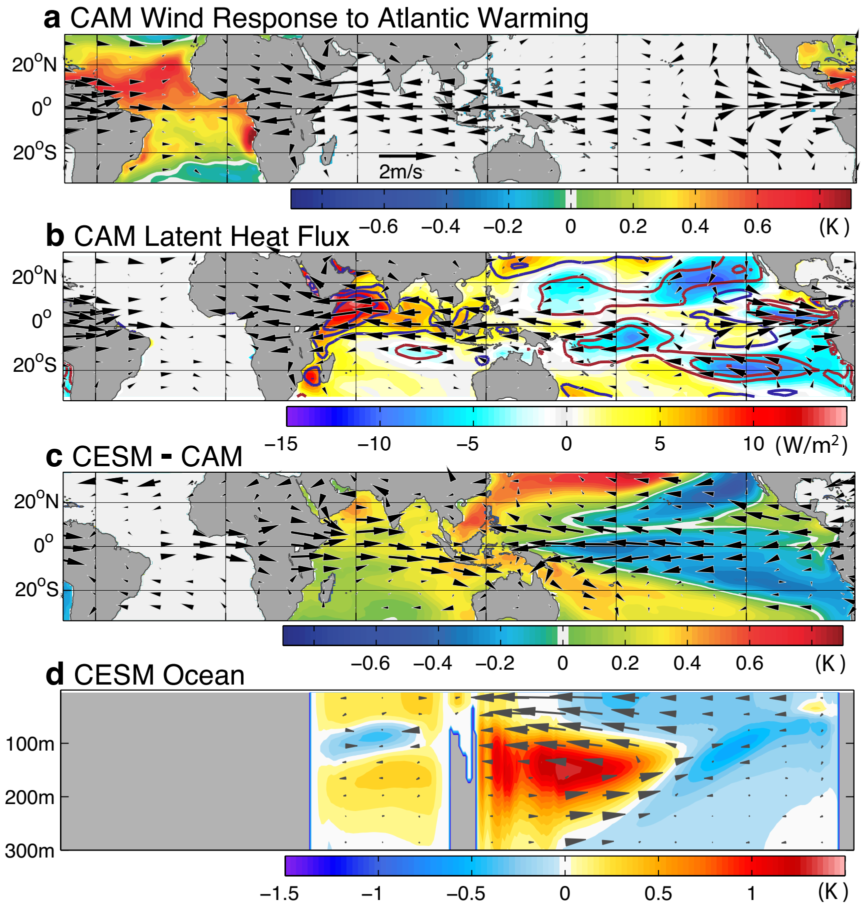


Figure 2 | Physical pathway for the Atlantic warming to drive tropical wide SST changes. a. shows the Atlantic SST forcing and 850hPa wind responses in CAM4. Deep convection forced by the tropical Atlantic warming induces convergent flows over the entire tropical region, i.e. easterly wind anomalies over the Indo-Western Pacific and westerly wind anomalies over the Eastern Pacific. **b**. The wind changes in CAM4 further reduce the surface wind speed (blue contours) over vast areas of the Indian Ocean, suppress evaporation, and thus reduce the latent heat flux (red/yellow shading) from the ocean to the atmosphere (equivalent to a heating in the ocean). They also increase the surface wind speed (red contours) over much of the off-equatorial Eastern Pacific and thus increase latent heat flux (blue shading) there. **c**. CESM - CAM4 differences in SST and 850hPa wind. The anomalous Atlantic warming heats the Indo-Western Pacific and cools the Eastern Pacific. This SST gradient generates a secondary atmospheric circulation change, characterized by an enhanced easterly wind anomaly over the Pacific, and a westerly wind anomaly over the Atlantic-Indian Oceans. **d**. sub-surface temperature and ocean current responses in CESM (the vertical velocity is magnified by 4000 times). The easterly wind anomaly further drives the ocean surface current, strengthens the equatorial undercurrent and generates a La Niña-like ocean dynamical response. Processes shown in **c** and **d** interact with each other through the Bjerknes feedback.

