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Evaluating the Mechanism of Tropical Expansion Using Idealized Numerical Experiments

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A wide range of evidence reveals that the tropical belt is expanding. Several mechanisms have been proposed to contribute to this expansion, some of which even contradict each other. The study of Yang et al. suggests that the poleward advancing mid-latitude meridional temperature gradient (MTG), originating from enhanced subtropical ocean warming, plays a leading role in driving tropical expansion. However, the abrupt4xCO2 experiment indicates that tropical expansion occurs at a faster rate than is indicated by changes related to ocean temperature rise. The idealized amip4K experiment illustrates that without introducing any ocean warming pattern, uniform ocean surface warming also drives tropical expansion. The results based on these idealized experiments seem to contradict the hypothesis proposed by Yang et al. In this study, we revisit these 2 experiments and show that both experiments actually support the hypothesis that MTG migration is driving tropical expansion. More specifically, in the abrupt4xCO2 experiment, although the rate of ocean warming is relatively slow, the poleward shift of the MTG is as rapid as tropical expansion. In the amip4K experiment, although ocean surface warming is uniform, the heating effect of the ocean on the atmosphere is nonuniform because of the nonlinear relationship between temperature, evaporation, and thermal radiation. The nonuniform oceanic heating to the atmosphere introduces a poleward shift of the MTG within the upper troposphere and drives a shift in the jet streams. By conducting an additional idealized experiment in which tropical expansion occurs under both a migrating MTG and a cooling climate, we argue that the migration of the MTG, rather than global warming, is the key mechanism in driving tropical expansion.

Introduction

A large number of observations and climate model simulations [1–7] reveal that the edges of the Hadley Circulation are migrating toward higher latitudes under climate change, a phenomenon widely known as tropical expansion. Understanding the mechanism driving tropical expansion is important because it not only affects the hydrologic conditions over the subtropical regions [2,8 ,9] but also relates to a systematic poleward shift in oceanic and atmospheric circulation [10–12].

Despite many investigations, there is still no consensus on the mechanism driving tropical expansion [7,13 ,14]. Earlier studies, mainly based on model simulations, proposed that changing concentrations of greenhouse gases [2], ozone [15,16], and black carbon aerosols [17] are the primary forcings of tropical expansion. Some of these simulations even do not include ocean feedback [18], hinting that tropical expansion is largely driven by atmospheric forcing. However, observations indicate that tropical expansion is region dependent and has strong interannual variability [19–22]. These variabilities are closely connected to the regional sea surface temperature (SST) evolution [23–26]. By separating the direct radiative forcing of CO_2 and indirect SST forcing, many numerical sensitivity simulations [12,27,28] have confirmed that changes in SST play a dominant role in driving tropical expansion.

On the basis of both observations and climate model simulations, Yang et al. [10] noticed that the position of meridional temperature gradients (MTGs), especially those around the mid-latitudes, is strongly connected to the position of zonal mean atmosphere circulation. They proposed that poleward migration of the mid-latitude MTG, which primarily arises from ocean warming patterns, plays a key role in driving tropical expansion. This MTG mechanism explains various aspects of tropical expansion, such as seasonal migration, regional characteristics, interannual variability, and long-term trends. On a seasonal time scale, the edge of the tropics moves toward higher/lower latitudes during summer/winter together with the migration of the mid-latitude MTG induced by seasonal migration in insolation. On interannual to decadal time scales, the SST seesaws between the central tropics and the subtropics (associated with the El Niño-Southern Oscillation or Pacific Decadal Oscillation) modulate the shape of the MTG and tropical width. Under global warming, relatively strong subtropical ocean warming promotes a poleward advancing mid-latitude MTG and drives tropical expansion. Using a coupled aquaplanet model, Yang et al. [12] further diagnosed the causality of subtropical warming and tropical expansion. Their results illustrate that the strong subtropical ocean warming is constrained by the mean circulation of subtropical gyres (Fig. 1). This enhanced subtropical ocean warming initially triggers the migration of MTG and drives tropical expansion.

Among the many hypotheses [7,14], the MTG mechanism also consistently explains how changing concentrations of CO_2, aerosol, and ozone in climate simulations contribute to tropical

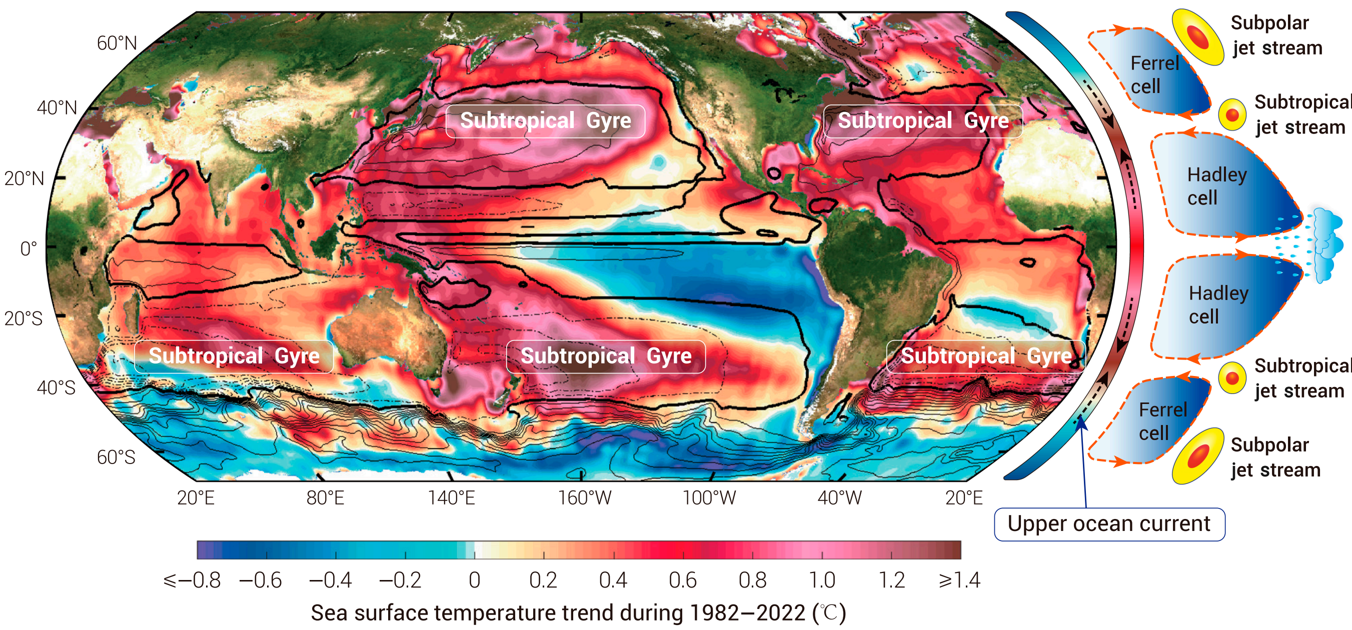

Fig. 1. Schematic diagram showing how the background subtropical gyres promote enhanced subtropical ocean warming and drives tropical expansion. Shading indicates the SST trend during the satellite era (1982 to 2022). Contours present the climatological oceanic barotropic stream function [69], which locates the major subtropical ocean gyres. On the right panel, the arrows illustrate the significant features of atmospheric (red) and upper oceanic (black) circulation. Under the forcing of increasing greenhouse gases, background subtropical ocean gyres promote enhanced subtropical ocean warming by converging the upper ocean water. The enhanced subtropical warming expands the low latitude warm water zones, pushes the mid-latitude MTGs toward higher latitudes, and thus forces tropical expansion. Figure modified from Yang et al. [10]. The National Oceanic and Atmospheric Administration OISSTv2 data [70] were used to calculate the linear SST trend.

