The Influence of Direct Radiative Forcing Versus Indirect Sea Surface Temperature Warming on Southern Hemisphere Subtropical Anticyclones Under Global Warming

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Abstract

Southern hemisphere subtropical anticyclones are projected to change in a warmer climate during both austral summer and winter. A recent study of CMIP 5 & 6 projections found a combination of local diabatic heating changes and static-stability-induced changes in baroclinic eddy growth as the dominant drivers. Yet the underlying mechanisms forcing these changes still remain uninvestigated. This study aims to enhance our mechanistic understanding of what drives these Southern Hemisphere anticyclones changes during both seasons. Using an AGCM, we decompose the response to CO₂-induced warming into two components: (1) the fast atmospheric response to direct CO₂ radiative forcing, and (2) the slow atmospheric response due to indirect sea surface temperature warming. Additionally, we isolate the influence of tropical diabatic heating with AGCM added heating experiments. As a complement to our numerical AGCM experiments, we analyze the Atmospheric and Cloud Feedback Model Intercomparison Project experiments. Results from sensitivity experiments show that slow subtropical sea surface temperature warming primarily forces the projected changes in subtropical anticyclones through baroclinicity change. Fast CO₂ atmospheric radiative forcing on the other hand plays a secondary role, with the exception of the South Atlantic subtropical anticyclone in austral winter, where it opposes the forcing by sea surface temperature changes resulting in a muted net response. Lastly, we find that tropical diabatic heating changes only significantly influence Southern Hemisphere subtropical anticyclone changes through tropospheric wind shear changes during austral winter.

1. Introduction

Subtropical Anticyclones (SA)s are semi-permanent high-pressure systems that are crucial components of the large-scale atmospheric circulation in both hemispheres. Climatologically, SAs in the Southern Hemisphere (SH) influence the hydrological cycle and precipitation in the subtropics and midlatitudes (Sturman and Tapper 1996; Tyson and Preston-Whyte 2000; Reboita et al. 2010). The precipitation variability and intensity of subtropical regions are reported to be changed in recent years due to changes in the area and strength of SH SAs that led to regional drought extremes (Burls et al. 2019). To understand how the weather and climate of SH subtropical and midlatitude regions will change in response to global warming, understanding how the SH SAs will respond is crucial. In this article, we use the word “change” to describe the difference between a model’s future projection (a warmer climate due to external forcings) and the respective control run (e.g. PiControl, Historical) of the same climate model.

In simulations conducted by the models participating in the Coupled Model Intercomparison Project (CMIP), it is well documented that the subtropical to midlatitude atmospheric circulation is significantly affected in both hemispheres under future warming (Li et al. 2012, 2013; Shaw and Voigt 2015; He et al. 2017; Song et al. 2018a; Fahad et al. 2020) (Fig. 1a & b). The mechanisms that drive SA changes in the Northern Hemisphere (NH) have been explored in a number of studies (Li et al. 2012; Shaw and Voigt 2015, 2016; He et al. 2017; Song et al. 2018a). The SH SAs have however received less attention, with open questions surrounding our understanding of what drives the simulated changes in the SH SAs during both the austral summer and winter season.

The SH SAs are projected to extend in the area and intensify along the poleward flank of the subtropics during both the austral summer (December-January-February or DJF) and winter (June-July-August or JJA) season (Li et al. 2013; Fahad et al. 2020). Li et al. (2013) found that all three SAs in the SH, namely the South Pacific SA (SPSA), South Atlantic SA (SASA), and South Indian SA (SISA) extend in area and strength due to increased land-sea thermal contrast due to intensified cooling over the ocean. This local diabatic heating mechanism is consistent with Wu and Liu (2003), which show a longwave, latent, and sensible heating pattern in the subtropical region drives changes in the climatological area and strength of the summertime SH SAs'.

Later, He et al. (2017) argued that changes in upper troposphere static stability have a significant influence on changes in the summertime SH SAs under global warming conditions. Using CMIP5 output He et al. (2017) analyzed changes in subsidence, low-level divergence, and rotational wind from 10°S-40°S focusing on the difference between future RCP8.5 projections (years 2050–2099) and historical (years 1950–1999). He et al. (2017) found that while the SPSA increases in strength; the SASA and SISA weaken in future climate during local summer even though decreased heating over the subtropical ocean supposedly acts to intensify the SH SAs. He et al (2017) argue that increased tropical upper troposphere static stability in a future climate leads to mean advection of stratification changes (MASC) that act to decrease the strength of the SASA and SISA during local summer (Ma et al. 2012; He et al. 2017). In the case of the SPSA, the contribution from the MASC mechanism is relatively small and the local diabatic heating decreases primarily acts to increase the SPSA's strength in future climate. Using a linear baroclinic model, He et al. (2017) show that the changes in SH SAs are consistent with prescribed changes in the heating and tropospheric static stability. The inconsistency of the austral summer SASA and SISA change in future climate between Li et al. (2013) and He et al. (2017) is due to the choice of domains to define the SH SAs. Li et al. (2013) defined the centers of the SAs as where the 925hPa stream function is at a maximum over the subtropical Ocean, whereas He et al. (2017) regionally averaged between 10°S-40°S, this latter definition focuses largely over the equatorward flank of the SAs where the MASC mechanism has a larger effect.

