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CMIP5 Simulations of Low-Level Tropospheric Temperature and Moisture over the Tropical Americas

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ABSTRACT

Global warming has been linked to systematic changes in North and South America's climates and may severely impact the North American monsoon system (NAMS) and South American monsoon system (SAMS). This study examines interannual-to-decadal variations and changes in the low-troposphere (850 hPa) temperature (T850) and specific humidity (Q850) and relationships with daily precipitation over the tropical Americas using the NCEP–NCAR reanalysis, the Climate Forecast System Reanalysis (CFSR), and phase 5 of the Coupled Model Intercomparison Project (CMIP5) simulations for two scenarios: “historic” and high-emission representative concentration pathway 8.5 (RCP8.5). Trends in the magnitude and area of the 85th percentiles were distinctly examined over North America (NA) and South America (SA) during the peak of the respective monsoon season. The historic simulations (1951–2005) and the two reanalyses agree well and indicate that significant warming has occurred over tropical SA with a remarkable increase in the area and magnitude of the 85th percentile in the last decade (1996–2005). The RCP8.5 CMIP5 ensemble mean projects an increase in the T850 85th percentile of about 2.5°C (2.8°C) by 2050 and 4.8°C (5.5°C) over SA (NA) by 2095 relative to 1955. The area of SA (NA) with T850 $\geq$ the 85th percentile is projected to increase from $\sim$ 10% (15%) in 1955 to $\sim$ 58% ($\sim$ 33%) by 2050 and $\sim$ 80% ($\sim$ 50%) by 2095. The respective increase in the 85th percentile of Q850 is about 3 g kg^{−1} over SAMS and NAMS by 2095. CMIP5 models project variable changes in daily precipitation over the tropical Americas. The most consistent is increased rainfall in the intertropical convergence zone in December–February (DJF) and June–August (JJA) and decreased precipitation over NAMS in JJA.

1. Introduction

The presence of a monsoonal type of circulation involving intense convective activity and heavy precipitation is the dominant climatic feature in the tropical Americas during the respective summer seasons. The North American monsoon system (NAMS) and the South American monsoon system (SAMS) are often interpreted as the two extremes of the seasonal cycle of heat, moisture transport, and precipitation over the Americas (Vera et al. 2006). The SAMS and NAMS seasonal cycles are essentially driven by the differential heating between the continent

and ocean. In the premonsoon season, the incoming solar radiation increases the diabatic heating over the tropical continent and land–ocean contrasts initiate the monsoonal circulations. The differential heating strengthens the cross-equatorial moisture transport by the trade winds toward the continent. Thermodynamic instability increases as the onset of the rainy season approaches and remains large throughout the wet season (Fu et al. 1999; Fu and Li 2004; Fisch et al. 2004). Convective activity intensifies on broad ranges of spatial and temporal scales to redistribute the excess of moist static energy accumulated near the surface (Adams and Comrie 1997; Rickenbach et al. 2011). Land–atmosphere processes control evapotranspiration and play a significant role on the onset and maintenance of the SAMS (Fu and Li 2004) and NAMS (Gutzler and Preston 1997; Gutzler 2000).

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TABLE 1. List of CMIP5 models used in this study. All 11 models were used for analyses of the historic experiment.

	Modeling center (or group)	Institute ID	Model name	Model expansion
1	Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2*	Second Generation Canadian Earth System Model
2	Centre National de Recherches Meteorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5	Centre National de Recherches Meteorologiques Coupled Global Climate Model, version 5
3	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6.0
4	National Oceanic and Atmospheric Administration/ Geophysical Fluid Dynamics Laboratory	NOAA/GFDL	GFDL-ESM2M*	Geophysical Fluid Dynamics Laboratory Earth System Model with MOM4 ocean component (ESM2M)
5	Institute for Numerical Mathematics	INM	INM-CM4	L'Institut Pierre-Simon Laplace Coupled Model, version 4
6	L'Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution
7	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h	Model for Interdisciplinary Research on Climate, version 4 (high resolution)
8	Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR*	Max Planck Institute Earth System Model, low resolution
9	Meteorological Research Institute	MRI	MRI-CGCM3*	Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3
10	Norwegian Climate Centre	NCC	NorESM1-M*	Norwegian Earth System Model, version 1 (medium resolution)
11	Met Office Hadley Centre	MOHC	HadCM3	Hadley Centre Coupled Model, version 3

* Model analyzed for the RCP8.5 scenario.

