

Interhemispheric Temperature Asymmetry over the Twentieth Century and in Future Projections

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ABSTRACT

The temperature contrast between the Northern and Southern Hemispheres—the interhemispheric temperature asymmetry (ITA)—is an emerging indicator of global climate change, potentially relevant to the Hadley circulation and tropical rainfall. The authors examine the ITA in historical observations and in phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5) simulations. The observed annual-mean ITA (north minus south) has varied within a 0.8°C range and features a significant positive trend since 1980. The CMIP multimodel ensembles simulate this trend, with a stronger and more realistic signal in CMIP5. Both ensembles project a continued increase in the ITA over the twenty-first century, well outside the twentieth-century range. The authors mainly attribute this increase to the uneven spatial impacts of greenhouse forcing, which result in amplified warming in the Arctic and northern landmasses. The CMIP5 specific-forcing simulations indicate that, before 1980, the greenhouse-forced ITA trend was primarily countered by anthropogenic aerosols. The authors also identify an abrupt decrease in the observed ITA in the late 1960s, which is generally not present in the CMIP simulations; it suggests that the observed drop was caused by internal variability. The difference in the strengths of the northern and southern Hadley cells covaries with the ITA in the CMIP5 simulations, in accordance with previous findings; the authors also find an association with the hemispheric asymmetry in tropical rainfall. These relationships imply a northward shift in tropical rainfall with increasing ITA in the twenty-first century, though this result is difficult to separate from the response to global-mean temperature change.

1. Introduction

The thermal contrast between the Northern and Southern Hemispheres is an emerging index of climate change. In paleoclimate, hemispheric cooling events may have

played important roles in abrupt climate changes during the last glacial period (Chiang 2009) and glacial–interglacial cycles (Toggweiler and Lea 2010). In the twentieth century, hemispheric differences in sea surface temperature (SST) have been shown to be important for tropical rainfall and the Hadley circulation and have been implicated in regional climate changes such as the onset of the Sahel drought in the late 1960s (Folland et al. 1986) and the decrease in the South Asian monsoon in recent decades (Chung and Ramanathan 2006; Bollasina et al. 2011). A review can be found in Chiang and Friedman (2012).

Observational and modeling studies over the past few decades have found different temperature responses to

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climatic forcings between the Northern Hemisphere (NH) and Southern Hemisphere (SH). Early modeling experiments showed that greenhouse gas (GHG) forcing resulted in greater NH warming because of the hemispheric asymmetry in land distribution and Southern Ocean vertical mixing (Stouffer et al. 1989; Manabe et al. 1991). On the other hand, sulfate aerosols are unevenly distributed in the NH, causing greater NH cooling (Kiehl and Briegleb 1993; Santer et al. 1996; Kaufmann and Stern 1997). Recently, Karoly and others studied simple indices, including the interhemispheric temperature contrast, for detecting and attributing global climate changes (Karoly and Braganza 2001; Braganza et al. 2004; Drost et al. 2012; Drost and Karoly 2012). These studies do not find robust significant trends in the twentieth century (unlike their other indices), which they suggest is because of compensating effects of GHGs and aerosols. However, they do find a significant increase in future projections from a subset of phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5).

Our main purpose in this study is to explore the interhemispheric temperature asymmetry (ITA) as an indicator of climate change. We continue from previous studies and report on the behavior of the ITA in updated observational datasets and multimodel simulations from CMIP3 and CMIP5. We investigate the causes of ITA changes by examining CMIP5 simulations of specific natural and anthropogenic forcings and by exploring the spatial pattern associated with the pronounced increasing ITA trend since the 1980s, which is projected to continue through the twenty-first century. Additionally, we return to the motivating climate impacts, discussing some of the ways that the ITA may explain historical and future responses of tropical circulation and precipitation. Finally, we briefly address the abrupt ITA shift in the late 1960s.

2. Indices and datasets

a. ITA index

We define the ITA index as the difference between the hemispheric-mean surface air temperatures, NH minus SH. The net hemispheric surface air temperature contrast has the benefit of consistency, as observational estimates can be constructed extending back to the late nineteenth century. Dynamically, there is a basis for comparing net hemispheric temperatures (as opposed to only SSTs) in that both extratropical land and ocean temperatures have been shown to influence tropical circulation and rainfall (Chiang and Bitz 2005). We compute anomalies (ΔITA) relative to 1891–1920, similar to Drost et al. (2012).

b. Datasets

We analyze hemispheric-average temperature anomalies from the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP; Hansen et al. 2010), which we also compare with those from the National Climatic Data Center (NCDC; Smith et al. 2008), and the Hadley Centre/Climatic Research Unit, version 4 (HadCRUT4; Morice et al. 2012). The datasets combine land surface air temperature with SST measurements to represent surface air temperature anomalies. The SST anomalies are used as they have been shown to closely approximate surface air temperature anomalies over large (ice free) areas, and there are more consistent SST measurements than of marine air temperature (Rayner et al. 2003). We also investigate hemispheric-average SST anomalies from the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed sea surface temperature dataset, version 3b (ERSST.v3b; Smith and Reynolds 2004).

We investigate available multimodel near-surface air temperature as output from CMIP3 (Meehl et al. 2007) and CMIP5 (Taylor et al. 2012). For the CMIP3, we use the twentieth-century climate simulation (20c3m) and the Special Report on Emissions Scenarios (SRES) A2 and B1; for the CMIP5, we use the historical simulation and representative concentration pathway (RCP) scenarios 4.5 and 8.5. The B1 and A2 are comparable in terms of net radiative forcing to the RCP4.5 and RCP8.5 scenarios, respectively (van Vuuren et al. 2011). We additionally examine CMIP5 historical simulations forced by specific agents: natural forcing, land-use change, well-mixed GHGs, and anthropogenic aerosols. Table 1 summarizes the CMIP3 models and Table 2 summarizes the CMIP5 models used. We show the ITA time series for CMIP3 and CMIP5 but focus most of our analysis on CMIP5. We do not apply any additional masking of model regions that are missing in the datasets, which we find has very little effect on the ITA index.

In section 5, we investigate precipitation pr and mean meridional mass streamfunction from most of the CMIP5 historical and RCP8.5 simulations, which are also shown in Table 2. The mean meridional mass streamfunction is calculated from meridional wind v [e.g., Eq. (6.9) in Hartmann 1994]. Streamfunction is shown in Sverdrups ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$); we use Sverdrups as a unit of mass transport (instead of the typical water volume transport).

All calculations use January–December annual-mean values unless noted otherwise. For trend analysis, we use ordinary least squares regression and Student's two-tailed t test for significance (Wilks 2006).

TABLE 1. List of CMIP3 models and respective scenarios used for the analysis. In this table, “X” denotes availability of the scenarios. One ensemble member from each scenario is used.