Analyzing the CMIP5 and CMIP6 models, Fahad et al. (2020) show that Sea Level Pressure (SLP) and 925hPa wind associated with SAs intensifies in the center and along the poleward flank in the SH comparing historical (years 1950–1999) to future projections (RCP8.5 for CMIP5 and SSP585 for CMIP6) (years 2050–2099). Fahad et al. (2020) defined the 1020hPa isobar area as the center of the SH SAs, and 25°S-45°S as the latitudinal extent of the domain for the austral summer (DJF), and 20°S-40°S as the latitude domain for the austral winter (JJA), Findings of SH SAs change in the future climate compared to the historical multi-model mean (MMM) are consistent between Li et al. (2013) and Fahad et al. (2020) for austral summer. However, Fahad et al. (2020) show that reduced baroclinic eddy growth in the future climate acts to intensify SAs along their poleward flank in both seasons. By using the metric for the Philipps criterion (Phillips 1954) to decompose the changes in baroclinic instability into the contribution from static stability changes and wind shear change, Fahad et al. (2020) find that an increase in

tropospheric static stability is the dominant driver of the baroclinic eddy growth reduction leading to intensified SH SAs along their poleward flank

The climatological influence of the tropical diabatic heating, especially heating over the Inter Tropical Convergence Zone (ITCZ) and the South Pacific convergence zone (SCPZ) on SAs in both hemispheres are documented in several studies (Hoskins 1996; Chen et al. 2001; Nigam and Chan 2009; Fahad et al. 2021). Future changes in NH SAs are reported by Song et al. (2018) to be related to the change in the tropical precipitation (and latent heating) resulting from a delay in the boreal spring to summer seasonal cycle of tropical rainfall and heating under global warming conditions. Changes in the onset of the rainfall band over the tropical ocean affect the Hadley circulation in the NH leading to a change in the zonal mean component of NH SAs (Song et al. 2018b, a). With the exception of the MASC mechanism (Ma et al. 2012, He et al. 2017), the influence of tropical diabatic heating changes under global warming conditions on SH SAs has received much less attention compared to their NH counterparts.

Focusing on the midlatitude atmospheric circulation, several studies have investigated the relative importance of the fast atmospheric response due to the direct radiative forcing component of CO₂ versus the slower atmospheric response due to the indirect forcing component related to the patterns of Sea Surface Temperature (SST) warming (Shaw 2014; Simpson et al. 2014; Grise and Polvani 2014; Shaw and Voigt 2015). For the summertime NH atmospheric circulation change in a warming climate, Shaw and Voigt (2015) show that the North Pacific SA responses to an increase in the direct radiative forcing from the elevated atmospheric CO₂ concentrations oppose those from the indirect SST warming. Using an atmospheric general circulation model forced with prescribed SSTs, Shaw and Voigt (2015) found the North Pacific SA increases in strength during boreal summer due to increased direct radiative forcing, however, this weakens in strength due to the SST warming patterns. In coupled model simulations these opposing responses to direct radiative forcing and indirect SST warming lead to a small net change of the North Pacific SA's strength under future warming. There is also a similar tug-of-war response between these two forcings found on upper troposphere atmospheric circulation in the North Pacific (Shaw and Voigt 2015).

As with the influence of tropical diabatic heating, the response of the SH SAs to direct CO₂ radiative forcing (fast atmospheric forcing), and indirect SST warming (slow oceanic forcing) has received much less attention compared to their NH counterparts. This study aims to determine which of these two forcings primarily drives changes in the SH SAs. Using the Community Earth System Model version 2 (CESM2) coupled ocean-atmosphere experiments from CMIP6, and prescribed SST Community Atmospheric Model 6 (CAM6) numerical experiments, we explore how the direct CO₂ radiative forcing versus indirect SST warming patterns drive the SH SAs during both austral summer and winter. We further investigate the relative contribution of these two forcing mechanisms to future changes in tropical diabatic heating and how changes in the tropical diabatic heating alone act as a remote forcing on the SH SAs. The sections of this study are structured as follows: Sect. 2 describes the experimental design, numerical model configurations, and data analyzed from different experiments. Results from the analysis

are presented in Sect. 3. Finally, in Sect. 4, the discussion and conclusions from the results are documented.