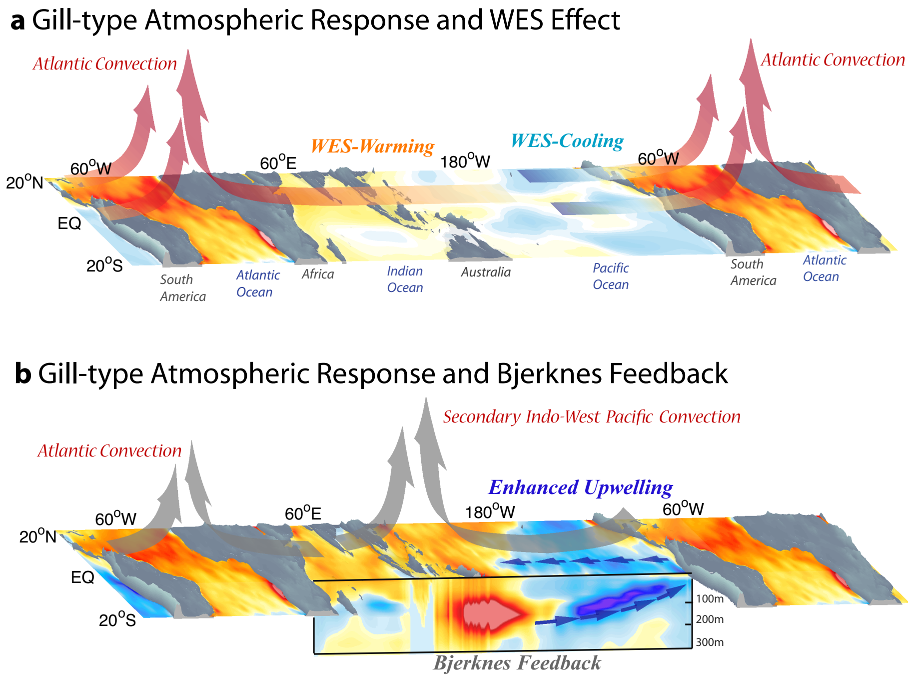


Figure 3 | Schematic graph of the physical mechanism. a Atlantic warming generates anomalous atmospheric deep convection, mimicking the Gill-convective-model[28]. The deep convection forces an easterly wind anomaly over the Indian Ocean that suppresses local evaporation and increases the SST there. This is accompanied by a Rossby-wave induced wind anomaly of opposing sign, which cools the Eastern Pacific. This atmosphere-ocean surface interaction initiates a temperature gradient over the Indo-Pacific oceans. **b** the Pacific ocean dynamic effect positively feeds back on this SST gradient, i.e. the SST gradient generates a secondary deep convection over Indo-Western Pacific warm pool, reinforcing the easterly wind anomalies over the Pacific basin, which intensifies the Ekman pumping over the Eastern Pacific and enhances the Pacific undercurrent. These dynamical effects cool the Eastern Pacific and warm the Western Pacific, forming a positive feedback. The vertical cross-section in **b** illustrates the temperature and circulation anomalies in the sub-surface Indo-Pacific.

Atlantic Induced Pan-tropical Climate Change over the Past Three Decades

Supplementary Information

POP simulation forced by the Atlantic-induced atmospheric circulation changes. The Atlantic induced atmospheric circulation changes involve an easterly wind anomaly over the Indo-Western Pacific and a westerly wind anomaly over the eastern equatorial Pacific. The former favors a La-Niña-type ocean dynamical response, while the latter favors an El-Niño-type response. To investigate the direct impact of the atmospheric circulation anomalies to the Indian Ocean and the Pacific, we perform an additional simulation using an ocean-only model (POP2, the oceanic component of the CESM model), forced by the Atlantic induced surface wind anomalies from CAM4 (**Fig. 2a**).