Model		Scenario		
Institute	Expansion (acronym)	20c3m	SRES A2	SRES B1
Bjerknes Centre for Climate Research (BCCR)	BCCR Bergen Climate Model, version 2.0 (BCCR-BCM2.0)	X	X	X
National Center for Atmospheric Research (NCAR)	Community Climate System Model, version 3.0 (CCSM3.0)	X	X	X
Canadian Centre for Climate Modelling and Analysis (CCCma)	Coupled Global Climate Model, version 3.1 (T47) [CGCM3.1(T47)]	X	X	X
CCCma	Coupled Global Climate Model, version 3.1 (T63) [CGCM3.1(T63)]	X		X
Centre National de Recherches Météorologiques (CNRM)	CNRM Coupled Global Climate Model, version 3 (CNRM-CM3)	X	X	X
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	CSIRO Mark, version 3.0 (CSIRO Mk3.0)	X	X	X
CSIRO	CSIRO Mark, version 3.5 (CSIRO Mk3.5)	X	X	X
Istituto Nazionale di Geofisica e Vulcanologia	ECHAM4 (ECHAM4)	X	X	
Max Planck Institute (MPI) for Meteorology	ECHAM5/MPI Ocean Model (ECHAM5/MPI-OM)	X	X	X
Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korean Meteorological Administration, and Model and Data Group	ECHAM and the global Hamburg Ocean Primitive Equation (ECHO-G)	X	X	X
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	GFDL Climate Model, version 2.0 (GFDL CM2.0)	X	X	X
NOAA GFDL	GFDL Climate Model, version 2.1 (GFDL CM2.1)	X	X	X
National Aeronautics and Space Administration (NASA) GISS	GISS, Atmosphere–Ocean Model (GISS-AOM)	X		X
NASA GISS	GISS Model E, coupled with the HYCOM ocean model (GISS-EH)	X		
NASA GISS	GISS Model E-R (GISS-ER)	X	X	X
Hadley Centre/Met Office	Hadley Centre Coupled Model, version 3 (HadCM3)	X	X	X
Hadley Centre/Met Office	Hadley Centre Global Environmental Model, version 1 (HadGEM1)	X	X	
Institute for Numerical Mathematics (INM)	INM Coupled Model, version 3.0 (INM-CM3.0)	X	X	X
L’Institut Pierre-Simon Laplace (IPSL)	IPSL Coupled Model, version 4 (IPSL-CM4)	X	X	X
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change	Model for Interdisciplinary Research on Climate, version 3.2 (high resolution) [MIROC3.2(hires)]	X		X
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change	Model for Interdisciplinary Research on Climate, version 3.2 (medium resolution) [MIROC3.2(medres)]	X	X	X
Meteorological Research Institute (MRI)	MRI Coupled Atmosphere–Ocean General Circulation Model, version 2.3.2 (MRI-CGCM2.3.2)	X	X	X
NCAR	Parallel Climate Model (PCM)	X	X	X

3. Results

a. Historical period: Observations and models

The GISTEMP hemispheric temperature anomalies are shown in Fig. 1a. Figure 1b plots ΔT_A for GISTEMP along with the other observational indices, which are almost identical. The GISTEMP ΔT_A

ranges between -0.39°C in 1972 and 0.41°C in 2010. We find no meaningful linear trend over the entire record. There is a noticeable drop in the late 1960s (0.25°C difference between 1950–67 and 1971–80), followed by a positive trend from 1981 to 2011 (0.17°C decade $^{-1}$; $p < 0.01$). There are also significant positive trends for each season: December–February,

TABLE 2. List of CMIP5 models and respective scenarios used for the analysis. The number of realizations investigated for each scenario is indicated for each scenario: H = historical, Nat = natural, GHG = well-mixed greenhouse gases, AA = anthropogenic aerosols, and LU = land-use change. All but the last column refer to near-surface air temperature tas. The last column indicates the models used in our analysis of meridional wind v and precipitation pr in the historical and RCP8.5 scenarios.

Institute	Model	Expansion (acronym)	tas					$v + pr$	
			H	RCP4.5	RCP8.5	Nat	GHG	AA	LU
CSIRO and Bureau of Meteorology, Australia	Australian Community Climate and Earth-System Simulator, version 1.0 (ACCESS1.0)		1	1	1	1			1
CSIRO and Bureau of Meteorology, Australia	Australian Community Climate and Earth-System Simulator, version 1.3 (ACCESS1.3)		1	1	1	1			1
Beijing Climate Center (BCC), China	BCC, Climate System Model, version 1.1 (BCC-CSM1.1)		1	1	1	1			1
Meteorological Administration	BNU—Earth System Model (BNU-ESM)		1	1	1	1			1
College of Global Change and Earth System Science, Beijing Normal University (BNU)	Second Generation Canadian Earth System Model (CanESM2)		1	1	1	5	5	5	5
CCCma	Community Climate System Model, version 4.0 (CCSM4.0)		1		1	1			1
NCAR	Community Earth System Model, version 1.0—Biogeochemistry (CESM1-BGC)		1	1	1	1			1
Community Earth System Model Contributors	Community Earth System Model, version 1.0—Community Atmosphere Model, version 5.0 (CESM1-CAM5)		1	1	1	1			1
Community Earth System Model Contributors	Community Earth System Model, version 1.0—Community Atmosphere Model, version 5.1—Finite Volume 2° [CESM1-CAM5.1 (FV2)]		1						
Community Earth System Model Contributors	Community Earth System Model, version 1.0—Whole Atmosphere Community Climate Model (CESM1-WACCM)		1	1	1	1			1
Community Earth System Model Contributors	CMCC Climate Model (CMCC-CM)		1	1	1	1			1
Euro-Mediterranean Centre on Climate Change (CMCC)	CNRM Coupled Global Climate Model, version 5 (CNRM-CM5)		1	1	1	1			1
CNRM/Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CSIRO Mark, version 3.6.0 (CSIRO Mk3.6.0)		1	1	1	1			1
CSIRO in collaboration with Queensland Climate Change Centre of Excellence	EC-EARTH		1	1	1	1			1
EC-Earth Consortium	Flexible Global Ocean—Atmosphere—Land System Model gridpoint, version 2.0 (FGOALS-g2.0)		1		1	1			1
State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences and Center for Earth System Science, Tsinghua University	Flexible Global Ocean—Atmosphere—Land System Model gridpoint, second spectral version (FGOALS-s2)		1	1	1	1			1
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	FIO Earth System Model (FIO-ESM)		1	1	1	1			1
The First Institute of Oceanography (FIO), State Oceanic Administration	GFDL Climate Model, version 3 (GFDL CM3)		1	1	1	3	3	3	3
NOAA GFDL	GFDL Earth System Model with GOLD ocean component (GFDL ESM2G)		1	1	1	1			1
NOAA GFDL			1	1	1	1			1

TABLE 2. (Continued)

Institute	Model	Expansion (acronym)	tas					v + pr	
			H	RCP4.5	RCP8.5	Nat	GHG	AA	LU
NOAA GFDL		GFDL Earth System Model with MOM4 ocean component (GFDL ESM2M)	1	1	1	1	1	1	1
NASA GISS		GISS Model E, coupled with the HYCOM ocean model (GISS-E2H)	1	1	1				
NASA GISS		GISS Model E, coupled with the Russell ocean model (GISS-E2-R)	1	1	1				1
National Institute of Meteorological Research/Korea Meteorological Administration		Hadley Centre Global Environmental Model, version 2, Atmosphere and Ocean (HadGEM2-AO)	1	1	1				1
Hadley Centre/Met Office		Hadley Centre Coupled Model, version 3 (HadCM3)	1						
Hadley Centre/Met Office		Hadley Centre Global Environmental Model, version 2, Carbon Cycle (HadGEM2-CC)	1	1	1				1
Hadley Centre/Met Office		Hadley Centre Global Environmental Model, version 2, Earth System (HadGEM2-ES)	1	1	1				1
INM		INM Coupled Model, version 4.0 (INM-CM4)	1	1	1				1
IPSL		IPSL Coupled Model, version 5, coupled with NEMO, low resolution (IPSL-CM5A-LR)	1	1	1				1
IPSL		IPSL Coupled Model, version 5, coupled with NEMO, mid resolution (IPSL-CM5A-MR)	1	1	1				1
IPSL		IPSL Coupled Model, version 5(B), coupled with NEMO, low resolution (IPSL-CM5B-LR)	1	1	1				1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies		Model for Interdisciplinary Research on Climate, version 5 (MIROC5)	1	1	1				1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies		Model for Interdisciplinary Research on Climate, Earth System Model (MIROC-ESM)	1	1	1				1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies		Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled (MIROC-ESM-CHEM)	1	1	1				1
MPI for Meteorology		MPI Earth System Model, low resolution (MPI-ESM-LR)	1	1	1				1
MPI for Meteorology		MPI Earth System Model, medium resolution (MPI-ESM-MR)	1	1	1				1
MPI for Meteorology		MPI Earth System Model, paleo (MPI-ESM-P)	1	1	1				1
MRI		MRI Coupled Atmosphere–Ocean General Circulation Model, version 3 (MRI-CGCM3)	1	1	1				1
Norwegian Climate Centre		Norwegian Earth System Model, version 1, medium resolution (NorESM1-M)	1	1	1	1	1	1	1