expansion. According to the aqua-planet sensitivity simulations [12], direct CO_2 forcing (without ocean feedback) introduces the strongest longwave radiation anomaly over the subtropics, where climatological outgoing longwave radiation is the strongest because of relatively low cloud and water vapor coverage. The anomalous subtropical heating induced by CO_2 promotes a poleward shift of the mid-latitude MTG within the troposphere and forces tropical expansion [12]. In contrast to the nearly uniformly distributed atmospheric CO_2, the distribution of aerosols and ozone exhibits regional patterns. Increased black carbon aerosol and tropospheric ozone in the mid-latitudes of the Northern Hemisphere [23], encourage a poleward shift of the mid-latitude MTG over the Northern Hemisphere. Comparably, the Antarctic ozone hole produces cooling over the Antarctica [15,29 ,30], which helps to steepen the high-latitude MTG and reorient the southern westerly jet toward high latitudes. It now appears that the MTG mechanism has successfully explained the dynamics of tropical expansion in both observations and numerical sensitivity simulations. However, controversy still exists.

To explore the mechanism of tropical expansion, a large number of numerical experiments have been investigated from various perspectives [2,18,31–38]. Several studies [31,39] examined the abrupt4xCO2 experiment, in which an instantaneous quadrupled-CO_2 forcing is imposed on the coupled ocean–atmosphere models. These studies found that tropical expansion occurs in a rapid manner and reaches 90% of its final location within a few years. In contrast, the rise in surface temperature is relatively slow, with transient behavior (Fig. 2A of [31]). In addition, the strength of the meridional surface temperature gradient presents a distinct trajectory when compared to tropical expansion (Fig. 2B in [31]). These facts seem to indicate that changes in surface temperature are unlikely to be the cause of tropical expansion. With a focus on the Southern Hemisphere, Chemke and Polvani [31] identified that increasing static stability (reducing vertical temperature gradient or lapse rate) around subtropical regions occurs at a similar rate as tropical expansion (Fig. 7 in [31]), supporting an earlier hypothesis that increasing static stability is the key driving mechanism [2,18,40,41]. In addition to the abrupt4xCO2 experiment, without introducing any changes in surface MTG, the amip4K experiment, which adds a uniform 4-K SST anomaly to the atmospheric model, also produces wider tropics. The amip4K experiment highlights that warming itself drives tropical expansion by increasing static stability [22,33,42–44].

These "conflicting" facts have sparked many debates, especially during the publishing process of Yang et al. [10,12]. To evaluate the mechanism of tropical expansion, in this study, we revisit the abrupt4xCO2 and amip4K experiments. We find that the abrupt4xCO2 experiment is a perfect experiment for testing the MTG hypothesis. Moreover, by combining the amip4K experiment with an additional idealized global cooling sensitivity simulation, we further deduce that warming does not directly drive tropical expansion. The MTG shift associated with warming causes tropical expansion.

Materials and Methods

AQ4

Data

The abrupt4xCO2 and amip4K experiments from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [45] are used in this study. The abrupt4xCO2 experiment is performed with CO_2 forcing abruptly quadrupled from the preindustrial level, using a fully coupled ocean–atmosphere general circulation model. The amip4K experiment is integrated by applying a spatially uniform 4-K SST anomaly using an atmospheric

Table 1. List of CMIP5 models used in the abrupt4xCO2 experiment.

Model name	Institution
ACCESS1-0	Centre for Australian Weather and Climate Research
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CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (CNRM/CERFACS)
CNRM-CM5-2	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (CNRM/CERFACS)
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
INM-CM4	Institute for Numerical Mathematics
IPSL-CM5A-MR	Institut Pierre Simon Laplace
IPSL-CM5B-LR	Institut Pierre Simon Laplace
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-LR	Max Planck Institute for Meteorology
MPI-ESM-MR	Max Planck Institute for Meteorology
MPI-ESM-P	Max Planck Institute for Meteorology
NorESM1-M	Norwegian Climate Centre

model. Seventeen abrupt4xCO2 simulations and 7 amip4K simulations are included in this study. The corresponding models are listed in Tables 1 and 2, respectively. Both experiments are compared with their corresponding control experiments, i.e., the piControl and amip experiments [45].

Atmospheric sensitivity simulation under cooling SST

To examine whether tropical expansion can be reproduced under cooling (or decreasing atmospheric static stability) conditions, we conduct a set of atmospheric sensitivity simulations using the atmospheric model ECHAM6 [46]. We first run a control simulation forced by climatological SST (1979 to 2008). Then, a sensitivity simulation is performed by introducing a globally nonuniform SST cooling anomaly. As shown in Fig. 2, the SST anomaly is designed with a meridional structure, with less cooling over subtropics than at other latitudes. This SST anomalous pattern introduces features of both global cooling and a poleward shift of the mid-latitude MTG. Both simulations run for 150 years, and the last 50 years are used for comparison.

Table 2. List of CMIP5 models used in the amip4K experiment.

Model name	Institution
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (CNRM/CERFACS)
IPSL-CM5A-LR	Institut Pierre Simon Laplace
IPSL-CM5B-LR	Institut Pierre Simon Laplace
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-LR	Max Planck Institute for Meteorology
MPI-ESM-MR	Max Planck Institute for Meteorology
MRI-CGCM3	Meteorological Research Institute

Methodology

Many previous studies [10,20,21,24,47,48] have noted that expanding tropics are region dependent with respect to the amplitude and the temporal evolution. To take into account the regional differences in tropical expansion, we define the tropical edge regionally as the latitude where the 10-m near-surface wind changes direction from easterly toward westerly over individual ocean basins. This is a similar approach that has been used in Yang et al. [10]. This metric is selected because previous evaluations [49,50] revealed that it is representative of the tropical width and shows a significant positive correlation with many AQ5 other metrics, such as those based on the meridional stream function, the precipitation minus evaporation, and the subtropical high. Considering that the Southern Ocean westerly winds migrate synchronously across different ocean basins, we define a simple index of the Southern Hemisphere tropical

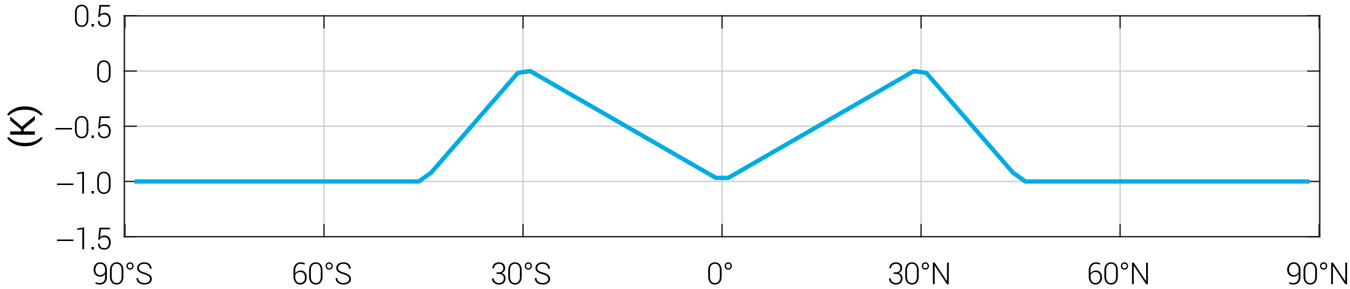

Fig. 2. Zonal-mean anomalies of SST in the ECHAM6 sensitivity experiment with respect to the control experiment.

edge, which includes all the Southern Hemisphere ocean basins. This definition is slightly different from Yang et al. [10], who separated the Southern Hemisphere into 3 ocean basins.