2. Methodology

In this study, we both analyze climate simulations performed as part of CMIP6 and perform a suit numerical experiments using CAM6 with prescribed climatological SST and sea-ice component sets (model compset F2000climo). A list of numerical experiments performed and/or analyzed in this study is presented in Table 1. CAM6 is the atmospheric component of CESM2.0 (Danabasoglu et al. 2020). A $1.9^\circ \times 2.5^\circ$ model resolution is used for the active atmosphere (CAM6) and land (CLM5) components, with data ocean and sea ice components. 30 ensemble members of a one-year control run (CAM Control) are carried out with prescribed climatological SST and sea-ice cover derived from a 50-year mean of the CMIP6 CESM2 Historical simulation (years 1950–1999) (i.e. every ensemble member was forced with this climatological mean SST). Every year of this 30-member ensemble is initialized with a random selection of January 1st initial conditions taken from a previously spun-up CESM2 Historical simulation. Details on the natural and external forcing used to force the CMIP6 CESM2 Historical simulation is documented in Eyring et al. (2016).

Table 1
List of experiments performed and/or analyzed in this study

Project		Control	Future SST	Future CO ₂	Future Tropical Heating	Future Global Warming Projection
CMIP6 Multi Models (includes CESM2)		Historical	Not Available	Not Available	Not Available	SSP585
CAM6 numerical experiments		CAM Control	CAM SST	CAM CO ₂	CAM Q	CAM SSTCO ₂
CESM2 From CMIP6	CFMIP	piSST	A4SST	piSST4XC02	Not Available	Abrupt4XC02
	AMIP	AMIP	AMIP4k	AMIP4xC02	Not Available	Abrupt4XC02

To isolate the influence of the SST changes in a future warm climate, a 30-ensemble-member, prescribed-SST run (CAM SST) is performed using a 50-year climatological mean SST from the CESM2 SSP585 experiment (years 2050–2099). The SSP585 experiment in CMIP6 is forced with the high radiative forcing projections for the end of the century (Matthes et al. 2017). The CAM SST run is initialized using initial conditions from the CAM Control run for both DJF (initialized on November 01 of that year and run until February of the next year) and JJA (initialized on May 01 of that year and run until the end of August). Similarly, a 30-ensemble-member, increased CO₂ concentration experiment (CAM CO₂) is done with the same boundary conditions as CAM Control except for the CO₂ concentration. In the CAM CO₂ experiment, the CO₂ is increased from the CAM Control run value of 370 ppm to 740 ppm. This CO₂

concentration increase is equivalent to an approximate average of the CESM2 SSP585 CO₂ concentration for the years 2050–2090 compared to the years 1950–1999 of the CESM2 Historical simulation (Matthes et al. 2017). Finally, the CAM SSTCO₂ experiment is done in which the CO₂ concentration is increased (global mean ~ 740 ppm) with prescribed SSP585 climatological SST (years 2050–2099). The purpose of the CAM SSTCO₂ experiment is to investigate the response of SH SAs to the combined CO₂ and SST forcing. The one-year, 30-ensemble-member approach is taken so that it is consistent with the design required for the diabatic heating experiments (as described in the next paragraph), as well as limit the influence of slow surface heating within the land component. To assess the influence of temporal adjustment on the SLP response within the respective experiments, the CAM SST, CAM CO₂, and CAM SSTCO₂ experiments have also alternatively been done as continuous 30-years simulations instead of a series of one-year branch the results of which are briefly discussed in the final section as a point of comparison.

To isolate the influence of tropical diabatic heating, a set of branched tropical added heating (CAM Q) experiments are done from the initial condition of every CAM Control year for both DJF (initialized on November 01 of that year and run until February of the next year) and JJA (initialized on May 01 of that year and run until the end of August) with same prescribed climatological SST. Heating is only added over the tropical oceans between 15°S–15°N with a gaussian decay applied to the magnitude at the edges of this domain. The added heating model technique is similar to that of Swenson et al. (2019) and Fahad et al. (2021). The added heating experiments (CAM Q) are done using an iterative process. 20% of the tropical diabatic heating difference between SSP585 (years 2050–2099) and the Historical (years 1950–1999) CESM2 CMIP6 simulations are added every time until the 1-year 30-ensemble-member climatological mean across the branched CAM Q experiments minus the 1-year 30-ensemble-member climatological mean across the branched CAM Control experiments converges toward a field similar to that seen between the SSP585 (years 2050–2099) – Historical (years 1950–1999) coupled experiments. The iteration of added heating run CAM Q is done 6 times for both DJF and JJA for every year starting from CAM Control initial conditions. The vertical structure of the added heating in the experiment CAM Q is shown in Fig. 2. The vertical mean spatial structure of the heating is the difference between CESM2 SSP585 (years 2050–2099) and Historical (years 1950–1999) simulations (Fig. 4b & 8b).