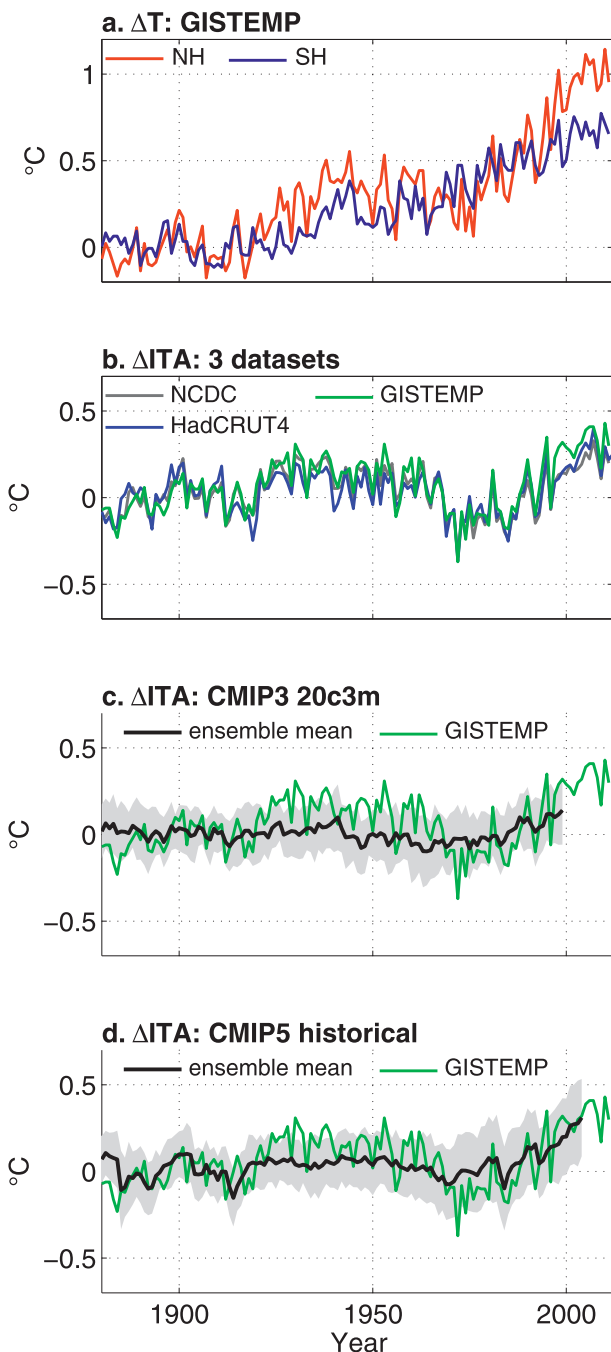


FIG. 1. (a) GISTEMP temperature anomalies for NH (red) and SH (blue). (b) GISTEMP (green), NCDC (gray), and HadCRUT4 (blue) Δ ITA. (c) CMIP3 20c3m Δ ITA. (d) CMIP5 historical Δ ITA. In (c),(d), the black solid line is the ensemble mean, the gray shading indicates $\pm$ one ensemble std dev, and the green line shows GISTEMP Δ ITA from (b).

March–May, June–August, and September–November ($p < 0.01$).

The CMIP3 and CMIP5 ensemble mean and standard deviation of Δ ITA are shown in Figs. 1c and 1d, respectively,

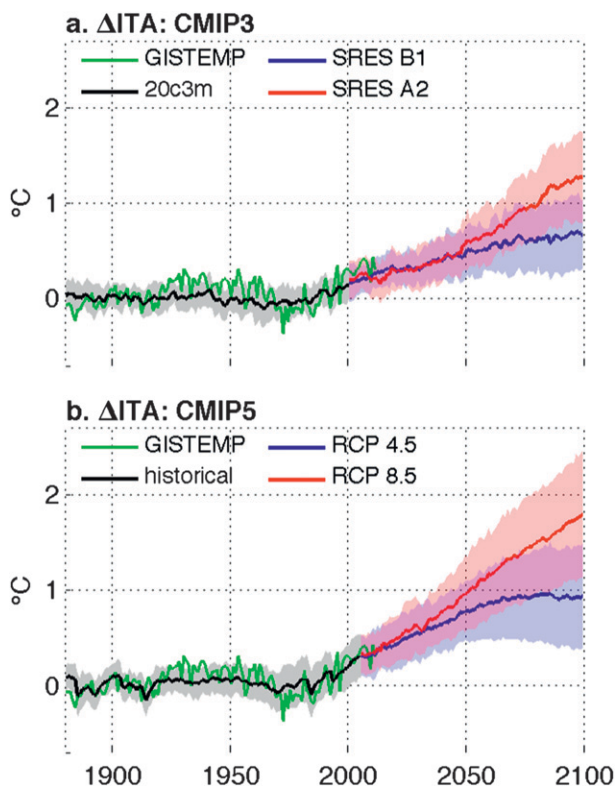


FIG. 2. Twentieth- and twenty-first-century projected Δ ITA. GISTEMP and twentieth-century scenarios are as in Fig. 1. (a) CMIP3 SRES B1 (blue) and SRES A2 (red). (b) CMIP5 RCP4.5 (blue) and RCP8.5 (red). Solid lines indicate the ensemble mean, and shading indicates $\pm$ one ensemble std dev.

along with the GISTEMP Δ ITA from Fig. 1b. The CMIP5 ensemble mean captures more of the observed multidecadal variability, with a correlation of 0.56 with the 5-yr running-mean GISTEMP Δ ITA (not shown) from 1880 to 1999, compared with 0.33 for CMIP3. Both the CMIP3 and CMIP5 ensemble means have positive trends since 1980; the CMIP5 trend is larger and more realistic [CMIP3: $0.08^{\circ}\text{C decade}^{-1}$ from 1981 to 1999; CMIP5: 0.10°C (0.13°C) decade^{-1} from 1981 to 1999 (1981 to 2004); GISTEMP: $0.19^{\circ}\text{C decade}^{-1}$ from 1981 to 1999 and from 1981 to 2004; $p < 0.01$ for all trends]; the CMIP5 trends are significant at all seasons ($p < 0.01$). Neither ensemble mean captures the drop in the late 1960s.

b. Future projections

Figure 2 shows the future projected Δ ITA. The striking feature of all future scenarios is the pronounced Δ ITA increase, exceeding well beyond the twentieth-century range. The future Δ ITA is apparently a continuation of the upward trend since 1980 (which we discuss in section 4). Within each CMIP, the scenario with the

larger radiative forcing has the larger increase. For the CMIP3, the mean 2080–99 ΔT_A ranges from 0.23° to 1.30°C (mean: 0.64°C) in the B1 scenario and from 0.61° to 1.87°C (mean: 1.15°C) in the A2 scenario. For the CMIP5, the 2080–99-mean ΔT_A ranges from -0.87° (FIO-ESM is the only model with a decrease) to 1.98°C (mean: 0.93°C) in RCP4.5 and from 0.01° to 2.96°C (mean: 1.63°C) in RCP8.5. The RCP8.5 ensemble-mean ΔT_A projection is highly linear: the trend of $0.17^\circ\text{C decade}^{-1}$ explains 99.5% of the variance from 2006 to 2099.