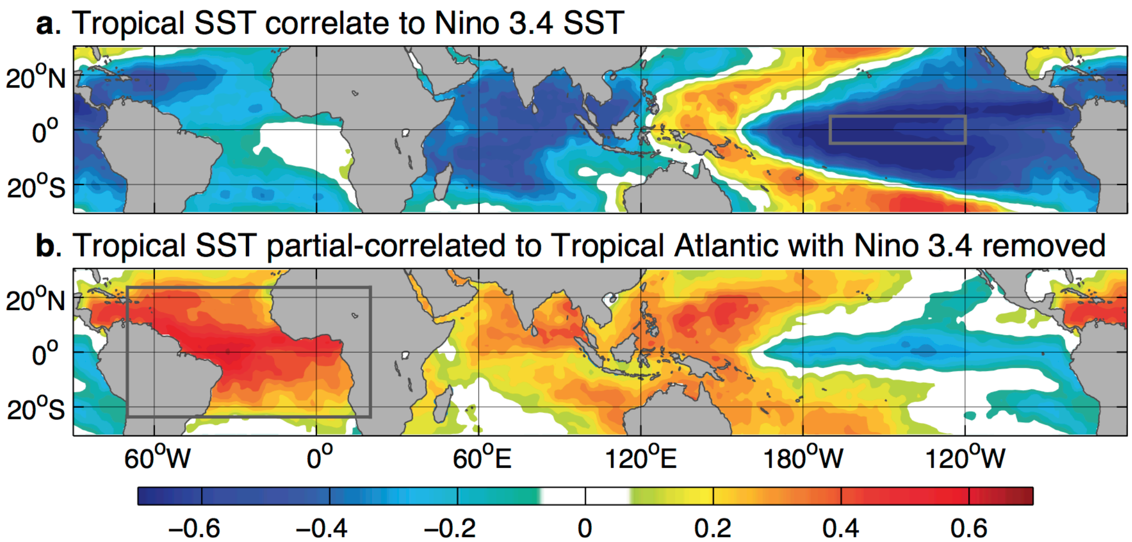
The SST anomaly patterns (**Supplementary Fig. 6a**) are similar to the latent heat flux anomalies (**Fig. 2b**), especially since both figures show cooling signals over the off-equatorial Pacific and the central equatorial Pacific, as well as warming anomalies over most of the Indian Ocean. These highlight the dominant effect of the WES forcing prior to the Bjerknes feedback.

There are two differences between the SST pattern and the latent heat flux pattern: 1) the warming SST anomaly over the eastern equatorial Pacific, and 2) the strengthened cooling SST anomaly over the southeastern Indian Ocean, both of which are related to the oceanic dynamical response. The former is forced by the westerly wind anomaly over the eastern equatorial Pacific (**Fig. 2a**), while the latter can be explained by the easterly wind anomaly over the Indian Ocean. These phenomena are also seen in the subsurface anomalies (**Supplementary Fig. 6b**): the thermocline shoals in the central equatorial Pacific but deepens in the eastern Pacific, while on the east coast of the Indian Ocean we see a narrow upwelling.

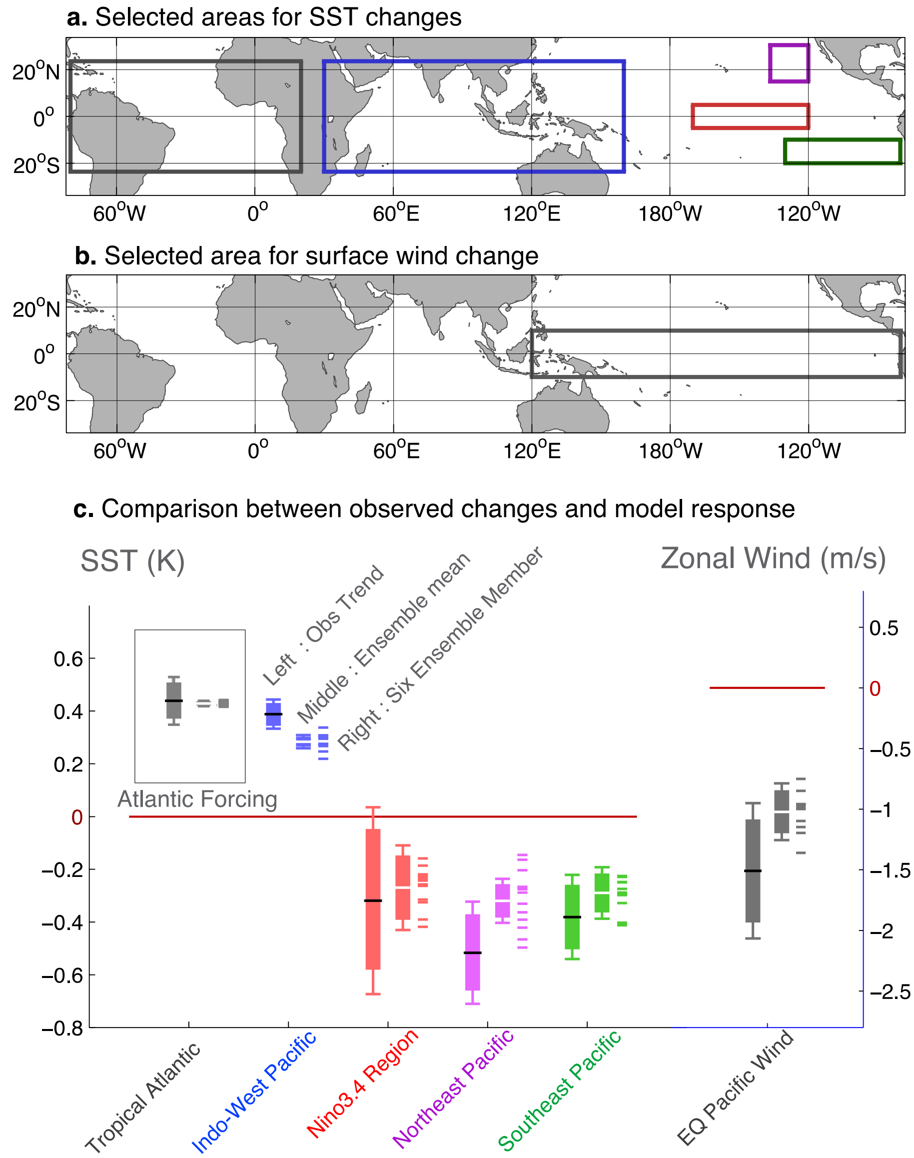
Note that the POP simulation results illustrate only the direct ocean response to atmospheric circulation changes, prior to any ocean-atmosphere feedbacks. We find the simulation results with an active ocean-atmosphere feedback to be different from this ocean-only model result. As shown in the main text, the temperature gradient over the Indo-Pacific basin enhances the Walker circulation. The Bjerknes feedback triggered by the easterly wind anomaly over the Pacific basin further cools the eastern equatorial Pacific and warms the southeastern Indian Ocean, leading to the observed SST changes.