As a complement to our CAM6 model simulations, we analyze sets of CESM2 experiments that form part of two CMIP6 projects: the Cloud Feedback Model Intercomparison Project (CFMIP) (Webb et al. 2017) and the Atmospheric Model Intercomparison Project (AMIP) (Gates et al. 1999), see Table 1. From CFMIP, experiment PiSST is compared with the experiment piSST4xCO₂, A4SST, and Abrupt4XCO₂. The piSST experiment is a 30-year AGCM run with monthly varying SST, sea-ice, and atmospheric constituents taken from the CMIP6 piControl experiment. The 30 years chosen from the piControl are parallel to the Abrupt4XCO₂ experiment's years 111–140. The piSST4xCO₂ experiment is the same as piSST except for the CO₂ concentration is quadrupled compared to the piSST. The A4SST experiment is the same as piSST, except for SST is taken from the coupled CMIP6 Abrupt4XCO₂ experiments (years 111–140 monthly varying SST output). Finally, 30 years (years 111–140) of the Abrupt4XCO₂ CMIP6 experiment

are analyzed to compare with these experiments. The AMIP experiments are forced by time-varying observed SST and sea ice concentration with present-day atmospheric composition for the years 1979–2014. For this study 30 years of AMIP data is analyzed (years 1979–2008). The AMIP4xCO2 experiment is the same as AMIP, except for CO₂ concentration is quadrupled. Similarly, the AMIP4k experiment is the same as AMIP except for increased SST warming 4 kelvins uniformly everywhere. The list of CMIP6 models used in the analysis is shown in the supplementary Table S1.

The CESM2 total diabatic heating is taken directly from the model's output. Additionally, the vertically integrated diabatic heating is calculated as a sum of net radiation going into the atmospheric column, latent heating, and sensible heating similar to Fahad et al. (2020) to compare it with the model output.

The Phillips criterion metric (C) (1954) is used to evaluate the conditions promoting baroclinic eddy growth, defined as in Lu et al. (2008) and Fahad et al. (2020):

$$C \equiv \frac{f^2(u_{500} - u_{lower}) * \theta}{\beta g H (\theta_{500} - \theta_{850})} \quad (1)$$

The Phillips criterion C increases with increased baroclinic eddy growth. Here H is the geometric height of the column - lower level (the average between 850hPa and 1000hPa) to 500hPa, θ is reference potential temperature. Similar to Fahad et al. (2020), the criterion changes are decomposed into changes due to static stability (Cs) and zonal wind shear (Cw) as:

$$\delta C_s = - \frac{f^2(u_{500} - u_{850})_h * \delta(\theta_{500} - \theta_{850}) * \theta}{\beta g H (\theta_{500} - \theta_{850})^2_h} \quad (2)$$

$$\delta C_w = \frac{f^2 * \delta(u_{500} - u_{lower}) * \theta}{\beta g H (\theta_{500} - \theta_{850})_h} \quad (3)$$

Here δ is the difference between future warmed climate projection and control simulation. Here the vertical level 850hPa and 500hPa are chosen as baroclinic eddy growth is primarily influenced by the lower tropospheric baroclinicity (Held and O'Brien 1992).

3. Results

3.1. Projected changes in the Southern Hemisphere Subtropical Anticyclone's during Austral Summer

The CMIP6 MMM SLP change (SSP585 - Historical) during austral summer (DJF) shows an increase in the center and along the poleward flanks of the SH SAs (Fig. 1a). The area of each SA's center defined as the area where SLP is $\geq$ the 1020hPa isobar increases and extends toward the pole in the future climate SSP585 (years 2050–2099) compared to Historical (years 1950–1999) simulation. The SLP change (SSP585 - Historical) in CESM2 coupled model run is largely similar to the CMIP6 MMM (Fig. 3b).

The vertically averaged (1000hPa – 200hPa) diabatic heating increases in the tropics in both the CMIP6 MMM and CESM2, especially over the tropical Pacific (Fig. 1c & 4b). The total diabatic heating increase in the tropical Pacific Ocean is ~ 0.6 k/day in the CMIP6 MMM, and ~ 1.0 k/day in the CESM2 during austral summer in the SSP585 scenario compared to the Historical experiment. A cooling zone (~ -0.5 K/day) is also present near subtropics of both hemispheres (near 10°N and 10°S, 120°W) in the SSP585 scenario compared to the Historical experiment.