4. Attribution of the ITA trend

Figure 3 shows the ensemble-mean ΔT_A from the CMIP5 specific-forcing simulations compared with observations. Neither natural forcings (Fig. 3a) nor land-use change (Fig. 3b) affect long-term ΔT_A departures over the historical period. In Fig. 3a, we have marked major tropical volcanic eruptions following Fig. 9.5 in Hegerl et al. (2007), which are largely followed by short-lived ΔT_A decreases from the large-scale effects of stratospheric sulfate aerosols. Anthropogenic aerosols (Fig. 3c) and GHGs (Fig. 3d) force opposing ΔT_A trends: aerosols (GHGs) disproportionately cool (warm) the NH. The compensating effects of these forcings explain why ΔT_A remained relatively stable over much of the twentieth century, until around 1980. This is similar to global temperature, in which anthropogenic aerosols are believed to have masked GHGs over the middle of the twentieth century, though the global warming trend resumed slightly earlier (Hegerl et al. 2007). The ΔT_A from anthropogenic aerosols levels off around 1970, when clean air laws took effect in much of Europe and North America, similar to previous findings of tropical Atlantic interhemispheric SST asymmetry (Chang et al. 2011). In contrast, the GHG-only ΔT_A continues to increase along with GHG accumulation in the atmosphere. Summing ΔT_A from the anthropogenic aerosol and GHG-only simulations (Fig. 3e) results in a positive ΔT_A trend starting around 1980, which is similar to the observational record.

A direct comparison between the global-mean temperature anomaly ΔT_{glob} and ΔT_A further highlights the origins and emergence of the ΔT_A trend after 1980. Figure 4 shows ΔT_A plotted against ΔT_{glob} , for GISTEMP observations (Fig. 4a) and CMIP5 historical and specific-forcing simulations (Figs. 4b–f). For the observations (Fig. 4a), the years before and after 1980 feature two modes of behavior. Until 1980, the relationship between ΔT_A and ΔT_{glob} is relatively weak ($r = 0.29$); however, from 1981 to 2011, ΔT_A and ΔT_{glob} both feature positive anomalies and are much more strongly correlated ($r = 0.84$). Though the CMIP5

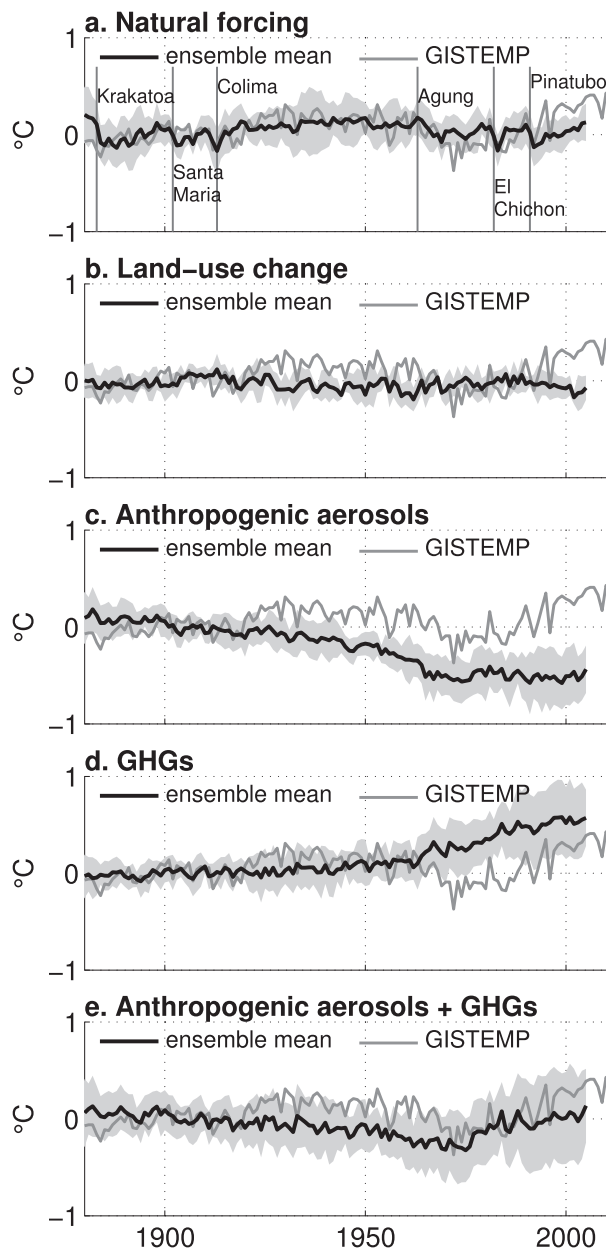


FIG. 3. CMIP5 twentieth-century specific-forcing ΔT_A . The black line shows the ensemble mean, and the gray line shows the observational ΔT_A as in Figs. 1 and 2. Shading indicates $\pm$ one ensemble std dev of the models indicated in Table 2. (a) Natural forcing, with major volcanic eruptions indicated: Krakatoa (1883), Santa Maria (1902), Colima (1913), Agung (1963), El Chichón (1982), and Pinatubo (1991). (b) Land-use change. (c) Anthropogenic aerosols. (d) GHGs. (e) Sum of anthropogenic aerosols and GHGs. The ensemble std dev for (e) is constructed by summing the ensemble std dev of (c),(d) in quadrature.

historical ΔT_A and ΔT_{glob} show much less overall scatter than the observations, most likely caused by ensemble averaging (Hegerl et al. 2007), they similarly feature positive anomalies and a much stronger correlation after

