Increased Indian Ocean-North Atlantic Ocean Warming Chain under Greenhouse Warming

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Article

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Abstract

Over the last half century, the Indian Ocean (IO) and the North Atlantic Ocean (NA) have shown strong warming trends that affected global and regional climates. Here, we investigate a closed linkage mechanism in warming between the two oceans by performing an Earth system model simulation. On the one hand, IO warming increases sea surface temperature (SST) over the NA by enhancing the warm oceanic advection around South Africa along with longwave radiative fluxes through upper tropospheric teleconnection. On the other hand, the warmer NA SST-induced atmospheric teleconnection leads to anomalous easterlies over the western Pacific, where sea level increases. The enhanced contrast in the sea levels of the Pacific and IO intensifies Indonesian throughflow, which increases ocean heat transport from the Pacific and warms the IO. This positive interaction (the IO-NA warming chain) reinforces further warming over both ocean basins. The IO-NA warming chain is projected to intensify due to a higher background SST under future climatic conditions with strong anthropogenic forcing, reducing precipitation over the western U.S. by 20%–50%.

Introduction

The Indian Ocean (IO) and Northern Atlantic Ocean (NA) have experienced significant warming trends during the past decades^{1,2,3,4,5,6,7}. IO warming affects East Africa, East Asia, El Nino-Southern Oscillation (ENSO), and the North Atlantic climate^{8,9,10,11}. NA has had significant impacts on South America, the Sahel, Atlantic hurricanes, and the U.S. and European climates^{12,13,14,15}.

Previous studies have discussed how the IO and the NA influence each other^{1,7,16,17,18,19}. On the one hand, IO warming induces NA warming via atmospheric teleconnection and oceanic processes^{1,16}. For instance, IO warming has changed the recent NA climate by influencing tropical rainfall and atmospheric heating^{7,17,18} and through the interoceanic transfer of seawater from the IO that leads to SST changes in NA¹⁹. Furthermore, NA warming may induce IO warming by increasing net longwave radiation^{20,21} or generating easterly surface wind anomalies^{22,23,24,25} that may lead to oceanic heat transport into the IO²⁶.

The above-mentioned studies reported the disconnected effects of the IO and the NA. However, interactions between IO and AO are not fully understood. Because SSTs of both IO and AO have increasing tendencies and can influence each other, we hypothesised that significant positive feedback in SST warming might exist between both regions. Thus, IO warming contributes to NA warming, and the warmed SST in the NA reinforces further IO warming.

Here, we demonstrate a positive feedback between the SSTs of IO and NA and reveal a novel process for forming the IO-NA warming chain. We conducted a historical experiment using an Earth system model following the Coupled Model Intercomparison Project Phase 6 (CMIP6) protocols, while achieving enforced control of SST anomalies over the IO (or the NA) by using observations. We also performed an idealised simulation with uniform surface warming or cooling (from -3°C to 3°C at intervals of 1°C) over

the IO (or the NA) at a fixed CO₂ concentration. We found that the NA SST increases linearly with given IO SST anomalies; additionally, the IO SST influenced by NA warming also increases monotonically. We elaborate on the mechanisms governing these links based on atmospheric teleconnection and oceanic processes. Furthermore, we show that under strong anthropogenic forcing, the IO-NA warming chain is strengthened by a warmer mean SST in the Pacific, which may reduce precipitation over the western U.S. by 20–50%.

Results

Observed evidence of the IO-NA relationship

To quantify the strength of the IO-NA warming chain, we defined the IO SST index (IO index) and the NA Ocean SST index (NA index) by using the SST averaged over each box (Fig. 1a). From 1970–2019, the IO index showed a warming trend (1.40°C per century), with strong multi-decadal fluctuations (Fig. 1d). Local maximum and minimum IO indices were observed close to 1940 and 1970, respectively. The NA index also showed a significant warming trend (2.02°C per century) and a maximum inter-decadal fluctuation close to 1940. The warming trends and interdecadal-to-multidecadal fluctuations in the IO and NA indices tend to overlap. The lead-lag correlation coefficient between the IO and NA indices (Fig. 1f) was positive regardless of lag. The maximum correlation coefficient was recorded at zero lag (0.80), indicating concurrent NA and IO warming. Global warming caused by the anthropogenic increase in CO₂ concentrations may explain warming trends in the two indices; however, global warming cannot fully explain the phase matching in interdecadal-to-multidecadal variations. The warming trend in both regions can be modified by the strong interactions between the two basins. Therefore, we conjecture that the IO and NA might serve as mutual pacemakers.