To evaluate the mechanism of tropical expansion, we used the abrupt4xCO2 experiment to compare the trajectories of tropical width with those of the mid-latitude MTG migration, subtropical static stability, ocean temperature change, and horizontal temperature gradient strength. The trajectory of the mid-latitude MTG migration is quantified using the same approach as in [10], which calculates the weighted latitudinal position of meridional SST gradients between 25° and 55° latitudinal belts, following Eq. 1 introduced in [10]:

$$Y_{MTG} = \left(\int_{25^\circ}^{55^\circ} G_{sst}(y) \cdot y dy \right) / \left(\int_{25^\circ}^{55^\circ} G_{sst}(y) dy \right) \quad (1)$$

where Y_{MTG} represents the meridional position of MTG, G_{sst} is the absolute value of meridional SST gradient, and y is the latitude.

The temporal evolution of subtropical static stability is estimated using the vertical temperature difference between the upper (400 to 600 hPa) and lower (600 to 850 hPa) troposphere at the latitudinal band of 35° to 45°N/S. The horizontal temperature gradient is obtained as the mean SST difference between the tropics (0° to 20°N/S) and the subtropics (35° to 45°N/S). These approaches are the same as those used in Chemke and Polvani [31]. The ocean temperature is calculated as the area-weighted SST in individual ocean basins between 0° and 50°N/S.

In the analysis of the amip4K experiment and the ECHAM6 atmospheric sensitivity simulation, the u-component of atmospheric wind is used to evaluate the signal of circulation displacement.

Results

Results from the abrupt4xCO2 experiment

The abrupt4xCO2 experiment imposes an abrupt forcing of quadrupled CO_2. The different response times of the coupled system enable us to determine the most influential factors in forcing tropical expansion. As shown in Fig. 3 (red lines), an abrupt increase in CO_2 results in an abrupt expansion of the tropics in the North Pacific Ocean, North Atlantic Ocean, and Southern Hemisphere. Comparably, increases in the mean ocean temperature (Fig. 3, green lines) are relatively slow and gradual, especially over the Southern Ocean, where dominant upwelling delays surface warming [51]. The different rates of tropical expansion and rising temperatures illustrate that ocean warming does not directly contribute to tropical expansion, as also suggested by Chemke and Polvani [31].

Unlike the relatively slow ocean temperature rise, the strength of meridional SST gradients (Fig. 3, gray lines) illustrates a rapid shift at the beginning of the abrupt4xCO2 experiment. However, the trajectories of these gradients exhibit complex evolution in different ocean basins, depending on the regional ocean dynamics: The SST gradient abruptly decreases and then slowly recovers over the North Pacific Ocean; in contrast, there is an abrupt weakening of SST gradients in the North Atlantic Ocean, followed by an overshoot; in the Southern Ocean, the SST gradient abruptly increases, followed by a gradually weakening trend. These trajectories are clearly distinct from those of tropical expansion, implying that the strength of the MTG is not the driving mechanism of tropical expansion.

Focusing on the Southern Ocean, Chemke and Polvani [31] identified that an increase in subtropical static stability (Fig. 3C, black lines) occurs abruptly, showing a similar trajectory as the evolution of tropical expansion. However, the trajectories of tropical width and subtropical static stability in other ocean basins show contradictory results, especially over the North Pacific Ocean. As illustrated in Fig. 3A (red line), the North Pacific tropical belt shows a rapid expansion with a relatively weak amplitude of ~0.5°, followed by a gradual contraction. In contrast, the static stability continues to increase as the ocean temperature rises. Their distinct trajectories evidently indicate that increasing static stability is not the dominant driver of tropical expansion. The unique tropical contraction in the Pacific Ocean has also been observed in earlier investigations [28,44,52]. Sensitivity simulations [28,44,52] revealed that the local surface temperature change is to blame.

Despite the slow mean ocean temperature rise, the abrupt4xCO2 experiment shows an abrupt poleward shift of the mid-latitude MTG, which is closely correlated with the evolution of tropical width (Fig. 3, red and blue lines). This close covarying between tropical width and MTG migration exists in all ocean basins. The abrupt shift of the mid-latitude MTG lies in the inhomogeneous ocean warming pattern at the onset of CO_2 forcing. As shown in Fig. 4A and B, relatively rapid subtropical ocean warmings, primarily concentrated in the western ocean basins, are found in all ocean basins. These subtropical warming patterns resemble the structure of subtropical ocean gyres (Fig. 4, contours) and the observed SST trend in the past 4 decades (Fig. 1). The relatively fast subtropical ocean warming reduces/increases the low/high latitude MTG and eventually abruptly shifts the mid-latitude MTG to higher latitudes.

Yang et al. [10] argued that the relatively strong subtropical ocean warming primarily arises from the background subtropical gyres, which accumulate the CO_2-induced anomalous heat. Sensitivity simulations suggest that the enhanced subtropical ocean warming is independent from tropical expansion [12].