The results from the CAM6 sensitivity experiments indicate that the SST change in the coupled SSP585 experiment is the dominant forcing that drives the SH austral summer SLP change in the subtropics and midlatitudes (Fig. 3). The SLP changes associated with the SPSA and SISA in the coupled CESM2 SSP585 – Historical experiment (Fig. 3b) are largely reproduced in the CAM SST experiment forced only by SSP585 SST (Fig. 3d). In contrast, direct radiative forcing by CO₂ increase appears to be a secondary influence on the SPSA and SISA SLP changes during DJF (Fig. 3e). For the SASA on the other hand, the increase in SLP along its poleward flank is best simulated in the CAM6 experiment forced by both direct CO₂ radiative forcing and prescribed SSP585 SST, indicating that both mechanisms play a role in the projected SASA changes (Fig. 3f).

The CAM6 experiment forced only by SSP585 SST captures the tropical heating change (CAM SST – CAM Control) seen in the CESM2 SSP585 coupled run (CESM2 SSP585 - Historical), indicating that the tropical diabatic heating change seen in the SSP585 CESM2 coupled run is primarily forced by the SST change rather than direct radiative forcing (Fig. 4b, c, & d). However, the diabatic heating sensitivity experiment (CAM Q) reveals that a remote response of the SH SA's to these tropical heating changes does not appear to be the dominant mechanism responsible for the SH subtropical SLP change during local summer (Fig. 3c & 4c).

The Phillips criterion metric for baroclinic eddy growth (C) decreases in the center, and poleward flank of SH SAs in the CESM2 coupled run (Fig. 5b). Fahad et al. (2020) found that a decrease in the conditions promoting the baroclinic eddy growth in the SH summer is primarily due to static stability changes rather than zonal wind shear changes. This result is consistent with the CAM6 numerical experiments. The CAM6 numerical experiments show that the prescribed SSP585 SST is the dominant driver that increases the local static stability in the SH subtropical and midlatitude regions and acts to decrease baroclinic eddy growth (Supplementary Fig. S1 & S2). Direct CO₂ radiative forcing similarly acts to decrease the conditions promoting baroclinic eddy growth but is a secondary forcing (Fig. 5e). Consistent with the SLP change, the baroclinic eddy growth change associated with SH SAs is well simulated in the CAM6 experiments when forced with both CO₂ concentration increase and SSP585 SST warming (Fig. 5).

Results from the CFMIP and AMIP experiments conducted using CESM2/CAM6 paint a consistent picture. The CFMIP Abrupt4XCO₂ – PiSST show SH subtropical SLP changes and tropical diabatic heating changes that are similar to those seen in CESM2 SP585 – Historical but intensified (Fig. 6). SST acts as a primary driver of these SH SA SLP and tropical diabatic heating changes, whereas the CO₂ increase acts as a secondary forcing during austral summer (Fig. 6c & d, Supplementary figure S3). It is

worth pointing out that the tropical diabatic heating change in the AMIP4k – AMIP is not as representative of the full (Abrupt 4xCO₂ -AMIP) diabatic heating change as seen in the other sets of experiments (e.g. CAM SST – CAM Control, CFMIP A4SST - piSST). This is due to the fact that the SST forcing in AMIP4k is increased uniformly by 4 Kelvin and therefore does not capture the influence of warming patterns on the atmospheric circulation changes. In contrast, the CMIP6 CFMIP and CAM6 numerical experiments have prescribed the full SST field from the future global warming scenario experiment.

3.2. Projected changes in the Southern Hemisphere Subtropical Anticyclone's during Austral Winter

During austral winter (JJA) the projected SSP585 (2050–2099) – Historical (1950–1999) SH subtropical SLP changes in the CMIP6 MMM and CESM2 coupled model runs are the most intense over the South Pacific and South Indian Oceans (Fig. 1b & 7b). One evident difference between these two is the SASA SLP doesn't change significantly in the CESM2 coupled model run, whereas the SASA SLP increases to some extent in the CMIP6 MMM. The pattern of vertically averaged (1000hPa – 200hPa) diabatic heating change in the SSP585 over the tropics is broadly similar in the CMIP6 MMM, and CESM2 coupled run, only more intensified in CESM2 (Fig. 1d & 8b). The vertically averaged JJA diabatic heating primarily increases over the tropical Pacific Ocean and decreases near the eastern tropical Pacific Ocean and eastern tropical Indian Ocean in future warmed climates. The total diabatic heating increase in the tropical Pacific Ocean is ~ 1.0 K/day in the CMIP6 MMM and ~ 1.3 K/day in the CESM2. The cooling over the eastern Pacific Ocean (near 10°N, 90°W) is ~ -1.0 K/day in the CMIP6 MMM ~ -1.3 K/day in the CESM2 in the SSP585 scenario compared to the Historical experiment.