Robustness of the tropical-wide SST pattern. We check the robustness of the model response to the observed Tropical Atlantic warming, by performing two additional sensitivity experiments forced by the Atlantic forcing scaled to 80% and 120% of the observed SST trend, respectively. The simulation results (**Supplementary Fig. 10**) are then compared with the results of the original experiment driven by the observed trend. While the amplitudes of the model responses vary with the intensity of the Tropical Atlantic forcing, all three experiments show a similar response to the external forcing, indicating a pan-tropical SST anomaly, with enhanced easterly wind anomalies around the equatorial Pacific region, which largely resemble the observed trends. These results further confirm the robust relationship between the tropical Atlantic and the entire Tropical Ocean, although many other characteristics of this teleconnection, such as the linearity, require additional investigation. These will be the subject of our future research.

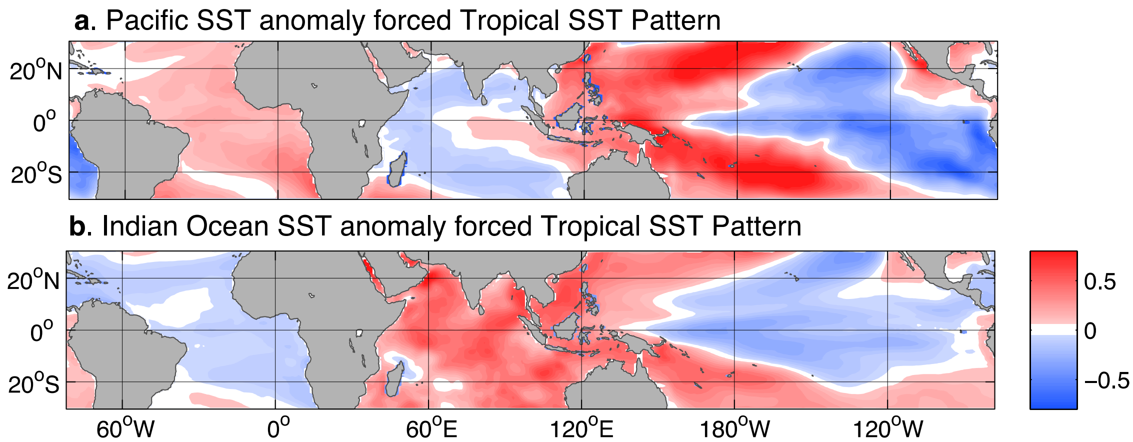
Supplementary Figures



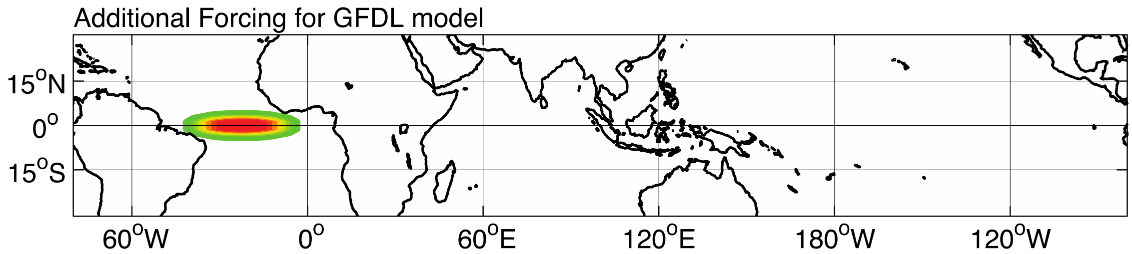
Supplementary Figure 1 | 3-month lagged correlation (lagged partial correlation) between tropical SST and Eastern Pacific (Tropical Atlantic). a 3-month lagged-correlation coefficients with the Niño3.4 time series, based on 1870-2012 HadISST datasets. The global warming trend was removed. All correlation coeffecients are multiplied by -1. An Eastern Pacific cooling cools the Indian Ocean and the Tropical Atlantic, opposite to the