To further analyse the IO-NA relationship, we examined global SST anomalies and surface winds regressed onto the NA index by using observational data from 1970 to 2018 (Fig. 1b). The NA warming pattern resembles a developing positive phase of the Atlantic Multidecadal Oscillation (AMO), and strong warming is observed in the tropical IO. The Pacific SST anomalies are close to the negative phase of the inter-decadal Pacific Oscillation and resemble local SST trends (e.g. Figure 1a). Thus, the warming trend in the Pacific may be related to both global warming and NA warming. The warm SST anomalies over the NA generate ascending motions and strong upper-level divergent flows, which are connected to upper-level convergences in the equatorial central and eastern Pacific (Supplementary Fig. S1), where descending motions dominate. Double anomalous anticyclonic circulation occurs in the central North and South Pacific (Fig. 1b). Descending motions in the central Pacific induce easterly anomalies over the central to western Pacific. In addition, warmer SST in the western Pacific strengthens Walker circulation by enhancing ascending motion over the equatorial western Pacific. The anomalous easterlies over the western Pacific deepen the equatorial thermocline and increase the sea surface height (SSH) (Supplementary Figs. S2c and S2d), thereby increasing ocean heat advection^{22,27} to the eastern Indian Ocean through enhanced south China Sea and Indonesian throughflows (Supplementary Fig. S3a).

Similarly, the SST and surface wind anomalies associated with IO warming are linked to strong NA warming. The NA warming pattern resembled the AMO positive phase. IO warming induces relatively higher SSH and SST near South Africa (Supplementary Figs. S2a and S2b), thereby enhancing the transport of warmer ocean water to the tropical AO. The ascending motion also generates westerly anomalies in the tropical AO by strengthening the sinking motion over the eastern Pacific (Supplementary Fig. S1b), which may contribute to tropical Atlantic warming. The ascending motion in the IO generates a descending motion in the tropical Atlantic region, which affects precipitation in the tropical Atlantic region (Supplementary Fig. S1b). Because the simultaneous regression does not explain causality, we conducted numerical experiments to illuminate the cause and effects of IO and NA warming.

IO-NA warming chain simulated in historical experiments

To explore whether IO and NA warming affect each other, we conducted two groups of numerical experiments using an Earth system model (see the 'Methods' section). The first group represents a historical simulation with prescribed IO SST warming (observed pattern) trends (0.01–0.70°C per 50 yrs) (HIS_OBS_IO). The model was freely coupled in other areas, and external forcings were based on the CMIP6 historical simulation protocol. Similarly, we conducted model simulations for the other group by specifying different trends of observed SST anomalies over the NA region (0.01–1.02°C per 50 yrs) (HIS_OBS_NA).

The ensemble IO Index simulated by the observed SST anomalies over the NA region (HIS_OBS_NA) captures the observed trends reasonably well for most periods (Fig. 2a). The range of each member from the ensemble mean is $\pm 0.12^\circ\text{C}$ (approximate biases of 10–15%), indicating that the impacts of internal variability on the simulated IO SST are moderate; thus, the response of the IO influenced by NA warming is realistic. We conducted the same historical simulation—except for the prescribed climatological SST of NA (HIS_CLIM_NA)—to eliminate the impact of NA warming on IO warming. The results show that the IO SST warming was reduced by 40–50% (green line in Fig. 2a), indicating that the observed IO warming arises from the remote effects of NA warming and local IO warming.