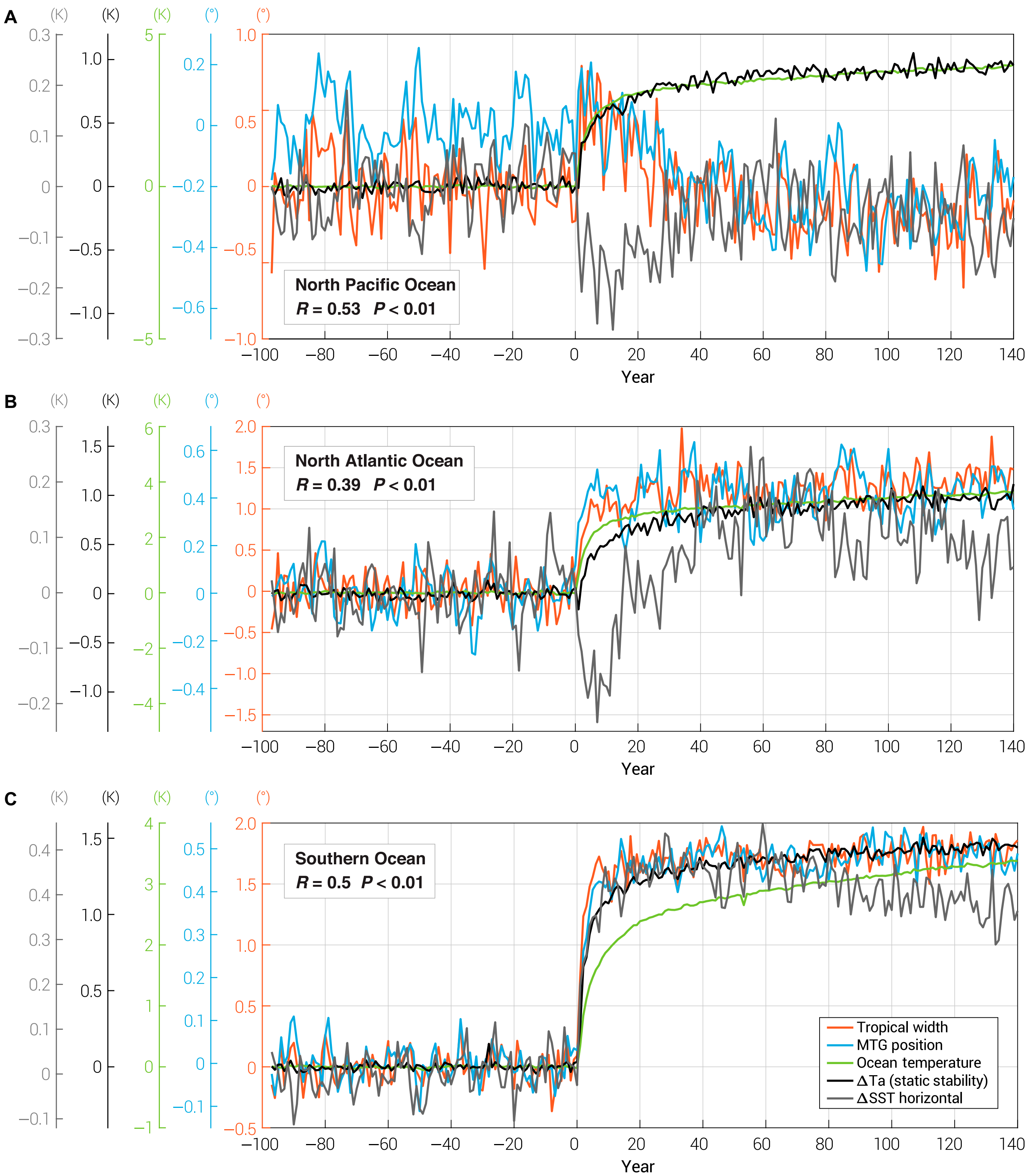

Fig. 3. Anomalies of tropical width (red lines), meridional migration of MTG (blue lines), ocean surface temperature (green lines), subtropical static stability (black lines), and horizontal SST gradient (gray lines) in the last 100 years of the piControl experiment (left) and 140 years of abrupt4xCO2 experiments (right). Detailed definitions of these variables can be found in Materials and Methods. The ensemble-mean correlation coefficients between the tropical width and MTG position in the abrupt4xCO2 experiment are given by *R*, with corresponding *P* values provided by *P* (Student's *t* test). All time series are shown as anomalies with respect to the corresponding piControl experiment.

In the North Pacific Ocean, the aforementioned abrupt widening of the tropics reverses its trend after a few years of abrupt CO_2 increases. This reversal is in close agreement with the equatorward shift of the mid-latitude MTG, which is caused by developing relatively weak subtropical ocean warming in the North Pacific Ocean (Fig. 4C). A previous study [52] also noticed this distinct response of atmospheric circulation attributed to changing SST.

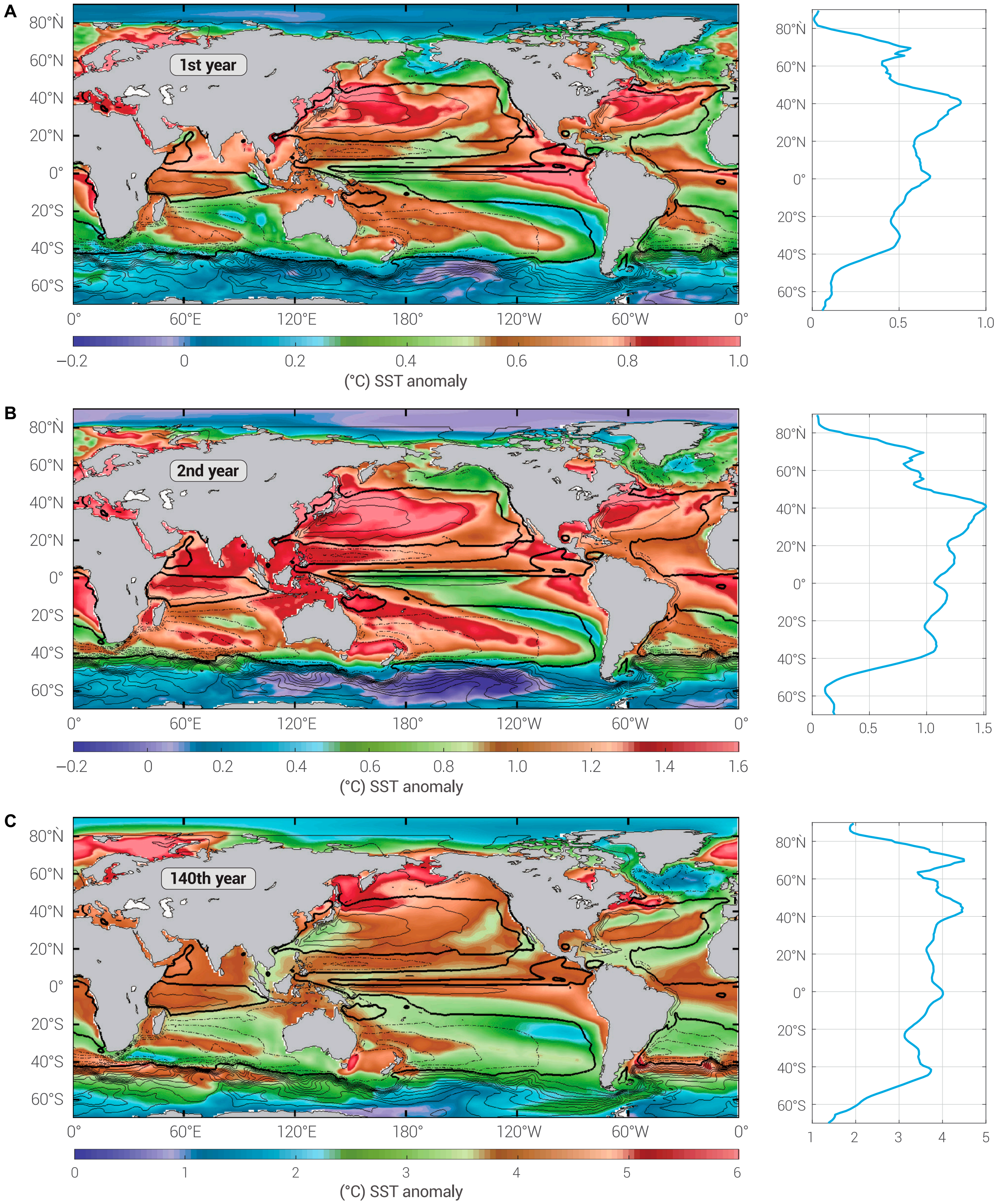

Fig. 4. Snapshots of SST evolution in the abrupt4xCO2 experiment. The SST anomalies for individual years are given with respect to the climatology SST of the piControl experiment. To illustrate the region where surface water converges (subtropical ocean gyres), the climatology barotropic stream function of oceanic circulation [69] is overlapped by the black contours. The right panels present the zonal mean SST anomaly. At the onset of the abrupt4xCO2 experiment, the subtropical ocean gyres exhibit a relatively strong surface warming. This relatively strong subtropical ocean warming causes a rapid poleward shift of the mid-latitude MTG, as shown in Fig. 3 (bule lines). Over the North Pacific Ocean, the long-term warming pattern induces a relatively weak subtropical warming and an equatorward shift of the mid-latitude MTG, contributing to a long-term regional contraction of the tropical belt as shown in Fig. 3A (red line). The results are based on the ensemble mean of 17 CMIP5 model outputs.