NAMS extends from the intertropical zone of the eastern Pacific Ocean to the Bermuda high and from Central America to Canada (Ropelewski et al. 2005; Mechoso et al. 2005). Rainfall associated with NAMS accounts for about 70% of the annual total precipitation over a large area centered in northwest Mexico (e.g., Douglas et al. 1993). In the United States, NAMS directly influences precipitation regimes in New Mexico and Arizona, where more than 40% and 25% of annual precipitation, respectively, is received during summer (Douglas et al. 1993; Higgins et al. 1997; Adams and Comrie 1997). There are also lowland areas associated with NAMS: the lower Colorado River valley and neighboring low desert areas. These regions play a significant role in the formation of the thermal low, which is an important feature of NAMS (Adams and Comrie 1997). In the present climate, the onset of NAMS occurs between May and June, when precipitation intensifies along the western slopes of the Sierra Madre Occidental (Douglas et al. 1993; Adams and Comrie 1997). NAMS is fully developed from July to early September and its

demise occurs during late September and early October (e.g., Vera et al. 2006). Nevertheless, NAMS exhibit regional characteristics. The rainy season in Central America and southern Mexico shows a bimodal distribution with maxima during June and September–October and a relative minimum during July and August, known as the midsummer drought (MSD) (Magaña et al. 1999).

Convection migrates from Central America into South America by September. The onset of the rainy season over the Amazon is preceded by an increase in the frequency of the northerly cross-equatorial flow over South America that increases moisture in the boundary layer (Marengo et al. 2001, 2010; Wang and Fu 2002). The onset of the wet season in central and southeastern Brazil in the present climate typically occurs between September and November (Silva and Carvalho 2007; Gan et al. 2004; Raia and Cavalcanti 2008). SAMS peaks from December through February when the main convective activity is centered over central Brazil and linked to a northwest–southeast-oriented band of cloudiness and precipitation that often extends over western subtropical

Atlantic and is known as the South Atlantic convergence zone (Kodama 1992; Carvalho et al. 2002). SAMS demise over central–eastern Brazil typically occurs from March to mid-April (e.g., Silva and Carvalho 2007; Marengo et al. 2010).

The global mean concentration of carbon dioxide and associated atmospheric radiative forcing has dramatically increased in the last decades (Forster et al. 2007). Changes in atmospheric forcing modify the distribution of the atmospheric heating with consequences to the hydrological cycle. The atmospheric moisture content increases in response to global warming following the Clausius–Clapeyron relationship, but the rate of precipitation increase is slower as predicted by climate models (Allen and Ingram 2002; Richter and Xie 2008; Cherchi et al. 2011). Model results and future scenarios of climate change indicate that rainfall tends to increase in convergence zones with large climatological precipitation and to decrease in regions with subsidence (Held and Soden 2006; Chou and Neelin 2004; Chou et al. 2009).

Cherchi et al. (2011), for instance, performed a set of experiments with a state-of-the-art coupled general circulation model forced with increased atmospheric CO₂ concentration (2, 4, and 16 times the present-day mean value) and compared with a control experiment to evaluate the effect of increased CO₂ on the monsoons. They concluded that all monsoon areas experience an enormous increase of vertically integrated specific humidity when the atmospheric carbon dioxide concentration is increased in the climate simulations, in consonance with the Clausius–Clapeyron relationship. However, the precipitation rate increase is smaller than the moisture content rise (Allen and Ingram 2002). The dominant player in the precipitation changes obtained by comparing the sensitivity experiments with a control simulation is the so-called q term (thermodynamic component): that is, the term that depends on the water vapor content change. Vertical velocity changes, horizontal moisture advection, and the evaporation play different roles depending on the region of the monsoon (Cherchi et al. 2011). The authors found that NAMS and SAMS experience a precipitation increase in the sensitivity experiments relative to the control mostly driven by the intensification of the upward motion. Moreover, they showed that, over South America, the moisture transport from the Atlantic Ocean is increased in all CO₂ experiments compared to the control.

Using the climate change experiments generated for the Fourth Assessment of the Intergovernmental Panel on Climate Change, Held and Soden (2006) examined some aspects of the changes in the hydrological cycle that were robust across the models. They show that many important aspects of the hydrological response to

TABLE 2. The 85th percentiles (1951–2005) of the historic runs for SA and NA and for NCEP–NCAR and CFSR reanalyses. The 85th percentile for CFSR was calculated from 1979 to 2005. Missing values indicate that the quantity is not available for the model.

Model name	South America (DJF)		North America (JJA)	
	T850 (°C)	Q850 (g kg ^{−1})	T850 (°C)	Q850 (g kg ^{−1})
CFSR	18.88	12.23	20.21	10.37
NCEP–NCAR	18.09	11.87	20.00	9.70
CanESM2	21.40	12.33	23.40	9.31
CSIRO Mk3.6.0	21.16	12.22	22.77	11.05
MIROC4h	20.62	12.07	21.75	9.63
HadCM3	19.40	—	19.55	—
GFDL-ESM2M	18.89	11.46	18.28	9.37
IPSL-CM5A-LR	18.77	10.98	18.52	8.39
CNRM-CM5	18.62	11.84	20.68	9.33
NorESM1-M	18.43	11.63	19.48	9.64
MPI-ESM-LR	18.07	11.89	19.21	10.16
MRI-CGCM3	17.80	12.92	17.57	10.09
INM-CM4	17.22	11.65	19.55	9.18