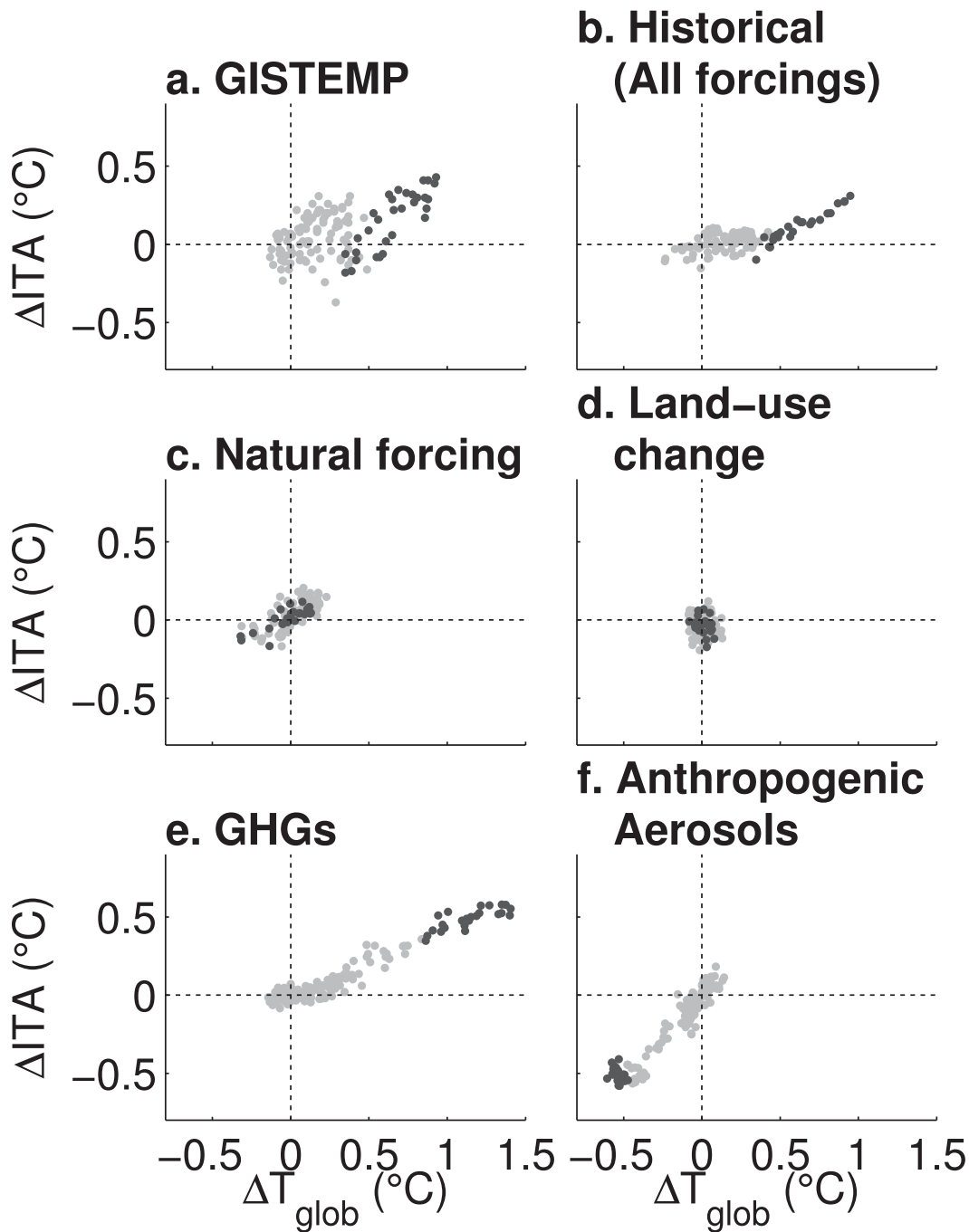


FIG. 4. ΔITA vs ΔT_{glob} for (a) observations and (b)–(f) CMIP5 ensemble means. Each point represents one year. (a) GISTEMP. (b) Historical (all forcings). (c) Natural forcing. (d) Land-use change. (e) GHGs. (f) Anthropogenic aerosols. Years before (since) 1981 are shaded light (dark) gray. GISTEMP is from 1880 to 2011, and CMIP5 is from 1880 to 2004.

1980 ($r = 0.46$ vs 0.96). Though ΔT_{glob} and ΔITA are positively correlated for the natural forcing (Fig. 4c) and anthropogenic aerosol (Fig. 4f) simulations, these forcings do not produce the strong positive anomalies of ΔITA and ΔT_{glob} after 1980. Of the specific-forcing

simulations, only GHGs (Fig. 4e) simulate the combination of post-1980 positive anomalies and positive correlation of ΔITA and ΔT_{glob} . (The positive slopes in both Figs. 4c and 4e likely reflect the disproportionate effects of global radiative forcing on the NH, which is

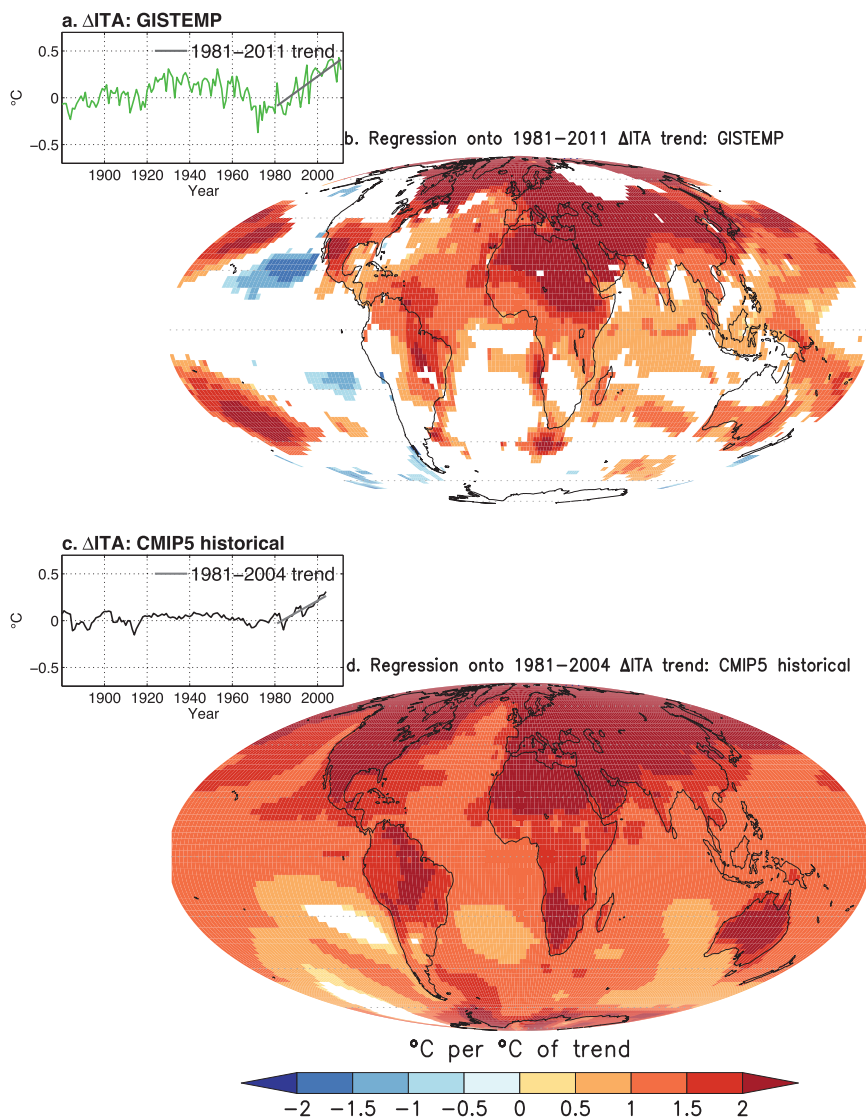


FIG. 5. (a) GISTEMP ΔT_{glob} with 1981–2011 linear trend indicated. (b) Regression of GISTEMP temperatures onto the 1981–2011 ΔT_{glob} trend ($^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ of ΔT_{glob} trend), plotted where $p < 0.05$. (c) CMIP5 historical ensemble-mean ΔT_{glob} with 1981–2004 linear trend indicated. (d) Regression of CMIP5 historical ensemble-mean surface temperatures onto the 1981–2004 ΔT_{glob} trend ($^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ of ΔT_{glob} trend), plotted where $p < 0.05$.

discussed below.) This comparison of the different forcing simulations thus suggests that GHGs have been dominant for ΔT_{glob} since 1980. Beforehand, the weak relationship between ΔT_{glob} and ΔT_{a} does not point to any specific forcing as the primary factor.