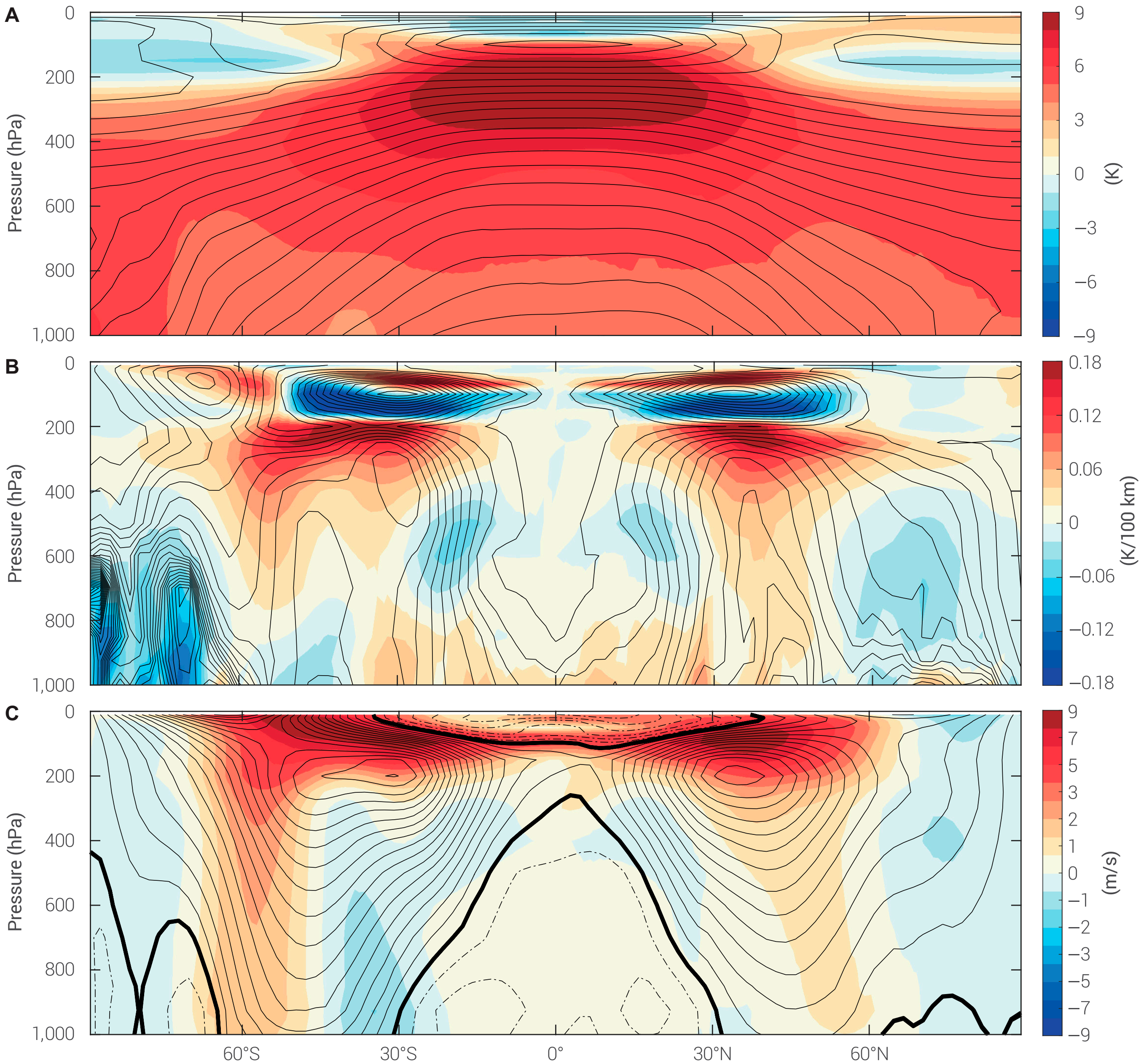

Fig. 5. Zonal-mean anomalies of (A) air temperature, (B) MTG, and (C) u-wind in the amip4K experiment with respect to the amip control experiment. The corresponding climatological distributions of air temperature, MTG, and u-wind are given by the contours. For the u-wind panel, positive values represent westerly wind anomalies, and vice versa. The black contours give the climatological u-wind distribution. Solid contours show westerly winds, and dashed contours are easterly winds. The thick black lines illustrate the zero-crossing of u-wind from easterly to westerly. The poleward shift of the tropospheric jet stream is visible in the amip4K experiment with westerly/easterly wind anomalies at the poleward/equator flanks of climatological position of westerly jets. The results are based on the ensemble mean of 7 model outputs from the CMIP5.

The abrupt4xCO2 experiment demonstrates that although ocean temperature rise delays the abrupt increase in CO_2, the position shift of the mid-latitude MTG is rapid, indicating a close relationship with the evolution of tropical edges. Moreover, the abrupt4xCO2 experiment further demonstrates that subtropical ocean warming is indeed fast because of the surface convergence dynamics of the subtropical gyres. These facts are all in line with the hypothesis proposed in Yang et al. [10].

Results from the amip4K experiment

The amip4K experiment is designed by introducing a spatially uniform 4-K SST anomaly with respect to the amip control experiment. This experiment is aimed to examine how the atmospheric circulation responds to warming without involving any SST warming pattern. As demonstrated [22,33,44], uniform 4-K SST warming also expands the tropics, which manifests as a poleward shift of the tropospheric jets (Fig. 5C) and surface wind (Fig. 6A). Many studies have argued that the increased static stability associated with warming provides the forcing behind tropical expansion [2,31,33]. In this context, changes in horizontal temperature gradients within the atmosphere were easily overlooked.

As shown in Fig. 5A, uniform surface warming produces an amplified warming in the upper troposphere, reduces the lapse rate, and increases the atmospheric static stability. However, the MTG within the troposphere is also modified (Fig. 5B).