the warming are direct consequence of the increase in lower-tropospheric water vapor. They found that robust responses of the models comprised the decrease in convective mass fluxes, the increase in horizontal moisture transport, the associated enhancement of the pattern of evaporation minus precipitation and its temporal variance, and the decrease in the horizontal sensible heat transport in the extratropics. Assuming that the lower-tropospheric relative humidity is unchanged or has little change and that the flow is unchanged, the poleward vapor transport and the pattern of evaporation minus precipitation ($E - P$) increases proportionally to the lower-tropospheric vapor. As a consequence, they postulated that wet regions will get wetter and dry regions will get drier in a warming planet.

In a recent study, Jones and Carvalho (2013) analyzed the Climate Forecast System Reanalysis (CFSR) and phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012) simulations for two scenarios [“historic” and high-emission representative concentration pathway 8.5 (RCP8.5)]. They used the same large-scale monsoon index discussed in Silva and Carvalho (2007). The reanalysis and 10 CMIP5 model simulations (historic experiment) consistently show statistically significant increases in seasonal amplitudes, early onsets, late demises, and durations of the SAMS. Jones and Carvalho (2013) also analyzed future changes in the SAMS with six CMIP5 model simulations of the RCP8.5 high-emission scenario. All simulations unquestionably show significant increases in seasonal amplitudes, early onsets, and late demises of the SAMS. Nonetheless, the increase in the seasonal precipitation does not occur over the entire present domain of SAMS. Most CMIP5 models simulate

FIG. 1. Decadal variation of $T850_{p85}$ during DJF (colored lines) and mean daily precipitation $> 5 \text{ mm day}^{-1}$ (gray shades) for the historic simulations (1951–2005). Values of $T850_{p85}$ were calculated over SA (see Table 2) and are indicated at the top of each frame ($^{\circ}\text{C}$): (a) NCEP–NCAR, (b) CFSR, (c) GFDL–ESM2M, (d) MRI–CGCM3, (e) MPI–ESM–LR, (f) NorESM1–M, (g) INM–CM4, (h) IPSL–CM5A–LR, (i) MIROC4h, (j) HadCM3, (k) CanESM2, (l) CSIRO Mk3.6.0, and (m) CNRM–CM5. For NCEP–NCAR in (a) and all CMIP5 models, averages were taken in the following decades: 1956–65 (black solid line), 1966–75 (dark blue dashed line), 1976–85 (light blue solid line), 1986–95 (light green dashed line), and 1996–2005 (red solid line). Decadal averages for CFSR in (b) were obtained for the periods 1979–85 (black solid line), 1986–95 (blue dashed line), and 1996–2005 (red solid line). The dark green shade indicates topography above 1500 m, and the gray shade bar indicates mean daily precipitation rate (mm day^{-1}) calculated for the entire historic period of the simulations (1951–2005).

FIG. 1. (Continued)

an increase in the monsoonal total precipitation over central and southeastern Brazil, whereas drier conditions are observed over eastern Brazil. The decrease in the seasonal precipitation over eastern Brazil has been consistently projected by the CMIP3 models for the A1B scenario (Bombardi and Carvalho 2009). E. Maloney et al. (2012, personal communication) examined changes in December–February (DJF) and June–August (JJA) ensemble mean precipitation from CMIP5 simulations for the RCP8.5 scenario. Their results project a decrease in JJA precipitation over the NAMS region during 2070–99 relative to 1961–90 with large anomalies over western Mexico.

Inspired by these previous studies and the availability of CMIP5 simulations and by the importance of future projections of the lower-tropospheric temperature and moisture for the American monsoon regions, this

work investigates changes in the 850-hPa temperature and specific humidity over tropical North and South Americas. CMIP5 simulations for two scenarios are examined: historic and high-emission representative pathway (RCP8.5). Although it is unquestionable that the radiative forcing of the RCP8.5 experiments will result in increased mean temperatures and specific humidity comparatively to the historic runs (Allen and Ingram 2002), assessing the patterns of warming and moistening, magnitude, and rate of change is critical to evaluate projected climate changes in monsoon regions.

This paper specifically focuses on multiannual-to-decadal variations and changes of the 85th percentiles of daily mean temperature and specific humidity at 850 hPa over South America (SA) and North America (NA) during the peak of SAMS and NAMS (December–February

and July–August, respectively) (section 2). We demonstrate that the 85th percentiles are predominantly observed over continental tropical areas and their increase in magnitude and spatial extent are good indicators of the expansion of the warming and moistening over NA and SA. These aspects are investigated along with daily mean rainfall (mm day^{-1}) calculated over the historic period (1951–2005) (section 3). We first examine the consistency between the two reanalyses and 11 CMIP5 simulations for the historic runs over South America (section 3a) and North America (section 3b). We then investigate the RCP8.5 projections of the expansion of the warming and moistening over South America (section 3c) and North America (section 3d) and how these projections are related to changes in daily mean precipitation. Summary and conclusions are presented in section 4.