observed SST trend for 1979-2012. **b** the lagged-partial-correlation coefficients with tropical Atlantic SST time series. The global warming trend and the Niño3.4 variability were removed. A tropical Atlantic warming leads to an SST anomaly, which closely resembles the observed SST trend for 1979-2012 and the CESM simulation results, with warming over the Indo-Western Pacific and cooling over the Central-Eastern Pacific.



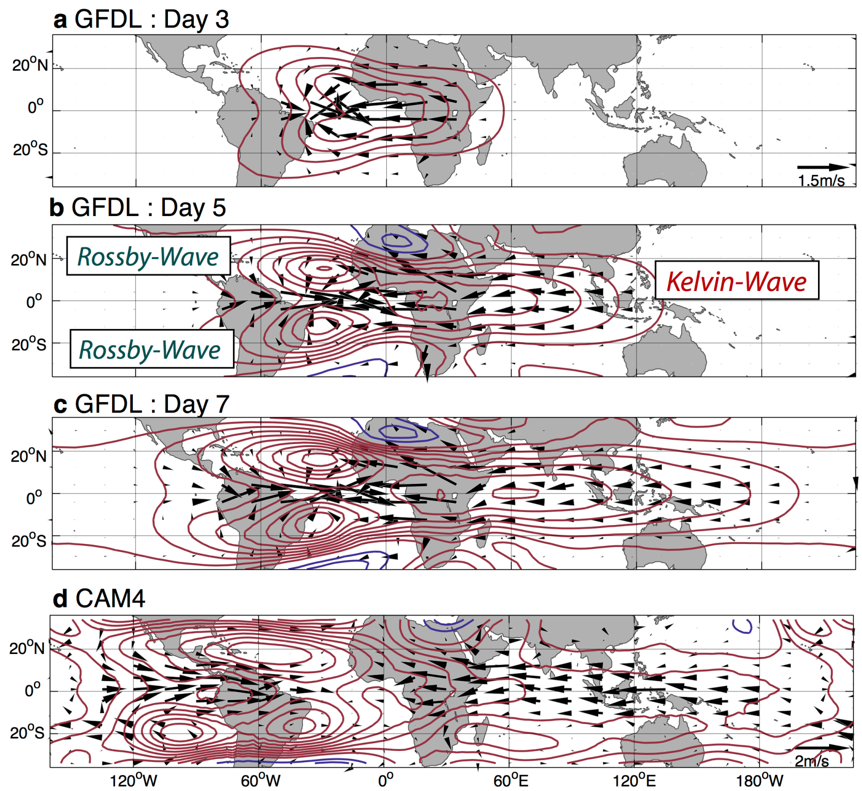
Supplementary Figure 2 | Magnitudes and confidence intervals of the observed and simulated SST changes over five tropical regions, and easterly wind anomalies over the equatorial Pacific. Panel **a** shows the five SST regions: the tropical Atlantic (grey), Indo-Western Pacific (blue), Niño 3.4 area (red), off-equatorial Northeastern Pacific (purple), and off-equatorial Southeastern Pacific (green). Panel **b** shows the equatorial Pacific region over which the zonal average is used to define the zonal wind index. Panel **c** shows the statistical analysis results. The observed changes over 1979-2012 are indicated by bars centered with black lines. The simulated changes are centered with white lines instead, with the model results of each of the 12 ensemble members marked as short horizontal bars on the right. The thick vertical bars show the 95% confidence intervals of these SST changes, and thin error bars indicate 99% confidence intervals. The SST restoring in the model captures 97% of the observed Atlantic SST trends. Results over the other regions capture about 55%~85% of the observed change.