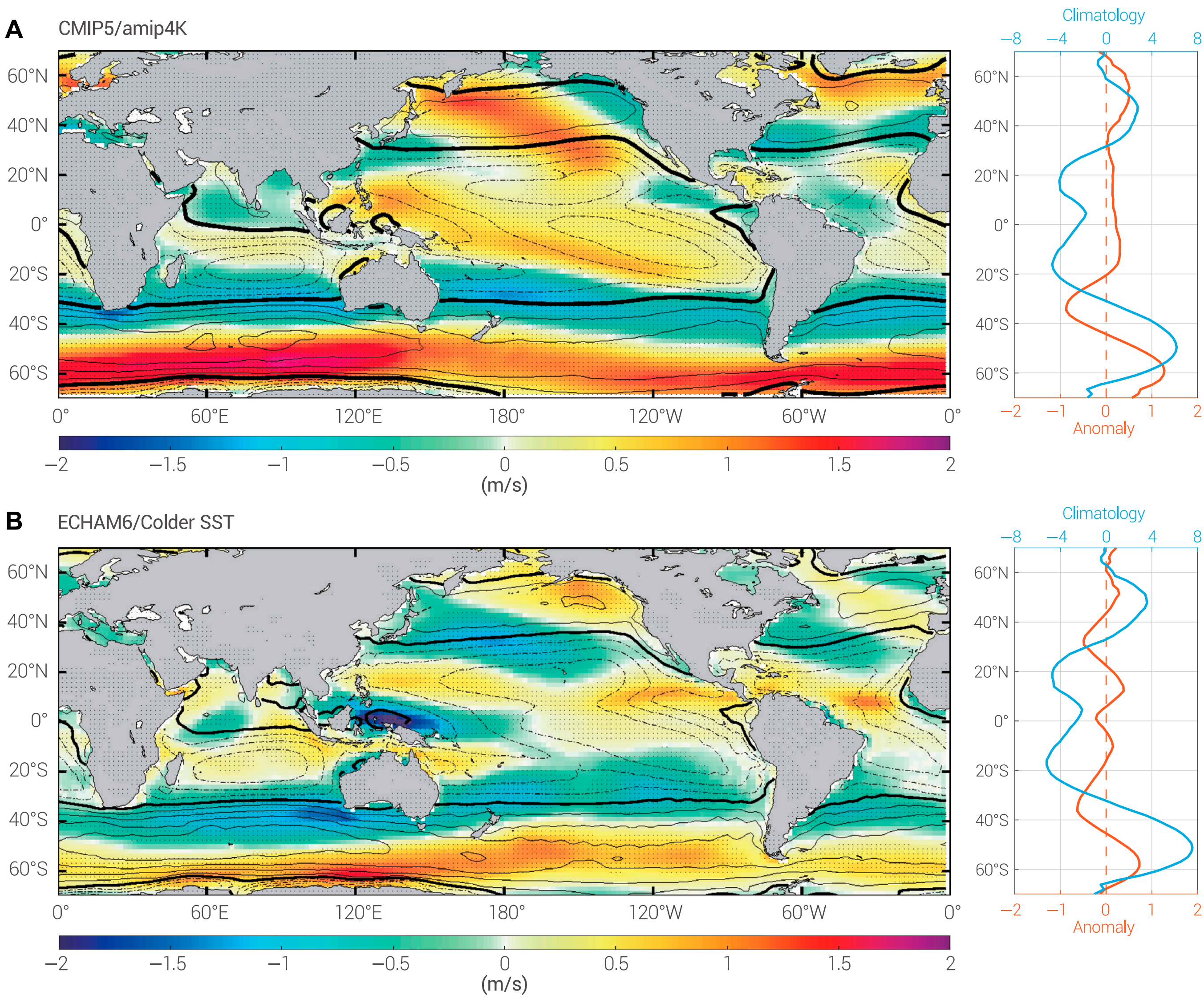

Fig. 6. Poleward shift of near-surface zonal wind in (A) CMIP5 amip4K and (B) ECHAM6 global cooling experiments. The shading illustrates the near-surface wind anomalies in the sensitivity experiments (i.e., amip4K and ECHAM6 cooling experiment) with respect to the corresponding control experiments (i.e., amip and ECHAM6 control experiment). The contours illustrate the climatology near-surface zonal wind. Dashed lines represent easterly winds, while solid lines illustrate westerly winds. The thick black lines are the zero-crossing of zonal wind. The right panels depict the zonal mean profile of the climatology (blue) and anomaly (red) of zonal winds. For the CMIP5 result, stippling indicates that more than 5 of 7 models agree on the signs of the anomalies. For the ECHAM6 result, stippling represents that the anomalies are statistically significant (pass the 95% confidence level, Student's *t* test).

Because of the background SST pattern, the ocean's heating effect on the atmosphere is not uniform despite spatially uniform surface warming. According to the Clausius–Clapeyron relationship, a given uniform surface warming is associated with a significantly greater latent heat supply to the upper troposphere at low latitudes than at high latitudes (Fig. 7A) due to the exponential increase in saturation water vapor pressure with temperature [53]. Moreover, on the basis of the Stefan–Boltzmann law, a 4-K SST increase from a level of 300 K at lower latitudes could introduce more upward longwave radiation than at higher latitudes (Fig. 7B). As a consequence, uniform SST warming produces more oceanic heating to the atmosphere in the region where background oceanic heating is strong. This situation reinforces the climatology pattern of oceanic heating to the atmosphere, which peaks around the subtropical region, where the maximum oceanic heat release into the atmosphere occurs (Fig. 7C).

As designed, uniform surface warming does not affect the surface MTG. However, the nonuniform surface heating (Fig. 7c) can penetrate into the troposphere via latent heat when the water vapor in the air condenses. This nonuniform surface heating eventually causes nonuniform warming in the upper troposphere [54], pushing the tropospheric (primarily 700 to 200 hPa) MTG toward higher latitudes. As shown in Fig. 5B, positive/negative MTG anomalies (red/blue shading) are found on the polar/equator flanks of the sharp mid-latitude MTG zones (contours). According to the thermal wind balance, the shift in MTG can thermodynamically drive a poleward shift of the tropospheric jets (Fig. 5C), which show the strongest anomalies approximately at the same location (upper troposphere) where the strongest MTG anomalies are achieved. As the subtropical jet is a regime that extends from the upper troposphere to the surface, it dynamically affects the surface westerlies as well (Fig. 6A), although the surface MTG has not changed. To this end,