2. Data

The large-scale features of temperature and specific humidity at 850 hPa and precipitation over tropical North and South America were characterized with daily reanalysis from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) at 2.5° latitude–longitude grid spacing and during 1 January 1948–31 December 2010 (Kalnay et al. 1996; Kistler et al. 2001). In addition, daily CFSR (Saha et al. 2010) was used at 0.5° latitude–longitude grid spacing during 1 January 1979–31 December 2010. The advantages of CFSR relative to NCEP include high horizontal and vertical resolutions, improvements in data assimilation and first-guess fields originated from a coupled atmosphere–land–ocean–ice system (Higgins et al. 2010; Saha et al. 2010). This study analyzes daily averages of specific humidity (Q850) and temperature (T850) at 850 hPa and daily precipitation rate (PREC). These variables have been used to characterize the onset, duration and amplitude of SAMS (Silva and Carvalho 2007; Carvalho et al. 2011a,b; Jones and Carvalho 2013) and are likely important to characterize variations in NAMS (Vera et al. 2006).

Changes in the above variables were examined with multimodel simulations from CMIP5 (Taylor et al. 2012). CMIP5 model simulations provide the basis for the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Additional information about CMIP5 can be found online (at <http://cmip-pcmdi.llnl.gov/cmip5/>).

The following model experiments were examined. The “historic” run (also known as the “twentieth-century simulation”) was forced by observed atmospheric composition changes, which include both anthropogenic and natural sources as well as time-evolving land cover. The

historic run covers the period 1 January 1951–31 December 2005. In addition, CMIP5 simulations of climate projection are forced with specified concentrations referred to as representative concentration pathways and provide a rough estimate of the radiative forcing in the year 2100 relative to preindustrial conditions (Moss et al. 2010; Taylor et al. 2012). To investigate future changes in the SAMS and NAMS, the high-emission scenario RCP8.5 was used. In this scenario, radiative forcing increases throughout the twenty-first century before reaching a level of $\sim 8.5 \text{ W m}^{-2}$ at the end of the century. RCP8.5 simulations cover the period 1 January 2006–31 December 2100. The focus of the analysis is during the peak of the SAMS (December–February) over central–eastern South America and NAMS (June–August) over large portions of Central and North America (Barlow et al. 1998).

Table 1 alphabetically lists the models used in this study. The analysis of the historic experiments includes all 11 models. Because of difficulties in accessing CMIP5 data and to examine future projections in which the daily historic and RCP8.5 simulations were available with the same resolution, the following models were analyzed for the RCP8.5 scenario: CanESM2, GFDL-ESM2M, MPI-ESM-LR, MRI-CGCM3, and NorESM1-M. In addition, given the large volume of data, only one run from each model and experiment was used in this study. Although more models are currently available in CMIP5, at the time this work was conducted daily outputs were available only for the models listed in Table 1.

3. Changes in T850 and Q850 over the tropical Americas

Cloudiness and precipitation play a fundamental role in controlling low-level temperatures in tropical areas. Regions characterized by monsoon systems experience their highest seasonal low-level temperatures during the premonsoon season when the solar radiation increases but convective activity is still modest (e.g., Gregory and Nieuwolt 1998). During the peak of the monsoon, the warmest temperatures in tropical regions are usually displaced poleward from areas of enhanced precipitation. In contrast, changes in precipitation and cloudiness in the tropics depend on low-tropospheric transport of moist static energy (e.g., Held and Soden 2006). Thus, identifying regions where temperature and moisture experience their most significant change provides important information to understand future projections of climate change in the monsoon regions. Uncertainties in precipitation regimes and unrealistic features over SAMS and NAMS domains in the CMIP3 simulations have been largely documented (e.g., Bombardi and Carvalho 2009; Vera and Silvestri 2009; Seth et al. 2010). Although some

FIG. 2. (a) Multiannual variability of $T850_{p85}$ after removing the intercept of the linear fit: NCEP–NCAR; CFSR; and CMIP5 ensemble mean (CMIP5–Ens), maximum (CMIP5–max), and minimum (CMIP5–min). (b) Multiannual variability of the fraction of SA with temperature $\geq T850_{p85}$ (%) calculated for the 1951–2005 period (1979–2005 for CFSR). All curves are 9-yr moving averages. The inset in (a) shows the actual temperatures (°C) for the NCEP and CFSR.

improvement in the simulations has been notable in the CMIP5 models relatively to CMIP3 models (e.g., Jones and Carvalho 2013; E. Maloney et al. 2012, personal communication), the accurate geographical distribution of wet areas and daily precipitation rates over the tropical Americas remain a challenge.