The CAM6 sensitivity experiment forced with SSP585 SST simulates SLP changes (CAM SST – CAM Control) over the subtropical South Indian Ocean and South Western Pacific Ocean that are similar to those seen in the CESM2 (SSP585 – Historical) coupled run (Fig. 7b & 7d). There are some key differences between these two runs in the South Indian Ocean where maximum SLP changes are centered around Southern Africa in CAM SST – Control (Fig. 7d), while the maximum SLP changes are centered near Australia in SSP585 – Historical (Fig. 7b). The major differences between these runs occur in the Eastern South Pacific and South Atlantic where they show roughly the opposite response (Fig. 7b & 7d). The center of the SPSA increases in strength in the SSP585 CESM2, whereas it decreases in the CAM6 sensitivity experiment forced with only SSP585 SST (CAM SST – CAM Control). The direct CO₂ radiative forcing plays a secondary role in the SH subtropical SLP change associated with SAs in the austral winter similar to austral summer (Fig. 7e). There are no significant changes in the area of SH SAs due to only CO₂ increase. However, the intensity of SISA increases in the south-western flank, the SPSA intensifies (particularly in the western flank), and SASA intensifies in the far south-western flank, whereas the SASA weakens over the south-eastern flank (Fig. 7e). Interestingly, a combination of both CO₂ increases and SSP585 SST forcing simulates an SPSA SLP increase in austral winter similar to the CESM2 coupled model run (Fig. 7f & 7b).

Similar to austral summer, the tropical diabatic heating change in the austral winter is also largely forced by the tropical SST change (Fig. 8b, c, & d). One exception is that the cooling in the eastern tropical Pacific Ocean (near 10°N, 90°W) and tropical Atlantic Ocean, which is largely forced by the CO₂ increase (Fig. 8e). The CAM6 numerical experiment forced only by tropical diabatic heating change (CAM Q) produces SH subtropical SLP change similar to the CAM6 experiment forced by SSP585 SST (CAM SST) (Fig. 8c & 8d). This result points out that the remote tropical diabatic heating forcing plays a significant role in the SH subtropical SLP response during austral winter. We reiterate however that this tropical diabatic heating change is in turn largely forced by the tropical SST change in the future climate (Fig. 8b & 8d).

The Phillips criterion metric for baroclinic eddy growth (C) decreases in the center and poleward flank of SISA and SPSA, and increases in the center of SASA in the CESM2 coupled model simulations (Fig. 9b). These changes are primarily dominated by the local subtropical SST change and the tropical diabatic heating changes invoked by these tropical SST changes. SST changes act to change the baroclinic eddy growth through both static stability and zonal wind shear changes (Supplementary Fig. S4). While tropical diabatic heating acts as a remote forcing on baroclinic eddy growth primarily by influencing the zonal wind shear (Fig. 9 & supplementary Fig. S5). This result suggests that subtropical to high-latitude SST changes exert their influence on JJA SH SAs primarily through their influence on local static stability and hence baroclinic eddy growth (Fig. 9 & supplementary Fig. S4).

Results from the CFMIP and AMIP experiments broadly show a similar response of SH subtropical SLP change due to direct CO₂ radiative forcing and indirect SST warming (Fig. 10 & supplementary Fig S6). However, the opposite response of the SASA SLP change due to these two forcings is more robust in the CFMIP and AMIP experiments. The indirect SST warming forces the SASA SLP to decrease, whereas the direct CO₂ radiative forcing acts to increase the SASA SLP. This tug of war response between these two forcings is similar to the response of North Pacific SA change during boreal summer in a warming climate (Shaw and Voigt 2015). This is potentially due to a remote connection between Asian boreal summer (JJA) monsoon heating and the strength of the SASA during austral winter (JJA) (Richter et al. 2008). The direct CO₂ radiative forcing increases diabatic heating over the Asian monsoon and intensifies SASA SLP during JJA during JJA (austral winter) (Fig. 10d & 10h). In contrast, indirect SST warming decreases diabatic heating over the Asian monsoon and weakens the SASA due to indirect SST warming (Fig. 10c & 10g). The opposing responses of the Asian monsoon to these two forcings are consistent with the findings of Shaw and Voigt (2015).

Contrasting the CFMIP and AMIP experiments indicates the importance of the patterns of SST warming and the associated changes in tropical diabatic heating on the SH SLP change during austral winter. In the CFMIP experiments, the tropical diabatic heating increases similar to CESM2 coupled model runs (SSP585 - Historical) forced by SST warming (Fig. 10). However, in the AMIP experiments, the SST warming is uniformly 4 Kelvin added and has a weak tropical diabatic heating change (Supplementary Fig. S6). As a result, the SH SLP response due to only SST forcings is different in the austral winter

between CFMIP and AMIP experiments (Supplementary Fig. S6). For example, SLP decreases in strength associated with SASA in the CFMIP, whereas, there is an increase in SASA SLP in the AMIP due to SST warming (Fig. 10c & S6c). There is also a significant SPSA SLP increase in the CFMIP compared to AMIP in the forced SST run.