For another historical simulation with observed SST forcings over the IO region (Fig. 2b), the ensemble mean SST over the NA region shows realistic temporal evolution, with negative SST anomalies being observed from the 1970s to the 1990s along with rapidly increasing positive SST anomalies after the late 1990s. The ensemble mean SST is slightly less than that observed, which may be attributed to the systematic mean SST biases of the model south of Greenland³⁴. The ensemble spread from each member is moderate ($\pm 0.26^\circ\text{C}$), signifying that all ensemble simulations capture the NA warming trends induced by IO warming reasonably well. The same historical simulation—but with climatological SST nudged over the IO region—yields a 50% reduction in NA SST warming (green line, Fig. 2b). This result suggests that approximately half of NA warming may be attributed to IO warming.

Historical runs that nudged IO (or NA) SST warming (Fig. 2c and 2d) demonstrated that increasing IO SST could lead to a warmer NA; likewise, IO SST would increase with a warmer NA. The IO SST trend forced by NA SST is smaller than the NA SST trends (by approximately 40–50%). Thus, IO warming may

be attributed to a remote NA impact and to local surface flux changes. We will further study this issue in the future. The linear relationship between IO and NA warming suggests that the IO-NA warming chain may occur without strong anthropogenic forcing.

IO-NA warming chain simulated without anthropogenic forcing effects

We hypothesised that the IO-NA warming chain could be generated without increasing the anthropogenic forcing. To verify this hypothesis, we conducted idealised numerical simulations with fixed CMIP6 preindustrial (PI) forcings to remove the warming effect caused due to increased CO₂ forcing. Under fixed PI external forcings, we conducted a suite of 100-yr simulations by using observed IO SST anomalies averaged from 1980–2018 (PI_IO) and progressively increased uniform SST anomalies by 1°C (PI_IO + 1), 2°C (PI_IO + 2), and 3°C (PI_IO + 3). We repeated the same experiment with decreased uniform SST anomalies by 1°C (PI_IO-1), 2°C (PI_IO-2), and 3°C (PI_IO-2). Additionally, we conducted a similar suite of fixed-forcing PI experiments with the nudged SST over the NA region (PI_NA).

The SST anomalies induced by 1°C warming over the NA region captured the observed patterns (Fig. 1a) and showed significant IO warming (Fig. 4a). Warming also occurred in the northern and southern subtropical Pacific and equatorial western Pacific; however, relatively cool SST prevailed in the equatorial eastern Pacific. The anticyclonic flows in the north and south Pacific generate easterly anomalies in the western Pacific that increase ocean heat transport from the western Pacific to the eastern Indian Ocean. SST and surface wind changes induced by 1°C IO warming (Fig. S4a) largely resemble those in the observations—except for the Indian Ocean surface winds (Fig. 1c). The above-mentioned simulation results suggest that the IO-NA warming chain can occur without the global warming effect.

We further examined how the NA warming trends were linked to the prescribed IO warming under PI forcings (Fig. 3a). When the IO warming increases, NA SST is progressively warmer. The increasing rate of NA SST per 1°C IO warming is approximately 0.39°C. The correlation coefficient between relative IO warming and the NA response is 0.98, implying that the response of NA by IO forcings is extremely linear from the model simulations. The simulation with NA warming forcings yields a rate of increase of IO SST per 1°C NA warming of 0.33°C; the correlation between IO and NA SST changes is 0.97. The results show that the IO-NA warming chain mechanism could occur without greenhouse gas forcing. The historical simulation shows much higher trends of NA warming by IO warming forcing than those observed using PI simulation. Thus, anthropogenic forcing may intensify the increasing trends of NA warming induced by IO warming.

Change in IO-NA warming chain under anthropogenic forcing

We conducted a suite of 100-yr simulations under quadruple CO₂ external forcings by using prescribed observed SST anomalies that were averaged from 1980–2018 in the Indian Ocean (4CO₂_IO); subsequently, we progressively increased uniform SST by 1°C, 2°C, and 3°C to determine how the IO-NA

warming chain would change with continued anthropogenic forcing. We repeated the same experiment but with decreased uniform SST anomalies at 1°C, 2°C, and 3°C. Additionally, we repeated 4CO2_IO experiments with observed SST anomalies over the NA region (4CO2_NA).