To assess and compare CMIP5 projections of T850 and Q850, we focused our analysis on the 85th percentiles during the peak of the NA and SA monsoon seasons (i.e., JJA and DJF, respectively). This method is useful because it does not make any presumptions about the geographic location of the monsoons that may vary

among the CMIP5 simulations. The 85th percentiles of T850 ($T850_{p85}$) and Q850 ($Q850_{p85}$) were calculated separately over the model's North America during JJA and over the model's South America during DJF. Only grid points with elevation below 1500 m were used in the calculation. The same rationale was applied for the two reanalyses. For simplicity, Central America was included in the calculation of percentiles over the North America domain. The inclusion of Central America in the calculation does not significantly affect the percentiles because of the coarse resolution of the models and dominant location of the high temperatures over North America. We

FIG. 3. As in Fig. 1, but for $Q_{850_{p85}}$ and (j) CanESM2, (k) CSIRO Mk3.6.0, and (l) CNRM-CM5. HadCM3 is not examined because of the unavailability of daily specific humidity at 850 hPa. Daily mean precipitation ($>5 \text{ mm day}^{-1}$) in the historic period (1951–2005) is also included (shades).

FIG. 3. (Continued)

will show that $T850_{p85}$ and $Q850_{p85}$ extend over tropical continental areas and are strongly linked to the American monsoons systems in the reanalyses and historic runs.

Two main aspects were investigated in these analyses: the area extent of the 85th percentiles and the multi-annual variation in the magnitude of the percentiles. The following approaches were adopted. The 85th percentiles were calculated for CMIP5 historic runs and for NCEP–NCAR reanalysis considering all DJF (JJA) seasons from 1951 to 2005 for South America (North America) (Table 2). A similar procedure was adopted for CFSR, except that the range of years extended from 1979 to 2005. Changes in the area of the 85th percentiles in the historic and RCP8.5 simulations and in the NCEP–NCAR and CFSR reanalyses were calculated using the values of the 85th percentiles obtained for the twentieth-century run. The main purposes of using fixed values of the 85th percentile for NA and SA was to examine patterns of warming and moistening of the lower troposphere and how they relate to patterns of mean daily precipitation rate, identify areas with rapid changes, and assess uncertainties in the CMIP5 models by comparing them with the two reanalyses.

The magnitudes of the 85th percentile were calculated for each DJF (JJA) season over South America (North America) and for the historic and RCP8.5 runs. All CMIP5 models show unrealistic large variance on interannual time

scales in the variables $T850$ and $Q850$ (not shown). Thus, to investigate long-term changes in these variables, all data in the historic and RCP8.5 runs were smoothed with a 9-yr moving average.

CMIP5 simulations exhibit significant biases in $T850$ in NA and SA. CanESM2, CSIRO Mk3.6.0, and MIROC4h are systematically warmer than the CFSR and NCEP–NCAR reanalyses and warmer than all other models. CanESM2 exhibits the largest positive bias in $T850$ followed by CSIRO Mk3.6.0 and MIROC4h over the tropical Americas. On the other hand, INM–CM4 shows the largest $T850$ negative biases over the tropical Americas. By comparing the 85th percentiles (Table 2), it is notable that, with the exception of CanESM2, CSIRO Mk3.6.0, MIROC4h, and HadCM3, all the models show differences in $T850_{p85}$ of less than 1°C (or less than 5%) over tropical SA when compared to NCEP–NCAR reanalysis during the same period. On the other hand, differences are larger for $T850_{p85}$ over NA, with GFDL–ESM2M and MRI–CGCM3 exhibiting the largest negative differences relatively to NCEP–NCAR.

CMIP5 historic simulations also exhibit biases in $Q850$. Table 2 shows that the largest differences relative to NCEP–NCAR are observed for MRI–CGCM3 over SA ($+1.05\text{ g kg}^{-1}$ or $\sim 9\%$). CSIRO Mk3.6.0 overestimates $T850_{p85}$ over SA and NA. MRI–CGCM3 shows positive differences of about 9% in the $Q850$ 85th percentile over

SA but about 4% over NA. IPSL-CM5A-LR shows the largest negative differences in $Q850_{p85}$ for SA ($\sim 7.49\%$) and NA ($\sim 13.5\%$).