4. Conclusions And Discussion

This study aims to understand what forcings drive SH SAs change under global warming, focusing on both the austral summer and winter seasons. The influence of direct radiative forcing due to increased atmospheric CO₂ concentrations and indirect SST warming is analyzed separately through prescribed SST CAM6 sensitivity experiments. To study the remote influence of tropical diabatic heating changes in the future climate, we have performed a set of CAM6 added heating experiments forced with a tropical heating change similar to that within the couple CESM2 projection (SSP585 - Historical). As a complement to our CAM6 experiments, a set of CESM2 experiments performed as part of the CMIP6 CFMIP and AMIP runs have been analyzed.

The key findings are summarized as follows:

1. Indirect SST warming in the future climate (years 2050–2099) is the dominant forcing that drives SH subtropical SLP changes during both the austral summer and winter seasons. The local SST change in the SH subtropical region acts to increase the static stability that in turn decreases the baroclinic eddy growth and increases SLP. Exceptions to this are the future SPSA SLP change in austral summer and SASA SLP change in austral winter where the response to direct CO₂ radiative forcing also plays a key role as summarized below.
2. The direct radiative forcing from increasing CO₂ plays a secondary role in the SH subtropical SLP change in future climate during both seasons. A combination of direct radiative forcing due to CO₂ increase and indirect SST warming acts as forcing to increase the austral summer SLP associated with the SPSA. The role of direct CO₂ radiative forcing and indirect SST warming found in this study is consistent with Grise and Polvani (2014), where they show direct CO₂ radiative forcing acts as a secondary forcing to influence the SH jet streams in a warming climate.
3. The SLP associated with the austral winter (JJA) SASA responses opposite to the direct radiative CO₂ forcing and indirect SST warming. The SST warming acts to decrease the SLP over the SASA, whereas the CO₂ radiative forcing acts to increase the SASA SLP. This is due to the opposite response of the Asian monsoon diabatic heating and lower-level circulation to direct CO₂ radiative forcing and indirect SST warming during JJA. As a result, the SASA net SLP change (SSP585 - Historical) in the CESM2 coupled model runs, and CMIP6 MMM is very small compared to the other two SH subtropical oceans during austral winter (JJA). A similar tug of war phenomena between these two forcings is also reported for the boreal summer (JJA) North Pacific SA in previous studies (Shaw and Voigt 2015).

4. Tropical diabatic heating changes (especially over the tropical Pacific) play a role in driving SH subtropical SLP changes during austral winter (JJA). These tropical diabatic heating changes are primarily forced by tropical SST changes rather than direct CO₂ forcing. The tropical diabatic heating change acts as a remote forcing to change the SH subtropical baroclinic eddy growth by driving changes in the zonal wind shear in JJA. As a result, the SLP changes in the SH subtropics associated with SAs are amplified as a combined response to local SST and tropical diabatic heating forcings. This is also consistent with the previous studies that show climatologically tropical diabatic heating influences the austral winter SH SAs, midlatitude jet streams, and storm tracks (Song Yang and Webster 1990).

As mentioned in the Methods Section, as an alternative to the short seasonal runs the CAM SST, CAM CO₂, and CAM SSTCO₂ experiments have also been performed as continuous 30-year-long runs with fixed climatological prescribed SST for every year. The results from these runs are largely consistent with the short seasonal runs, except that the long CAM SST run shows an exceptional diabatic heating change in the projected future climate, especially when forced with CO₂ (Supplementary Figs. S7, S8, S9, & S10). These differences are due to a continuous land-atmosphere model interaction with variability in the land surface, whereas the ocean surface temperature (SST) is fixed to climatological values over the 30-year-long period creating land-sea thermal contrast that is stronger than the variable SST run (He and Soden, 2016) and our short seasonal runs. This phenomenon is a limitation of running long climate simulations with an active land component with fixed climatological SSTs. The prescribed SST and CO₂ experiments from CFMIP and AMIP projects cross-validate our short CAM6 numerical simulations forced with prescribed variable climatological SST and CO₂ forcings.

In conclusion, SAs are key elements of largescale atmospheric circulation in both hemispheres. SH SAs are projected to increase in the area and strength in future warmed climate during both seasons. The indirect SST warming in the future is the dominant mechanism that drives the baroclinic eddy growth reduction in the SH subtropics and leads to an increase of SLP associated with SH SAs. Tropical diabatic heating increases mostly over the tropical Pacific Ocean driven by tropical SST warming during both seasons. The tropical diabatic heating increase has a significant influence on SH SAs during austral winter. The direct radiative forcing due to CO₂ increase plays a secondary role to influence SH SAs during both seasons.