The NA response to IO warming forcing was extremely linear in the 4CO2-IO experiment. The rate of NA SST increase with 1°C of IO warming is approximately 0.56°C, which is 50% higher than that observed in the PI_IO (Fig. 3). Under strong anthropogenic forcing, the mean SST warmed considerably in South Africa and the South Indian Ocean, thereby increasing ocean heat transport via the Agulhas Current (Supplementary Fig. S3b). Similarly, the change in IO SST due to NA warming remains extremely linear, with a correlation of $r = 0.98$. The rate of increase in IO SST due to NA (0.39°C) warming under strong anthropogenic forcing was slightly higher than that of the PI (0.33°C). Under enhanced greenhouse gas forcing, the eastern Pacific is warmer than the western Pacific. NA warming generates strong anomalous easterlies in the central Pacific with the movement of warm seawater to the western Pacific, resulting in a warmer SST, a higher SSH, and more IO warming (Supplementary Figs. S2c and S2d). These results show that the IO-NA warming chain is intensified by anthropogenic forcing.

Reduction of North American precipitation by the IO-NA warming chain

The intensified IO-NA warming chain due to global warming may affect IO-induced (NA-induced) precipitation changes in the mid-latitudes. In the PI_IO run, precipitation in western North America due to IO warming of 1°C is reduced by 7–18% (Fig. 3c). IO warming generates anticyclonic circulation in the North Pacific, thereby transporting cold water around the Bering Sea to the west of North America. The NA warming induced by IO warming generates strong sinking motions in the western U.S. region, thereby inducing less precipitation. Under anthropogenic forcing, the decreasing rate of precipitation change due to IO warming is approximately 15–47% (average of approximately 30%), which is approximately double the corresponding PI run. Similarly, the warm NA SST caused by IO warming strengthened the descending motion and further reduced precipitation in the western U.S. by 10–35%.

Discussion

IO-NA warming chain mechanisms

The IO responds to NA warming through the atmospheric teleconnection-induced surface heat flux change and oceanic heat transport.

To investigate the effect of the surface heat flux on IO warming forced by NA warming using the PI_NA simulation (Fig. 4), we conducted a surface heat budget analysis by computing the differences in four surface heat flux components over the NA region for 1°C warming and no warming. Positive longwave radiation and latent heat fluxes are consistent with IO warming and thus contribute to IO warming. However, negative shortwave radiation anomalies dampen IO warming. Among the four surface fluxes, net longwave radiation was the principal contributor to IO warming. NA warming could enhance

convective cloudiness over the IO region through atmospheric teleconnections (Fig. S1). Increased IO cloudiness can increase downward longwave radiation and warm the ocean surface. However, the enhanced cloudiness significantly reduces downward shortwave radiation at the surface owing to cloud reflection processes, which tend to cool the SST. This cloud–radiation-SST feedback over the IO region may induce ample IO warming. Likewise, analysis of surface heat fluxes over the NA region forced by IO warming indicates that strong positive longwave radiation occurs in the tropical AO; additionally, positive latent heat flux simulated in the sub-tropical region increases NA SST (Supplementary Fig. S4).

The IO warming caused by NA warming may also be attributed to oceanic processes. The results suggest that ocean heat advection from the western Pacific to the eastern IO through the Indonesian throughflow (ITF) enhances warming over the IO (Supplementary Fig. S3a). NA warming of 1°C increases the ITF heat transport by approximately 20–25%, which primarily warms the upper IO (supplementary Fig. S3a). We argue that NA warming generates anomalous easterlies over the equatorial central-western Pacific, thereby increasing SST and SSH with thermocline deepening in the western Pacific (Supplementary Figs. S2c and S2d). The anticyclonic anomalies associated with NA warming contribute to the generation of easterly anomalies in the western Pacific, thereby enhancing the zonal SST and SSH gradients in the tropical Pacific. The changes in the zonal SST and SSH gradients are consistent with the increasing intensity of the ITF.

We investigated how IO warming affects NA SST. The NA warming caused by IO warming could be a result of the inter-basin transfer of seawater from the IO to the AO through Agulhas leakage (Supplementary Fig. S3b). The change in ocean heat advection through the Agulhas current is dominant in the PI simulation, with 1°C of IO warming. Model simulations of zonal SST and SSH gradients near South Africa confirm the role of the Agulhas current in the westward transport of warmer IO water into the colder South Atlantic Ocean (Supplementary Figs. S2a and S2b).