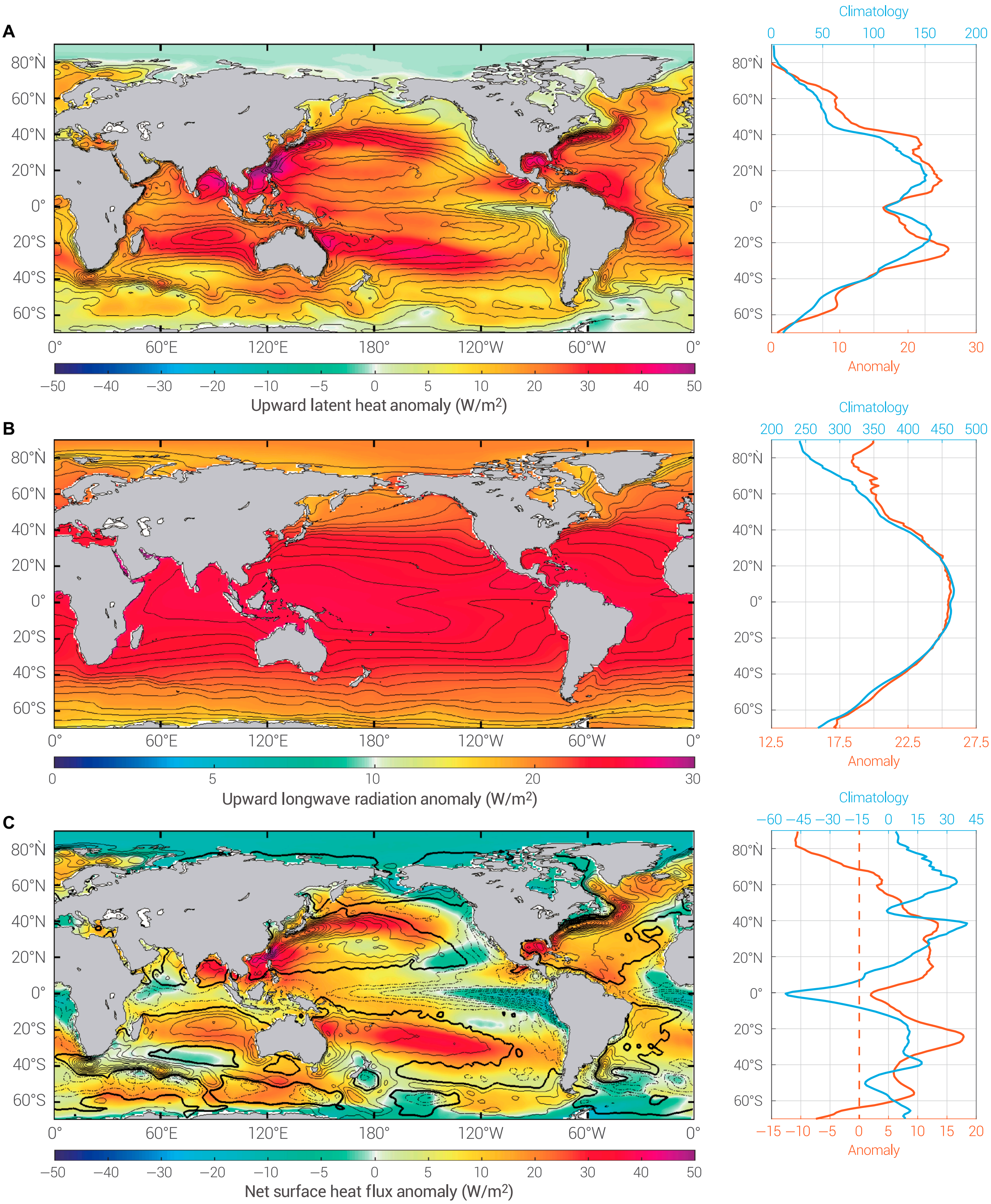

Fig. 7. Anomalies of (A) latent heat flux, (B) upward thermal radiation, and (C) net surface heat flux in the amip4K experiment with respect to the amip control experiment. The contours illustrate the climatology distribution of different heat fluxes. Forthe net surface heat flux, solid lines represent oceanic heat release into the atmosphere, and dashed lines indicate net ocean heat gain. The contour interval is 15 W/m^2 The results are based on the ensemble mean of 7 CMIP5 model outputs.

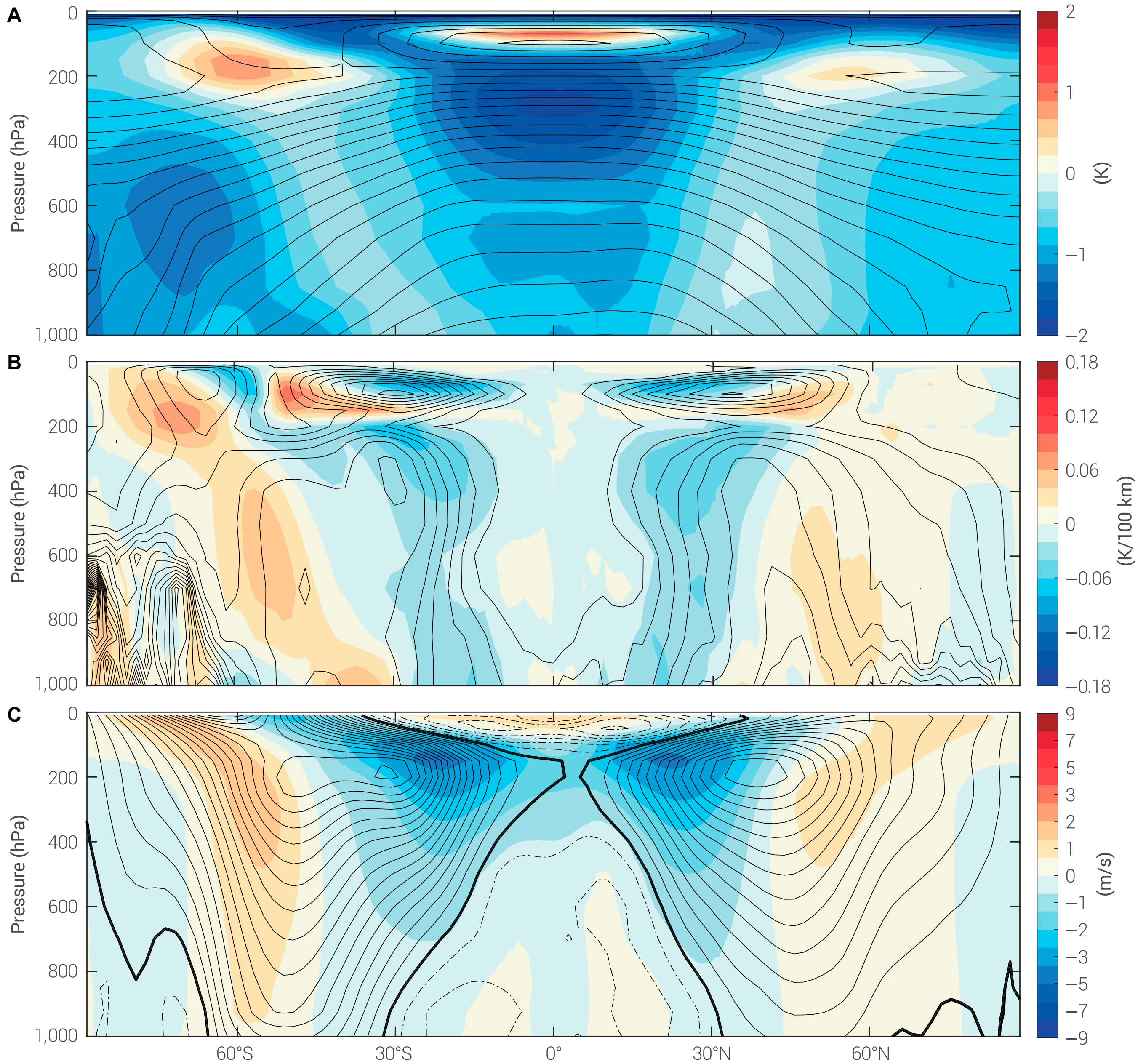

Fig. 8. Zonal-mean anomalies of (A) air temperature, (B) MTG, and (C) u-wind in the ECHAM6 sensitivity experiment with respect to the control experiment. The corresponding climatological distributions of air-temperature, MTG, and u-wind are given by the contours. For the u-wind panel, i.e., subpanel (C), positive values represent westerly wind anomalies, and vice versa. The black contours give the climatological u-wind distribution. Solid contours show westerly wind, and dashed contours are easterly wind. The thick black lines illustrate the zero-crossing of u-wind from easterly to westerly.

the amip4K experiment is also in line with the MTG hypothesis. In this very specific case, although the surface MTG has not changed, the MTG aloft has been shifted due to the difference in surface heating.

