Atlantic-induced pan-tropical climate change over the past three decades

**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 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 coefficients 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 pattern²⁵ (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 subsurface 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.