Questions regarding the weakening and decaying of the IO-NA warming chain, which could be broken by a change in ocean circulation over the NA region (e.g., the AMOC), have remained unanswered. If the AMO phase changes to negative, NA SST trends become negative and cannot contribute to further IO warming; this change weakens or breaks the warming chain. The role of the Pacific in the IO-NA warming chain may be important for exploring the associated mechanisms. NA warming induces relatively more warming in the western Pacific than in the eastern Pacific, contributing to enhanced ocean heat advection. Fixing the Pacific SST in the PI_NA experiment significantly reduced the IO warming caused by NA SST forcings, suggesting that Pacific behaviour is a medium for heat transport from the NA to the IO.

In this study, we demonstrated a strong relationship between IO and NA warming (the IO-NA warming chain) and future precipitation changes induced by the IO-NA warming chain. Observations in the last half of the century show that NA (IO) warming increased when the IO (or NA) SST increased. The IO-NA warming chain intensified under strong anthropogenic forcing. The stronger IO-NA warming chain significantly reduces precipitation compared to those obtained via historical simulations (by up to 50%) in western North America.

A re-examination should be performed using other Earth system models that potentially have different patterns and magnitudes of interbasin interactions.

Methods

Observed data and diagnostic methods

For monthly mean SST, we used the National Oceanic and Atmospheric Administration Extended Reconstructed SST version 5²⁷. Ocean temperature and thermocline depth data were derived from the European Centre for Medium-Range Weather Forecasts Ocean reanalysis, and ocean heat content datasets were used as observation data²⁸. Wind and precipitation data were extracted from the National Centres for Environmental Prediction dataset from the NOAA-CIRES Twentieth Century Reanalysis v3 (1943–1992)²⁹.

Earth system model

We used the third version of the Nanjing University of Information Science and Technology Earth System Model (NESM3.0)^{30,31,32,33,34}, which consists of atmosphere, ocean, sea ice, and land models that are fully coupled by an explicit coupler. The resolution of the atmospheric model was T63L47. The ocean model has a grid resolution of 1°, with a meridional resolution refined to 1/3° over the equatorial region. The model uses 46 vertical layers, with the first 15 layers being in the top 100 m. NESM3.0 simulates reasonable climatology and the key characteristics of multi-decadal variabilities.

Ocean mixed-layer heat budget analysis

Heat budget analysis of the ocean mixed-layer temperature tendency was used to quantify the contributions of zonal ocean heat advection to the IO³⁵.

Preindustrial, historical, and quadratic CO₂ simulations

We conducted idealised simulations using pre-industrial forcings. First, only the ocean model of NESM3.0 was integrated for 4000 yrs with atmospheric forcings to elucidate the stable upper- and deep-ocean initial conditions. Second, NESM3.0 was integrated for 500 yrs, with an initial condition that 4000 yrs of ocean simulation would be performed with preindustrial forcings based on the CMIP6 protocol; this was aimed at obtaining a stable equilibrium state between the atmosphere and ocean. To investigate the warming relationship between the IO and NA regions, we conducted the 100-yr simulations by nudging the observed SST anomalies over the Indian Ocean (PI_IO) and increasing the SST anomalies uniformly by 1°C (PI_IO + 1), 2°C (PI_IO + 2), and 3°C (PI_IO + 3). Similarly, we repeated PI experiments with decreased SST anomalies at 1°C (PI_IO-1), 2°C (PI_IO-2), and 3°C (PI_IO-2). Additionally, we conducted the same PI experiments—except for nudged SST—over the NA region (PI_NA and PI_NA ± 1–3). For historical runs, we conducted two groups of numerical experiments using the same model. In the first group, observed NA warming signals were engaged in the model by nudging the observed SST anomalies that were averaged from 1900–2018 for the NA region (80°–0°W, 0°–70°N) (HIS_NA); elsewhere, the model

was freely coupled. The external forcings were based on historical simulations suggested by the CMIP6 project. We obtained a wide range of NA SST trends ($0.01-1.02\text{ C }50\text{ yrs}^{-1}$) and corresponding IO SST responses by multiplying various scale factors on the observed SST time series over the NA region. Similarly, we prepared the model with observed SST anomalies over the IO region ($0.01-0.7\text{ C }50\text{ yrs}^{-1}$) by using the same method and analysed the NA SST trends via IO warming.