5. Declarations

Conflicts of interest/Competing interests: No conflict of interests.

Availability of data and material: CMIP6 data are available online (<https://esgf-node.llnl.gov/projects/cmip6/>). CESM2 CAM6 experiments data will be available upon request.

Code availability: Codes will be available upon request.

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Figures

Figure 1

The CMIP6 MMM change, SSP585 (2050-2099) – Historical (1950-1999), in (a) DJF SLP, (b) JJA SLP, (c) DJF diabatic heating, & (d) JJA diabatic heating (SLP unit: hPa, diabatic heating units: k/day). The 1020hPa Historical SLP isobar is contoured in black and the future projection SSP585 isobar is contoured in red. Contour plots are stippled when there is at least 75% agreement across the CMIP6

models on the sign of the SLP and diabatic heating change respectively. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Zonal mean heating structure of the added heating experiment (CAM Q) forcing file (units: k/day) for (a) DJF & (b) JJA. The CAM Q heating perturbation for the forcing file is taken from the CESM2 coupled run experiments (SSP585 – Historical).

DJF SLP (hPa)

Figure 3

CAM6 numerical experiments. DJF mean SLP (unit: hPa) climatological mean of (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO2 (CAM CO2) – CAM Control, and (f) Increased CO2 with prescribed SSP585 SST (CAM SSTCO2) – CAM Control. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

CAM6 numerical experiments. DJF mean diabatic heating (unit: k/day) climatological mean for (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO₂ (CAM CO₂) – CAM Control, and (f) Increased CO₂ with prescribed SSP585 SST (CAM SSTCO₂) – CAM Control. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

DJF Phillips Criterion metric C

Figure 5

CAM6 numerical experiments. DJF climatological mean of the Phillips Criterion metric C for (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO₂ (CAM CO₂) – CAM Control, and (f) Increased CO₂ with prescribed SSP585 SST (CAM SSTCO₂) – CAM Control. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from the 30-year sample. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Negative C values indicate a reduction in the conditions supporting baroclinic eddy growth, which in turn supports high SLP. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

CFMIP CESM2 DJF 30-year mean of SLP (unit: hPa) for (a) Pi Control (piSST), (b) Abrupt4XCO2 - piSST, (c) PiCO2 with Abrupt SST (A4SST) - piSST, (d) piSST with 4XCO2 (piSST4XCO2) - piSST, and diabatic heating SLP (unit: k/day) for (a) Pi Control (piSST), (b) Abrupt4XCO2 - piSST, (c) Pi with Abrupt SST (A4SST) - piSST, (d) piSST with 4XCO2 (piSST4XCO2) - piSST. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

JJA SLP (hPa)

Figure 7

CAM6 numerical experiments. JJA mean SLP (unit: hPa) climatological mean of (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO2 (CAM CO2) – CAM Control, and (f) Increased CO2 with prescribed SSP585 SST (CAM SSTCO2) – CAM Control. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

CAM6 numerical experiments. JJA mean diabatic heating (unit: k/day) climatological mean of (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO₂ (CAM CO₂) – CAM Control, and (f) Increased CO₂ with prescribed SSP585 SST (CAM SSTCO₂) – CAM Control. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

JJA Phillips Criterion metric C

Figure 9

CAM6 numerical experiments. JJA climatological mean of Phillips Criterion metric C of (a) CAM Control, (b) CESM2 SSP585 – Historical, (c) tropical added heating (CAM Q) – CAM Control, (d) prescribed SSP585 SST (CAM SST) – CAM Control, (e) Increased CO2 (CAM CO2) – CAM Control, and (f) Increased CO2 with prescribed SSP585 SST (CAM SSTCO2) – CAM Control. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 10

CFMIP CESM2 JJA 30 years mean of SLP (unit: hPa) for (a) Pi Control (piSST), (b) Abrupt4xCO2 - piSST, (c) Pi with Abrupt SST (A4SST) - piSST, (d) piSST with 4xCO2 (piSST4xCO2) - piSST, and diabatic heating SLP (unit: k/day) for (a) Pi Control (piSST), (b) Abrupt4xCO2 - piSST, (c) Pi with Abrupt SST (A4SST) - piSST, (d) piSST with 4xCO2 (piSST4xCO2) - piSST. Figures are stippled at 95% significance computed using a difference of means 2-sided t-test from 30 years sample. The 1023hPa Control SLP isobar is contoured in black and the future projection isobar is contoured in red. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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