a. Historic runs: South America

Decadal variations in the area with T850 greater or equal $T850_{p85}$ in the historic runs and in the two reanalyses during DJF are shown in Fig. 1. The decadal variations are shown along with the mean daily rainfall rate during DJF calculated for the entire historic simulation (1951–2005). The NCEP reanalysis (Fig. 1a) indicates a progressive warming over central–eastern SA since 1956. Areas with daily precipitation intensity above 9 mm day^{-1} are observed eastern of the Andes and over eastern and northern South America as an extension of the intertropical convergence zone (ITCZ) (Fig. 1a). NCEP–NCAR overestimates daily precipitation over northeastern Brazil and east of the Andes and underestimates daily rainfall over central–western Brazil comparatively to Tropical Rainfall Measurement Mission (TRMM) daily precipitation (see Carvalho et al. 2012, Fig. 5). The warming of the recent decades progressively advanced toward the area with large daily mean precipitation in the NCEP reanalysis. The CFSR (Fig. 1b) shows similar pattern of warming, with the most remarkable differences occurring in the last decade (1996–2005) comparatively with the previous ones. It is notable that the 85th percentile is larger for CFSR than NCEP–NCAR, which partially explains the differences in the spatial patterns of $T850_{p85}$. In addition, the period (1979–85) is shorter than the equivalent period (1976–85), which contributes to the observed differences. Daily mean precipitation rates in CFSR exhibit more realistic characteristics compared to the NCEP–NCAR reanalysis such as the oceanic SACZ and the magnitude and spatial location of the maximum daily precipitation over central–western South America, even though precipitation rates over northwestern South America and the eastern Andes are overestimated [see Carvalho et al. (2012) for further comparisons between CFSR precipitation and multiple datasets]. Interestingly, the progressive warming observed with CFSR seems to follow the spatial pattern of intensive land-use change observed over eastern Brazil in the Brazilian savanna in recent decades (Brannstrom et al. 2008).

The majority of the CMIP5 models simulate well the pattern of warming over tropical SA, in particular the remarkable expansion of $T850_{p85}$ in the 1996–2005 decade in spite of the large intermodel variability of the pattern of daily precipitation (Figs. 1c–m). The eastward enlargement of the $T850_{p85}$ over central–eastern SA in the 1996–2005 decade comparatively with the 1956–65 decade is evident in most models, with the exception of

CanESM2 (Fig. 1k) and CSIRO Mk3.6.0 (Fig. 1l), which show a signal of the recent warming over the northwestern Amazon. Nonetheless, regional differences in the spatial pattern of the warming are to some extent related to the large degree of uncertainty and errors in the simulations of precipitation in the tropical South America. Some models such as the MPI-ESM-LR (Fig. 1e), IPSL-CM5A-LR (Fig. 1h), HadCM3 (Fig. 1j), CNRM-CM5 (Fig. 1m), CanESM2 (Fig. 1k), and CSIRO Mk3.6.0 (Fig. 1l) indicate temperatures above $T850_{p85}$ over the western Amazon that do not seem realistic when compared to the two reanalyses. These models incorrectly represent the climatology of daily precipitation over tropical South America, in particular the excessive rainfall over central–eastern Brazil and dry conditions over northwestern South America, comparatively to TRMM (Carvalho et al. 2012). The unrealistic excessive precipitation over eastern Brazil in DJF and in the above-mentioned models has been documented for the CMIP3 models (Bombardi and Carvalho 2009; Vera and Silvestri 2009) and have persisted in the CMIP5 historic runs. It is worth noting that the GFDL-ESM2M (Fig. 1c) $T850_{p85}$ pattern of warming is quite consistent with the CFSR (Fig. 1b) over central–eastern South America, especially in the last decade of the historic simulation.

The multiannual variation of $T850_{p85}$ (9-yr moving average) in the CMIP5 historic simulations and CFSR and NCEP–NCAR reanalyses are shown in Fig. 2. The NCEP–NCAR reanalysis shows a cold bias and more moderate warming trend comparatively to CFSR (not shown). The NCEP–NCAR slope of the linear trend over the 1955–2000 period is about $0.024^\circ\text{C yr}^{-1}$, whereas the respective slope for the CFSR is about $0.03^\circ\text{C yr}^{-1}$ (1983–2000). All models underestimate the NCEP–NCAR trend, with the exception of GFDL-ESM2M and CanESM2 (0.02° and $0.025^\circ\text{C yr}^{-1}$, respectively). To assess the performance of the CMIP5 models in simulating the observed trends in $T850_{p85}$ regardless of existing biases in T850, the intercept of the linear fit of all CMIP5 model simulations was removed and the resulting temperature anomalies (plus trends) are displayed in Fig. 2a. The intercepts do not differ significantly from the mean values over the historic period for NCEP–NCAR and CMIP5 models. Nonetheless, since all CMIP5 models and the two reanalyses exhibited linear trends during the historic period, the intercepts were removed to allow a comparison with short record of CFSR. The resulting CMIP5 ensemble mean, minimum, and maximum anomalies are plotted along with NCEP–NCAR and CFSR anomalies. Figure 2a reinforces that the observed magnitude of the temperature anomalies were well captured by the maximum CMIP5 anomalies (dominated by GFDL-ESM2M and

FIG. 4. As in Fig. 2, but for $Q850_{p85}$ (without removal of the intercept of the linear fit) and with CFSR in the entire 1951–2005 period.