What spatial features account for the positive ΔT_{a} trend in the last few decades along with global-mean temperature? We focus on the period 1981–2011 in the observations, with the trend line delineated in Fig. 5a. Figure 5b shows the regression onto the 1981–2011 ΔT_{a} trend line from Fig. 5a. This pattern of pronounced

warming over the continents and NH extratropics has been discussed in previous analyses of global temperature change (Hansen et al. 2006; Trenberth et al. 2007), with eastern Pacific Ocean cooling described as part of the interdecadal Pacific oscillation (Wang et al. 2012). Figure 5c delineates the 1981–2004 trend in the CMIP5 historical ensemble mean, and Fig. 5d shows the regression slopes onto the trend line. The spatial pattern is similar to that of the observations (minus the eastern Pacific Ocean cooling), with more distinct NH extratropical and continental warming because of the ensemble

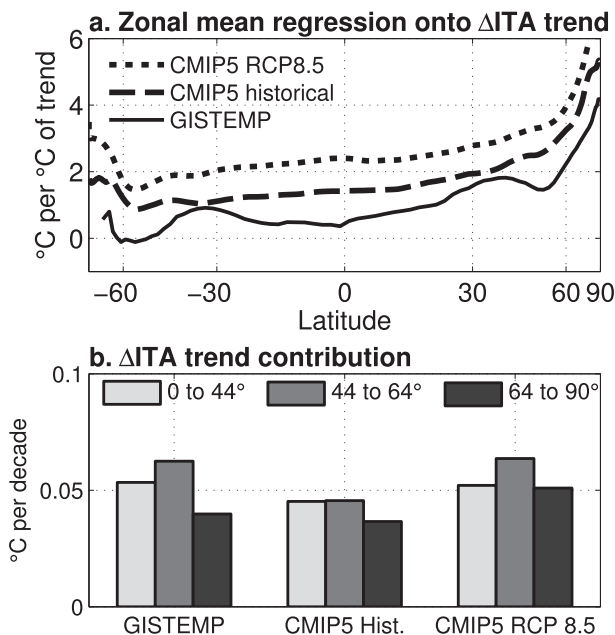


FIG. 6. (a) Regression of zonal-mean temperatures onto the Δ ITA linear trend ($^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ of Δ ITA trend) for GISTEMP (1981–2011), CMIP5 historical ensemble mean (1981–2004), and CMIP5 RCP8.5 ensemble mean (2006–99). The x axis is linear in sine of latitude so that spacing corresponds to surface area. Positive (negative) latitude values indicate degrees north (south). (b) Contribution to Δ ITA trend by latitude zone ($^{\circ}\text{C decade}^{-1}$) for GISTEMP (1981–2011), CMIP5 historical ensemble mean (1981–2004), and RCP8.5 ensemble mean (2006–09).

averaging that filters out each model's natural variability (Hegerl et al. 2007). The observational and model slopes are strongly spatially correlated ($r = 0.67$). [The correlation with the 1981–2004 CMIP5 ensemble-mean trend is higher for the GISTEMP trend through 2011 than through 2004 ($r = 0.55$), which suggests that the observational trend signal has become more significant over the last decade.] The 1981–2011 GISTEMP regression slopes are also highly correlated with the spatial regression slopes of Δ ITA in future simulations ($r = 0.64$ for the RCP8.5 2005–99 ensemble mean).

The regression slopes of zonal-mean observational, CMIP5 historical, and RCP8.5 temperature anomalies, shown in Fig. 6a, have very similar latitudinal gradients, though the mean warming differs among them. This hemispherically asymmetric zonal-mean pattern, also similar to regressions onto global temperature trends (Xu and Ramanathan 2012), has long been studied as a robust feature of the transient climate change response (Stouffer et al. 1989; Manabe et al. 1991). The prominent Arctic amplification has been attributed to feedbacks from melting snow and sea ice, water vapor, increasing clouds, and lapse rate changes (Bekryaev et al. 2010;

Serreze and Barry 2011; Hwang et al. 2011). Outside the Arctic, the zonal-mean pattern has largely been attributed to hemispheric differences in land and ocean, resulting in less NH evaporation and heat uptake (Hegerl et al. 2007), as the land–ocean warming contrast has been shown to be a robust feature of the global warming response (Lambert and Chiang 2007). However, we find that there has also been an increase in interhemispheric SST asymmetry over the last few decades [$0.09^{\circ}\text{C decade}^{-1}$ ($p < 0.01$), 1981–2011; ERSST.v3b], which contributes to the Δ ITA increase. The recent interhemispheric SST asymmetry increase may have more than one cause. First, land and ocean temperatures are correlated because of land–sea advection (Thompson et al. 2009). Additionally, the warming minimum around 60°S has been attributed to heat uptake in the Southern Ocean, which mixes heat downward (Xie et al. 2010). Ocean dynamical variability may also play a role, which we discuss (for a different time period) in section 6.

Figure 6b shows the relative contribution of three latitude zones to the Δ ITA trends. The Δ ITA trend contribution is calculated as the interhemispheric temperature asymmetry of the specific latitude band, multiplied by its surface area fraction. These zones (0°–44°, 44°–64°, and 64°–90°) cover about 70%, 20%, and 10% of the globe, respectively. To first order, these three latitude bands with very different areas have similar contributions to the Δ ITA trend, which illustrates that the high latitudes are proportionally more important. However, it also puts the large Arctic warming in Fig. 6a into perspective: with its limited area, the Arctic amplification alone does not explain the majority of the Δ ITA increase.

5. Impacts on tropical circulation and precipitation

Previous studies have found that increasing ITA causes weakening of the NH Hadley cell, strengthening of the SH Hadley cell, and a northward shift of tropical precipitation (Yoshimori and Broccoli 2008; Kang et al. 2009; Frierson and Hwang 2012). Our analysis of the CMIP5 ensemble-mean future projections largely agrees with these prior findings.

First, we consider the Hadley circulation changes. Figures 7a and 7b show the time series of NH and SH maximum meridional overturning mass streamfunction in the historical and RCP8.5 simulations. Comparing these with Fig. 2, the increase of Δ ITA in the twenty-first century is accompanied by a significant weakening of the NH Hadley cell and a small strengthening of the SH Hadley cell. Hemispheric differences can be explained by the combination of the increased ITA and the overall