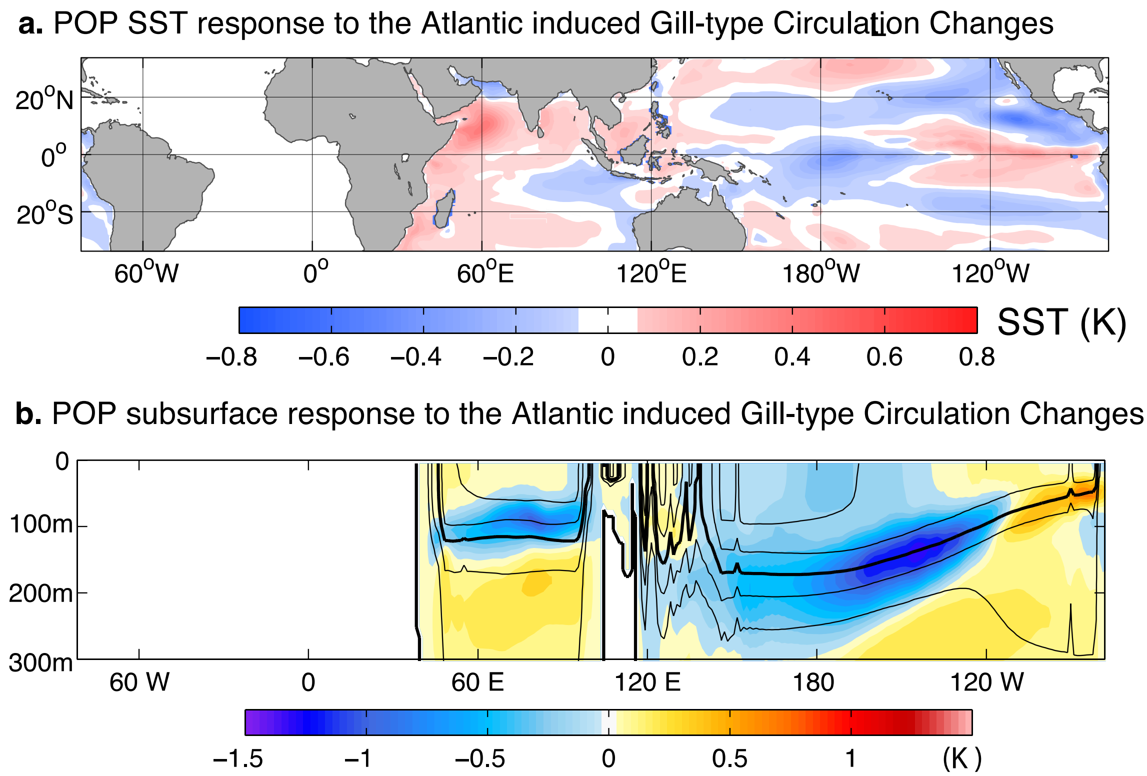
Supplementary Figure 3 | Sea surface temperature (SST) patterns forced by the Pacific (upper panel) and Indian Ocean (lower panel) SST changes, simulated in the coupled model.