CanESM2). Trends that result from the ensemble mean are not realistic for SA. For instance, NCEP–NCAR shows an increase of 1.0°C in the 85th percentile from 1955 to 2000. CFSR indicates that the NCEP–NCAR reanalysis may have underestimated temperature anomalies by about 0.5°C . The CMIP5 ensemble mean indicates much less increase in temperature ($\sim 0.5^{\circ}\text{C}$) between 1955 and 2000.

Figure 2b examines the multiannual variation in the area with $T850 \geq T850_{p85}$ over SA. We recall that the areas were obtained for $T850_{p85}$ calculated over the entire 1951–2005 period. The area was calculated for each DJF season and further smoothed with a 9-yr moving average. Given the differences in resolution among models and reanalyses and implications for the estimation of the area, Fig. 2b shows the fraction (percentage) of SA that was observed with $T850 \geq T850_{p85}$. There is good agreement among CMIP5 models and the NCEP–NCAR reanalysis, with all models showing positive trends. In addition, most models show an increase in the slope

of the positive trend in the last two decades, as suggested in Fig. 1. CFSR indicates a large trend ($0.70\% \text{ yr}^{-1}$) during 1979–2000. NCEP–NCAR reanalysis indicates a weaker trend ($0.45\% \text{ yr}^{-1}$) during 1955–2000. It is worth noticing that trends increase around 1993 in both reanalyses.

Decadal variations in $Q850_{p85}$ for the historic simulations are investigated along with patterns of mean daily precipitation (1951–2005) (Fig. 3). Figures 3a,b indicate that CFSR and NCEP–NCAR exhibit distinct patterns of decadal variations of $Q850_{p85}$. NCEP–NCAR shows $Q850_{p85}$ displaced toward northwestern Amazon, whereas CFSR shows a much broader area extending from the central Amazon toward southeastern Brazil resembling the South Atlantic convergence zone (Carvalho et al. 2002). In addition, CFSR shows a remarkable increase in $Q850_{p85}$ in the 1995–2005 decade. Dessler and Davis (2010) argue that the NCEP–NCAR Global Reanalysis 1 (used in this study) contains large biases in specific humidity in the tropical mid and upper troposphere,

FIG. 5. As in Fig. 1, but for NA during JJA. Shading indicate daily mean precipitation ($>5 \text{ mm day}^{-1}$) in JJA.

which could explain the differences with respect to the more comprehensive data assimilation used in the CFSR (Saha et al. 2010). Nonetheless, areas with $Q850_{p85}$ are largely coherent with regions with intense

daily precipitation for both reanalyses and CMIP5 models (except INM-CM4; Fig. 3g).

Although the spatial patterns of $Q850_{p85}$ do not necessarily coincide with the patterns of $T850_{p85}$, most

FIG. 5. (Continued)

CMIP5 models show progressive increases in $Q850_{p85}$ over the SAMS region, which are more evident in the last 1–2 decades of the historic runs and in particular over regions where the climatological precipitation is already enhanced. INM-CM4 is the most conservative model, showing an increase in $Q850_{p85}$ only in the last decade and over eastern Brazil. IPSL-CM5A-LR (Fig. 3h) is the only model that indicates a decrease in $Q850_{p85}$ over southeastern Brazil from the first (1956–65) to the last decade (1996–2005). The CMIP5 most consistent feature is the decadal increase in $Q850_{p85}$ over central South America and southern Amazon, which is supported by CFSR (Fig. 3b).

Figure 4a shows the multiannual variations of the 9-yr moving average of $Q850_{p85}$ and exhibits the historic CMIP5 ensemble mean, maximum, and minimum

$Q850_{p85}$ along with NCEP–NCAR and CFSR reanalyses. NCEP–NCAR shows a negative bias with respect to CFSR as suggested in Dessler and Davis (2010). Nonetheless, both reanalyses show positive trends in $Q850_{p85}$, consistent with the warming of the lower troposphere. NCEP–NCAR indicates a linear trend of $\sim 0.008 \text{ g kg}^{-1} \text{ yr}^{-1}$ (1955–2000). The NCEP–NCAR trend in $Q850_{p85}$ is not constant. The CFSR trend is $\sim 0.016 \text{ g kg}^{-1} \text{ yr}^{-1}$ (1983–2000), whereas the NCEP–NCAR trend is $\sim 0.010 \text{ g kg}^{-1} \text{ yr}^{-1}$ in the same period (1983–2000). All CMIP5 models indicate positive trends in $Q850_{p85}$ varying from 0.005 (MRI-CGCM3) to $0.014 \text{ g kg}^{-1} \text{ yr}^{-1}$ (MPI-ESM-LR). However, MPI-ESM-LR shows the largest positive bias in $Q850_{p85}$ (not shown). The CMIP5 ensemble mean is remarkably consistent with CFSR.

FIG. 6. As in Fig. 2, but for NA during JJA.