Tropical expansion under shifting MTG and decreasing static stability

In the amip4K experiment, although drifting MTG is dynamically consistent with tropical expansion, it is not possible to rule out the contribution of increasing static stability (or warming) in driving tropical expansion, because changes in both MTG and static stability are the results of uniform surface warming. To further examine whether the migration of the MTG can lead to tropical expansion without global warming, we conduct a sensitivity simulation with globally cooling SST forcing (see Materials and Methods). SSTs are purposefully cooled worldwide, but subtropical regions are forced to experience relatively weak cooling (Fig. 2). In this specific setup, we introduce signals of both cooling and poleward migration of the MTG.

Surface cooling produces an amplified cooling signal in the upper troposphere, thereby increasing the lapse rate and reducing the static stability (Fig. 8A). Interestingly, despite the reduced static stability, we still obtain a poleward shift of the jet stream extending from the surface to the upper troposphere (Fig. 6B and 8C). This shift in the jet stream is primarily a result of poleward migration of the MTG throughout the entire troposphere

(Fig. 8B). Changes in zonal wind(Fig. 8C) follow a similar pattern as MTG anomalies (Fig. 8B), with negative anomalies at low latitudes and positive anomalies at mid- to high-latitudes.

Our "cooling" SST experiment suggests that warming (or increasing static stability) does not necessarily drive tropical expansion. In contrast, the migration of the MTG plays a more important role in the drifting pattern of mid-latitude atmospheric circulation.

Discussion

The fundamental driver of atmospheric circulation is the temperature gradient. Tropical expansion links to a systematic poleward shift of the mid-latitude circulation, characterized by prevailing westerlies. Following the thermal wind theory, the westerlies are maintained by the strong MTG. Therefore, it is reasonable to deduce that changes in MTG can affect the mid-latitude circulation. Previous studies have shown that tropical expansion can occur under conditions of both increased [18,55] and decreased [56] MTG. This "confusing" fact is also reflected in our results (Fig. 3, gray lines). We argue that the strength of the MTG does not determine the width of the tropics. In contrast, it is the MTG distribution (or position) that fundamentally impacts the position of mid-latitude circulation and tropical width.

The mid-latitude circulation is an eddy-dominated regime that relies on strong baroclinicity. Both horizontal and vertical temperature gradients contribute to atmospheric baroclinic instability. Previous studies [40,41] have argued that increasing static stability (reduce vertical temperature gradient) contributes to tropical expansion. Chemke and Polvani [31] found that increased static stability around the subtropical region occurs at a similar rate as expanding tropics in the abrupt4xCO2 experiment. This increase in static stability is primarily related to enhanced upper troposphere warming as a result of warming. Indeed, by introducing a warming signal into the climate system, many climate model simulations show both tropical expansion and increasing subtropical static stability [2,31,57–59]. However, the cause of the static stability response is probably not independent from tropical expansion [14].

Many previous studies have investigated tropical expansion on a hemispheric scale, ignoring the regional characteristics that are valuable for evaluating the mechanism. In the abrupt4xCO2 experiments, not all ocean basins follow the same tropical expansion trajectory. The North Pacific Ocean exhibits abrupt tropical expansion, followed by slow contraction (Fig. 3a). This situation is clearly unrelated to the steadily increasing atmospheric static stability. Moreover, in our global cooling experiment, we simulate both reducing static stability and tropical expansion. These results question the role of static stability in driving tropical expansion.

The tropical atmosphere features a higher tropopause height than that over the subtropical regions. When the tropics expand, the tropopause height in the subtropical region rises. This can lead an enhanced temperature rise in the subtropical upper troposphere, which increases the subtropical static stability. It is worth noting that the enhanced subtropical tropospheric warming was initially considered to be the very first observational manifestation of tropical expansion [1] and was later interpreted as a mechanism of tropical expansion [31]. Wang and Huang [54] investigated the mechanism of upper tropospheric warming. They showed that tropical expansion can lead to upper tropospheric warming near subtropical latitudes (Fig. 1D in [54]). This warming reduces the vertical temperature gradients and increases the subtropical static stability. Therefore, it is debatable whether the increase in subtropical static stability is an independent forcing or a manifestation of tropical expansion. We propose that, in comparison to horizontal temperature gradients, vertical temperature gradients (or static stability) play a less important role in driving tropical expansion.

The abrupt4xCO2 experiment shows a rapid tropical expansion, which contrasts with the gradual warming of the ocean. Despite the fact that ocean warming is gradual, the migration of oceanic MTG is as abrupt as tropical expansion. This abrupt shift in MTG arises from different rates of ocean warming at different latitudes (Fig. 4). It acts as an independent forcing for tropical expansion. Previous aqua-planet sensitivity simulations have confirmed that enhanced subtropical ocean warming occurs in the absence of any dynamic changes in oceanic and atmospheric circulation [12]. Furthermore, our results reveal that tropical expansion not only illustrates the same trend as the MTG shift but also has a close correlation with MTG migration on an interannual time scale. This close relationship can be found over all ocean basins (Fig. 3). Hence, we argue that the abrupt4xCO2 experiment does not contradict the MTG mechanism. In contrast, it is an ideal experiment that helps verify the hypothesis that rapid subtropical ocean warming, constrained by subtropical gyres, promotes a rapid poleward shift in the MTG, and drives tropical expansion.

Tropical expansion has also been reproduced by atmospheric models forced by uniform SST warming [22,33,42–44]. Such results seem to support the hypothesis that mean warming drives the circulation shift [18,59–61]. However, spatially uniform ocean warming produces nonuniformed heating to the atmosphere, which could induce a poleward shift of the MTG within the troposphere and drive tropical expansion. Previous investigations have found that the atmospheric warmings over both the central tropics [62–65] and polar region [66–68] contribute to an equatorward contraction of the tropical belt. Compared to other latitudes, the warming around the subtropical regions contributes the most to tropical expansion [35,63]. Our ECHAM6 sensitivity simulation reproduces wider tropics under global cooling conditions (Fig. 8). These facts reveal that warming itself does not necessarily drive tropical expansion. We propose that it is the tropospheric MTG migration associated with warming that forces tropical expansion in the amip4K experiment. To this end, the amip4K experiment also does not contradict the MTG mechanism.

To summarize, we revisited the abrupt4xCO2 and amip4K experiments, which were previously thought to contradict the hypothesis that tropical expansion is driven by a poleward shift in the MTG caused by ocean warming patterns. The abrupt4xCO2 experiment demonstrates a rapid subtropical ocean warming, which promotes abrupt migration of the mid-latitude MTG and tropical expansion. The amip4K experiment shows a consistent poleward shift of the mid-latitude MTG and jet streams in the troposphere, despite uniform surface warming. These are all in line with the MTG mechanism. Using an idealized global cooling experiment, we further simulated tropical expansion under conditions of reducing static stability and poleward shifting of the MTG. All of these results support our hypothesis that MTG migration is the key driver of tropical expansion.

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Data Availability

All the CMIP5 data used in this study are publicly available through their official website at https://esgf-node.llnl.gov/projects/cmip5/.

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