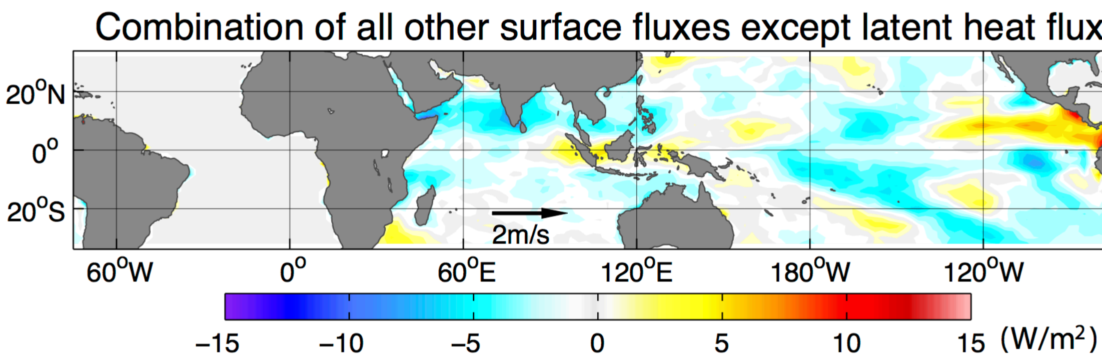
Supplementary Figure 4 | The horizontal structure of the external forcing in the GFDL atmospheric dynamical-core.



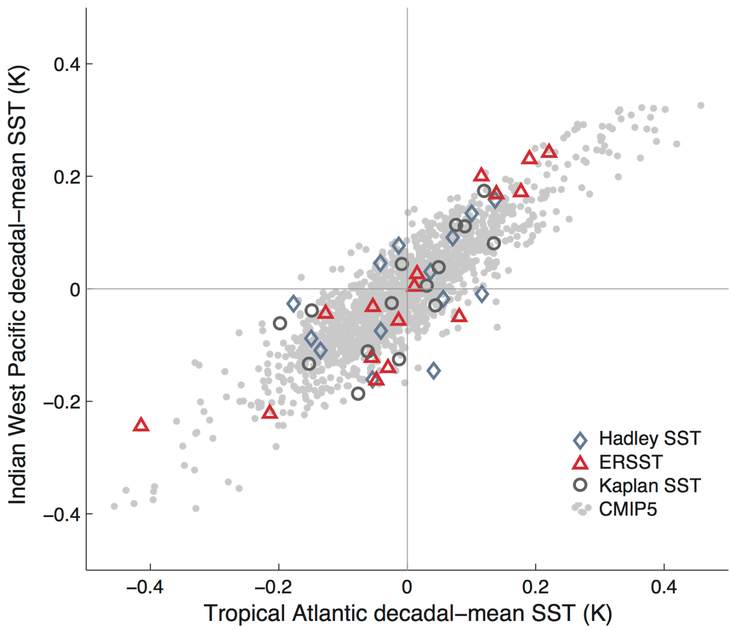
Supplementary Figure 5 | Atlantic warming induced atmospheric circulation changes, simulated by GFDL dynamical-core and CAM4. a to **c** show the GFDL simulated 850hPa wind (vectors) and 200hPa geopotential height (contours) anomalies on day 3, day 5, and day 7 respectively, after initiating an external heating mimicking the tropical Atlantic warming. The Atlantic heating first generates deep convection (**a**)**,** which further forms a classic Gill-type pattern[25] (**b**). The Kelvin-wave-induced easterly wind anomalies extend from the Atlantic to the Indian Ocean and to the Central-Western Pacific within a week (**c**), while the two Rossby wave packets occupy the central America and the Eastern Pacific with equatorial westerly wind anomalies. The CAM4 simulation (**d**) results agree with those from the dry GFDL idealized model (**c**), although the southern packet of the Rossby wave is interrupted by topography.