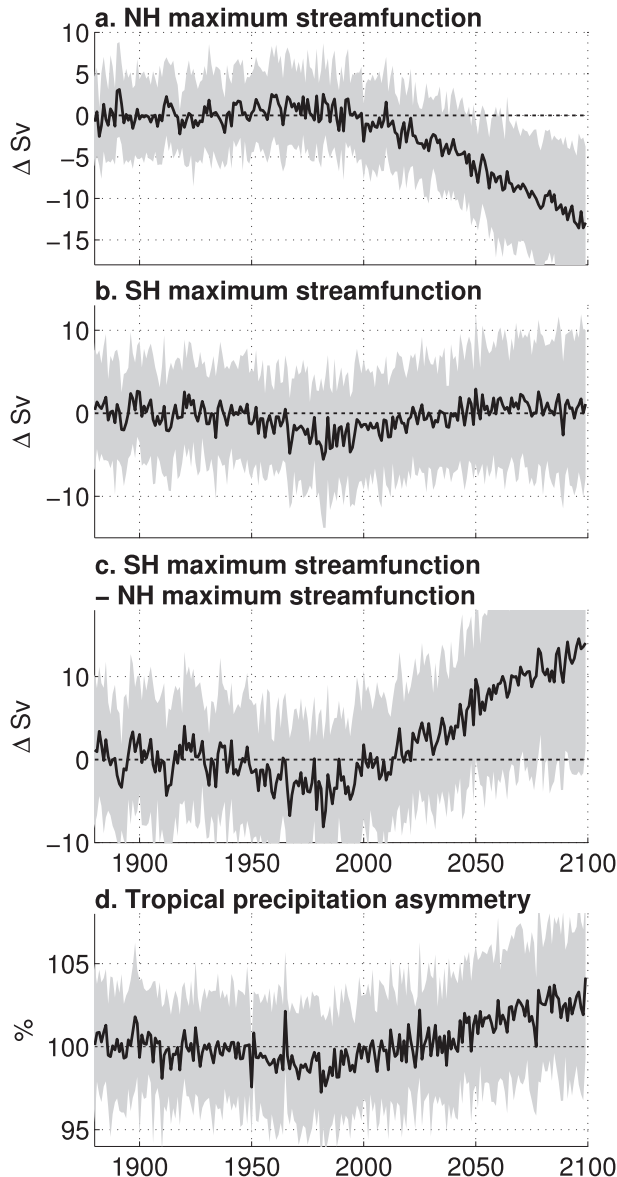


FIG. 7. Mean meridional overturning mass streamfunction maximum anomalies for (a) NH, (b) SH, and (c) SH minus NH. (d) Tropical precipitation hemispheric asymmetry index $[(0^{\circ}\text{--}20^{\circ}\text{N}) - (0^{\circ}\text{--}20^{\circ}\text{S})]/(20^{\circ}\text{S}\text{--}20^{\circ}\text{N})$ as a percentage of the 1891–1920 mean. The black line shows the ensemble mean and shading indicates $\pm$ one ensemble std dev of CMIP5 historical (1880–2004) and RCP8.5 (2005–99) simulations indicated in Table 2.

weakening of tropical circulation with global warming (Zhang and Song 2006; Vecchi and Soden 2007). In the NH, both the increasing ITA and global warming weaken the circulation after around 1980, whereas in the SH the increasing ITA compensates for global warming and results in a small strengthening trend during this period. Figure 7c, the SH minus the NH maximum streamfunction (Fig. 7a minus Fig. 7b), removes much of the tropical-mean signal and thus more strongly shows

the influence of the ITA on the Hadley circulation asymmetry.

Recent studies have also suggested that strengthening of the SH Hadley cell and weakening of the NH Hadley cell should lead to a northward shift of the tropical rainbands in the twenty-first century (Kang et al. 2009; Frierson and Hwang 2012). However, this signal is difficult to separate from a precipitation intensification from global warming (Held and Soden 2006), which would disproportionately increase NH tropical rainfall since there is more tropical NH rainfall in the present-day climate (Chou et al. 2007). We remove part of this effect by normalizing the precipitation changes by the tropical-mean amount. We define the precipitation asymmetry index as precipitation from the equator to 20°N minus precipitation from the equator to 20°S , normalized by tropical-mean precipitation ($20^{\circ}\text{S}\text{--}20^{\circ}\text{N}$). Even with this normalization, however, defining a precipitation index to represent the northward shift is challenging, as different GCMs project different kinds of spatial patterns in precipitation changes that affect our tropical precipitation asymmetry index. For example, some GCMs project a uniform northward shift of the present-day precipitation pattern, whereas some project a tropical precipitation shift toward the north without shifting the location of maximum precipitation.

Figure 7d shows the change in this tropical precipitation asymmetry index. Qualitatively, it resembles the behavior of the historical and projected ΔITA in Fig. 2: a relative lack of trend over the first half of the twentieth century and a northward trend starting around 1980 and extending into the future. However, we note that the positive trend in the precipitation asymmetry after 1980 appears to be smaller than expected from increasing ΔITA alone. The northward shift does not become significant (compared with the twentieth-century ensemble standard deviation) until 2040, whereas ΔITA is anomalously positive from the beginning of the twenty-first century. We have also noticed that some GCMs with a smaller increase of ΔITA actually project a relative decrease in the SH minus NH Hadley circulation difference and a southward shift of tropical precipitation (which can be inferred from the wide ensemble standard deviation shading in Figs. 7c,d).

Though the association in the CMIP5 models is promising, there are additional caveats to directly linking the ITA with the shifts in tropical precipitation. First, the marine ITCZ is more strictly dynamically tied to the tropical SST asymmetry (Lindzen and Nigam 1987), so latitudes closer to the equator may have a larger effect on tropical rainfall for a given change in ΔITA . Precipitation variability in CMIP5 models has recently been attributed to SST change disparities among models

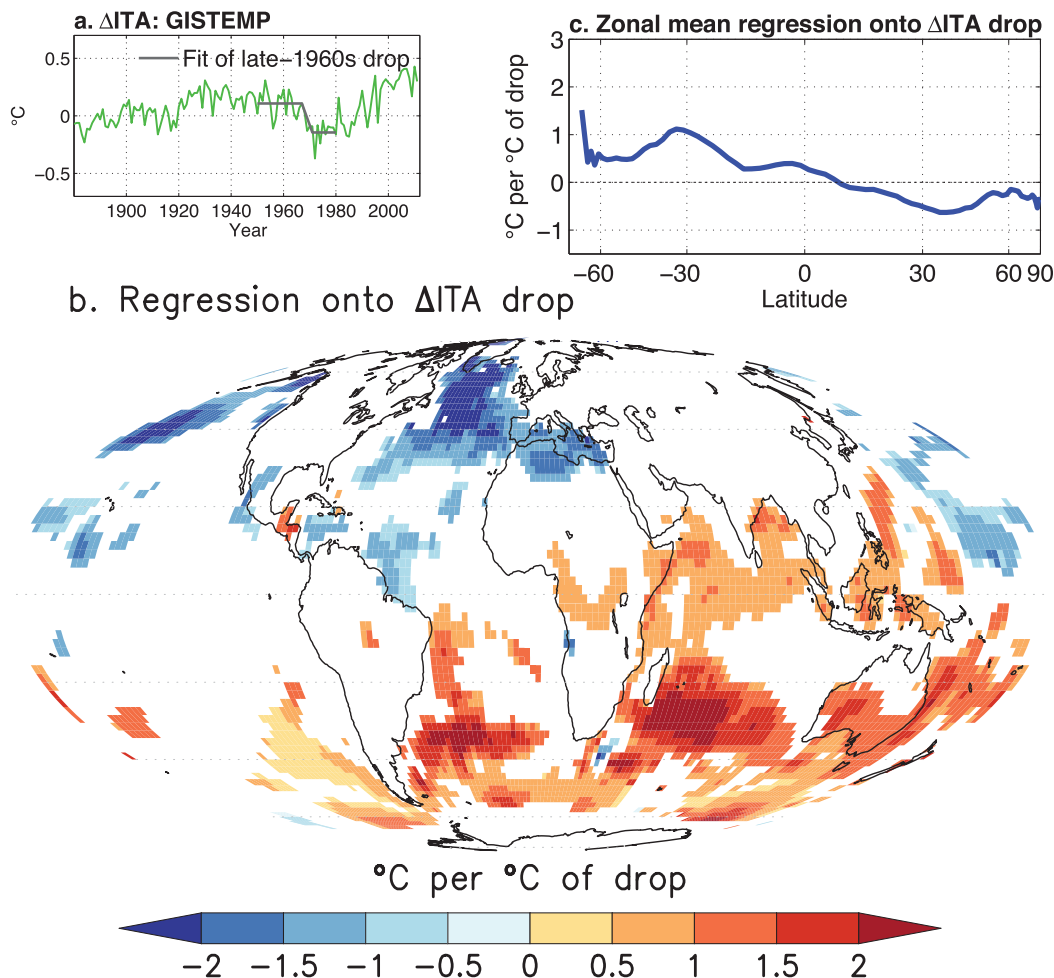


FIG. 8. (a) GISTEMP Δ ITA with a linear fit of the late-1960s Δ ITA drop constructed by linearly interpolating between the means of 1950–67 and 1971–80, similar to the interhemispheric SST difference fit in Thompson et al. (2010). (b) Regression of GISTEMP temperatures onto the linear fit of late-1960s Δ ITA drop ($^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ of Δ ITA drop), plotted where $p < 0.05$. (c) Regression of GISTEMP zonal-mean temperatures onto the linear fit of late-1960s drop ($^{\circ}\text{C } ^{\circ}\text{C}^{-1}$ of Δ ITA drop). The x axis in (c) is linear in sine of latitude so that spacing corresponds to surface area. Positive (negative) latitude values indicate degrees north (south).