Data and materials availability

All observed data used in this study are publicly available, and new data generated from this study are available upon request. The codes and data can be downloaded at <https://figshare.com/articles/software/code-ENSO-induced-precipitation-change/13273271>.

Declarations

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Author Contributions

Y.-M. Yang, S.-I. An and B. Wang conceived the idea. Y.-M. Yang performed model experiments and analyses. S.-I. An, Y.-M. Yang, B. Wang, and J. H. Park wrote the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Competing Interests statement

The authors declare no competing interests.

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Figures

Figure 1

Historical warming trends. a Observed trends (1970–2020) in annual-mean sea surface temperature (SST; units: °C 50 yr⁻¹). The red (blue) box represents the region where the Indian (North Atlantic) Ocean index is defined. b Observed SST (K) and surface wind anomalies (arrow, m/s) regressed onto the NA index (0°–70°N, 80°–0°W). The 11-year running average data were used for 1970–2019. The hatched area represents the regressed SSTA and is significant at the 95% confident level. c Same as b but for the IO index (35°S–30°N, 40°–120°E). d Observed time series of the NA (red line) and IO (blue line) indices. e Observed lead–lag correlation coefficient between the IO and NA indices. The lag is positive (negative) when the IO leads (lags). Long-term linear trends in the SST data were removed before regression, and the last 5 years were excluded from the analysis.

Figure 2

IO-NA warming trends simulated in the historical experiments. a Temporal evolution of the IO index derived from historical simulations with the observed SST anomalies (blue) and climatological SST (green) prescribed over the NA region. The black curve denotes the observed IO index. b Same as c but for the NA index from the historical simulations with the observed SST anomalies (blue) and climatological SST (green) prescribed over the IO regions. The blue (green) curves represent the model ensemble mean, and the light blue (green) shadings show the ensemble spread. The black lines are observations. c Scatter plots between IO and NA index trends in units of °C per 50 yrs derived from the historical simulations with prescribed NA warming trends. The red line is the linear regression curve; the correlation coefficient is shown. Red (orange) circles represent models with very small (small) SST trends (1970–2020), whereas green (blue) circles indicate large (very large) SST trends. The black circle shows observed SST trends. d Same as c but for historical simulations with specified IO warming trends.

Figure 3

IO-NA warming trends derived from PI and 4CO2 simulations. a Changes of NA index versus changes of IO index in different preindustrial (PI) and quadruple CO2 (4CO2) experiments. The NA SST change is defined by the difference of the NA index between the PI simulation with observed SST anomalies and that with relatively 1 °C uniformly warmer SST over the Indian Ocean. The blue (red) solid represents PI (4CO2) simulations. The blue (red) line shows the corresponding linear regression curve. Each circle represents data from one experiment averaged within the last 30 years of the 100-year-long integration. b Same as a but for the simulation with observed NA SST anomalies. c Precipitation changes over the western U.S. in different preindustrial (PI) and quadruple CO2 (4CO2) experiments. The changes are defined as the difference in precipitation between the PI simulation with observed IO SST anomalies and

that with relatively warmed IO SST Anomalies by 1 °C. d Same as c but for the simulation with observed NA SST anomalies.

Figure 4

Global climate response to NA warming from fixed anthropogenic PI experiments. a Anomalies in SST (°C) and surface wind (vector in units of 0.6 mm per day) from the fixed preindustrial (PI) simulation with observed NA SST anomalies. b Anomalies in longwave radiation at the surface over the IO. c, d, e, and f

are the same as in b but for shortwave radiation, latent heat flux, sensible heat fluxes, and total cloud cover. The anomalies are computed for the last 50 years of the PI_NA+1C experiment with respect to the pre-industrial simulation (PI_NA, see Methods).

Figure 5

Schematic for IO-NA warming chain. The red (blue) circle shows SST warming (cooling). The curved arrows represent upper and lower circulation. The hatched area shows ocean heat advection by Indonesian throughflow (ITF) and the Agulhas current (ALC).

Supplementary Files

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