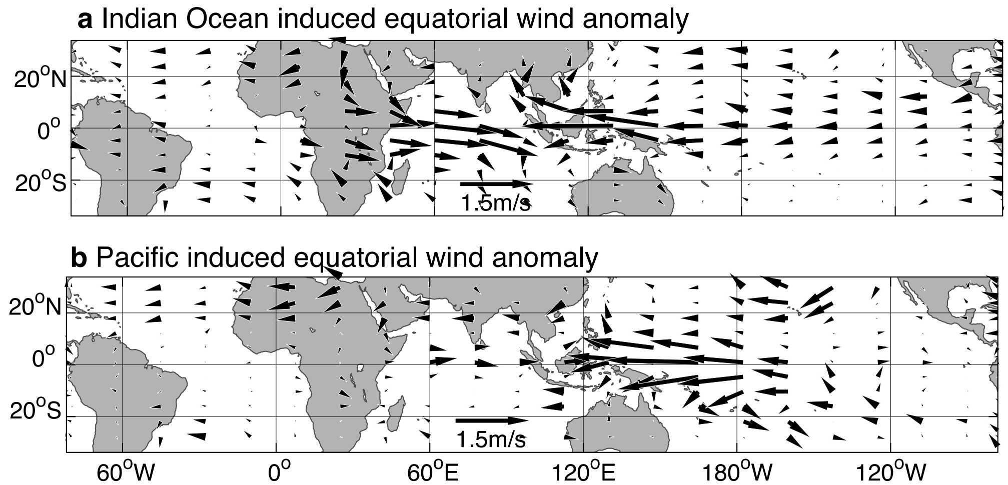
Supplementary Figure 6 | Ocean model responds to the Atlantic warming induced atmospheric circulation changes. a shows the SST responses, and **b** shows the sub-surface temperature responses.



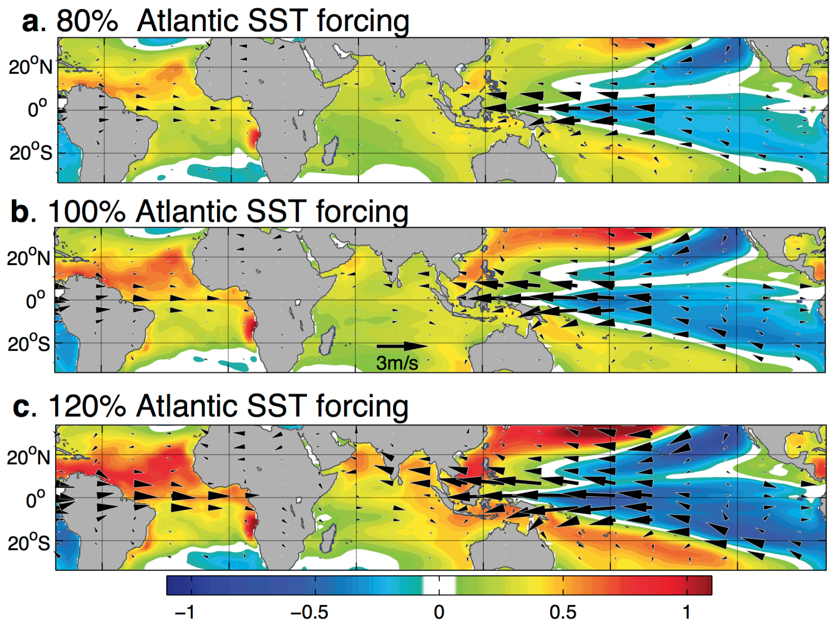
Supplementary Figure 7 | The combined anomalies of atmosphere-ocean sensible heat flux, solar radiation and long wave radiation in CAM4. These three terms combined have a weaker effect than the latent heat anomaly induced by the Atlantic warming (see **Figure 2b**).



Supplementary Figure 8 | Relationship between the decadal mean sea surface temperature (SST) of the Tropical Atlantic and Indo-Western Pacific in observations and unforced historical CMIP5 simulations from 1850 until the present. The long-term global warming trends are removed from each dataset. In both observations (colored symbols) and CMIP simulations (grey dots), the Tropical Indo-Western Pacific SST tightly co-varies with the Tropical Atlantic SST.



Supplementary Figure 9 | Wind anomaly in CAM4, forced by the Atlantic-induced Indian Ocean and Pacific SST changes, separately. Both SST forcing terms drive easterly wind anomalies over the equatorial Pacific. The Indian-Ocean-induced easterly wind anomaly occupies the entire equatorial Pacific, while the Pacific-induced wind anomaly is part of the Bjerknes feedback. The easterly wind induced by Pacific SST changes is strong over the Western Pacific and is weaker over the Eastern Pacific.



Supplementary Figure 10 | Tropical SST and 850hPa wind anomalies responding to the Tropical Atlantic warming of different amplitudes. Panels **a** – **c** show the CESM simulation results forced by the Tropical Atlantic warming with 80%, 100%, and 120% of the observed trend, respectively. In all cases, the Tropical Atlantic warming drives similar tropical-wide SST and lower-troposphere wind patterns, resembling the observed trend during the last three decades, although the amplitudes of the model responses vary with the strength of the Atlantic forcing.