(Ma and Xie 2013). For example, SST warming at the equator (which may be caused by, e.g., a weaker Walker circulation) does not contribute to the ITA index; however, it is expected to cause a southward ITCZ shift (Vecchi et al. 2006; Seager and Naik 2012). Furthermore, from an energy flux perspective, an increasing ITA may not necessarily lead to southward cross-equatorial atmospheric heat transport and a northward ITCZ shift; the ITCZ can actually shift away from the warmed hemisphere when enhanced GHG warming leads to increased outgoing radiation (Frierson and Hwang 2012; Zelinka and Hartmann 2012). Thus, we caution against applying a simplistic association between future ITA changes and tropical rainfall asymmetry. Another hemispherically asymmetric process we have yet to

consider for both circulation and rainfall is Antarctic stratospheric ozone depletion. Twenty-first-century ozone recovery is projected to strengthen the SH summer Hadley cell and contract the subtropical dry zones, opposing greenhouse forcing (Polvani et al. 2011).

6. Late-1960s ITA shift

Finally, we consider the abrupt ITA shift in the late 1960s. The rapid time scale and the spatial pattern associated with the late-1960s ITA drop suggest different processes than those contributing to the ITA increase of the last few decades. Figure 8a shows the GISTEMP Δ ITA, with a linear fit connecting the means of 1950–67 and 1971–80. Figure 8b shows the regression slopes of

GISTEMP anomalies onto this linear fit of the drop. The slopes are characterized by extratropical SST cooling in the NH and warming in the SH, with the largest magnitude slopes corresponding to cooling in the North Atlantic. Additionally, there is warming in the southern Atlantic and Indian Oceans and also cooling in the North Pacific. Comparison with Fig. 5b shows that this spatial pattern is quite distinct from that of the increasing ITA trend since 1980, which is driven by hemispherically asymmetric warming in the Arctic and northern landmasses. Figure 8c, the zonal-mean regression slopes onto the linear fit of the drop, shows values of opposite sign and similar magnitude that are strongest in the midlatitudes of both hemispheres. This zonal-mean midlatitude dipole can be contrasted with the zonal-mean trends in Fig. 6a, which are positive in both hemispheres and feature strong Arctic amplification.

What caused the abrupt shift? Baines and Folland (2007) speculate that either global ocean meridional overturning circulation (MOC) or an increase in anthropogenic sulfate aerosols was responsible. Investigating unsmoothed monthly data, Thompson et al. (2010) argue that the rapid time scale of the interhemispheric SST shift points to an abrupt change in ocean circulation centered in the dynamically active North Atlantic. They suggest that the source was a rapid freshening in the northern North Atlantic, previously identified as the “Great Salinity Anomaly” from the late 1960s through early 1970s (Zhang and Vallis 2006). Dima and Lohmann (2010) describe an interhemispheric mode of SST variability with a large amplitude in the North Atlantic that underwent a shift around 1970. They ascribe this mode to the Atlantic MOC response to freshwater forcing, triggered by the great salinity anomaly. A recent attribution study of North Atlantic SSTs also points to internal ocean variability as primarily responsible for the late-1960s cooling event that contributed to the interhemispheric SST difference (Terray 2012).

As shown in Figs. 1c and 1d, the CMIP historical ensemble means do not simulate the observational ITA shift in the late 1960s, suggesting that the observed drop is caused by internal variability. However, some individual CMIP5 realizations do produce a realistic ITA shift during this period (not shown), which leaves open some questions about the extent to which it was externally forced. The impacts of the late-1960s ITA shift on tropical circulation and precipitation also remain a topic of investigation. Concurrent changes have been identified in several atmospheric circulation indices in the late 1960s, correlated with the interhemispheric SST shift (Baines and Folland 2007; Mantsis and Clement 2009). There was also a coordinated weakening of the West African and Asian monsoons around this time, which

has been linked the decrease in North Atlantic SST (Liu and Chiang 2012).

7. Conclusions

In this study, we have presented the interhemispheric temperature asymmetry as an index of climate change. In addition to being conceptually simple and available from observations prior to the satellite record, we argue that it can provide insight into climate change forcings and also point to changes in tropical circulation and precipitation.

Our major findings about the ITA are as follows: The observed ITA did not exhibit a significant trend over most of the twentieth century; however, it began a pronounced upward trend (north warming faster than south) around 1980, which the CMIP5 simulations reproduce more strongly. Our analysis of the CMIP5 specific-forcing simulations suggests that the effects of GHGs and aerosols on the ITA largely compensated for each other until around 1980, when steadily accumulating GHGs overtook aerosols that had leveled off from pollution regulations. The upward trend continues in the twenty-first-century projection simulations we examined. Spatial regressions show that the positive ITA trend of the last few decades is primarily driven by disproportionate warming in the Arctic and NH landmasses, which was previously shown to be a hemispherically asymmetric response pattern to global climate forcing.

The CMIP5 simulations indicate that the atmospheric circulation will respond to the increased ITA via a strengthening of the southern Hadley cell and a weakening of the northern Hadley cell, a result that is not predicted from the dynamical response to global warming alone. Our analysis suggests that this will be accompanied by a northward shift in tropical precipitation, though there are difficulties distinguishing this response from other components of the hydrological response to global warming. Another caveat is that tropical circulation and rainfall may also have hemispherically asymmetric responses to projected ozone recovery.

We ended with a short discussion of the late-1960s abrupt ITA decrease. Unlike the response to GHGs, which is characterized by hemispherically asymmetric warming with polar amplification, the late-1960s ITA shift is characterized by a midlatitude SST dipole. We presented evidence that the abrupt decrease was driven by a sudden change in the ocean meridional overturning circulation centered in the North Atlantic; though intriguing, the mechanisms remain to be worked out. Future steps in pursuing this problem include investigating the high-resolution ITA time series to follow the propagation of temperature anomalies and studying the

behavior of individual models that do simulate a realistic ITA shift. The impacts of the late-1960s abrupt ITA shift on the Hadley cell and tropical rainfall will also be a focus of future studies.

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Data sources: GISTEMP hemispheric and zonal-mean averages (<http://data.giss.nasa.gov/gistemp/>) and gridded data (<http://www.esrl.noaa.gov/psd/data/gridded/data.gisstemp.html>; 1200-km smoothing); NCDC hemispheric averages (<http://www.ncdc.noaa.gov/cmb-faq/anomalies.php>); HadCRUT4 hemispheric averages (<http://www.metoffice.gov.uk/hadobs/hadcrut4/>; median "best estimate" realization); CMIP3 output (<https://esg.llnl.gov:8443/index.jsp>); and CMIP5 output (<http://pcmdi3.llnl.gov/esgcat/home.htm>) are all available online.

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