The CMIP5 ensemble mean, maximum and minimum of the fraction of SA with $Q850 \geq Q850_{p85}$ are shown in Fig. 4b. In spite of differences in the spatial patterns of $Q850_{p85}$, NCEP–NCAR is within the range of variation of the CMIP5 models. There is a large discrepancy between CFSR and NCEP–NCAR, which is also evident in the decadal variation of $Q850_{p85}$ (Fig. 3a). CFSR exhibits a sharp change in the slope around 1993 that can be also identified in $T850_{p85}$ (Fig. 2b). All CMIP5 models show large areal coverage of $Q850 \geq Q850_{p85}$ when compared to CFSR.

b. Historic runs: North America

Decadal variations in the area with $T850 \geq T850_{p85}$ for NA and daily mean precipitation in the CMIP5 historic runs and in the two reanalyses during JJA are shown in Fig. 5. $T850_{p85}$ is observed over tropical NA, north of the region with daily mean precipitation above 5 mm day^{-1} in the two reanalyses and in all CMIP5 simulations (Fig. 5). As stated before, the warm temperatures in tropical regions are usually away (poleward) from the area with enhanced precipitation. The two reanalyses and most CMIP5 models show the monsoonal precipitation extending from northwestern South America toward northwest Mexico, with the largest values of daily precipitation observed west of the

Mexican Plateau, consistent with Barlow et al. (1998). NCEP–NCAR shows much large areas with daily precipitation greater than 5 mm day^{-1} also over the Caribbean. We emphasize that, because of the coarse resolution of the models and steep topography, these analyses underrepresent existing variations and changes in many valleys and regions with complex terrain located in the NAMS domain. NCEP–NCAR (Fig. 5a) and CFSR (Fig. 5b) indicate a modest increase in the area with $T850_{p85}$ over NA during 1996–2005 comparatively to previous decades with progressive warming southeastward of the United States. Most CMIP5 models show similar trends, with exception of NorESM1-M that shows almost no changes over the United States in the historic run (Fig. 5f). Moreover, it is worth noting that all models indicate an increase in temperature off the west coast of Mexico toward the eastern Pacific. Opposite trends are shown in the NCEP–NCAR reanalysis (Fig. 5a). The eastern Pacific stratocumulus clouds (Yuter et al. 2000) are likely among the causes of the uncertainties in the simulations of the CMIP5 in the region (Bony and Dufresne 2005).

Figure 6a shows the NCEP–NCAR, CFSR, and CMIP5 multiannual variations of $T850_{p85}$ (9-yr moving average) calculated over NA. CFSR correlates well with NCEP–NCAR (linear correlation of about 0.96) but

shows $T850_{p85}$, on average, 0.33°C warmer than NCEP–NCAR, with differences increasing up to 0.5°C in the last decade. CanESM2, CSIRO Mk3.6.0, CNRM-CM5, and MIROC4h overestimate both reanalyses, with mean biases ranging from 1.0° (MIROC4h) to 3.4°C (CanESM2) relative to the NCEP–NCAR mean. All other CMIP5 models underestimate NCEP–NCAR (and therefore CFSR); MRI-CGCM3 shows the largest negative bias (-2.19°C) and HadCM3 shows the least bias among all CMIP5 models investigated here (-0.15°C) (not shown). With exception of CNRM that shows no trend in the historic run, all other models indicate a positive trend in $T850_{p85}$, with rates that increase at the end of the historic period. Figure 6a shows the CMIP-5 ensemble mean and maximum and minimum temperature anomalies (plus linear trends) and reanalyses after removing the intercept of the linear fit. As stated before, this was done to remove the bias in the models and compare CMIP5 with the reanalyses. CMIP5 ensemble mean agrees well with the observed trend in the anomalies in recent decades as indicated by CFSR and NCEP–NCAR reanalyses. The NCEP–NCAR and CFSR are within the minimum and maximum ranges of the CMIP5 $T850_{p85}$ anomalies.

Figure 6b shows interannual variations of the fraction of NA with $T850 \geq T850_{p85}$. NCEP–NCAR does not indicate any linear long-term trend in area during the 1955–2001 period. A method for detection of shifts in the mean (Rodionov 2004) (using a sliding window of 10 yr and 5% significance level) was applied to NCEP–NCAR time series and indicated that changes in the regime of the mean occurred in 1962, 1977, and 1996. Moreover, the consistency between NCEP–NCAR and CFSR is also notable. CMIP5 ensemble mean, maximum, and minimum indicate a progressive increase in the area with $T850 \geq T850_{p85}$ and an increase in the slope of the trend from 1985 to 2001 (Fig. 6c).

The decadal variation of areas with $Q850_{p85}$ for NA along with daily mean precipitation in JJA is shown in Fig. 7. As shown for SA, $Q850_{p85}$ is largely consistent with daily precipitation over tropical NA for all models and the two reanalyses. NCEP–NCAR (Fig. 7a) indicates a progressive increase of the 85th percentile over NA and eastern Pacific, north of the equator. Over NA, the largest increase in area is observed over central and southern United States, east of the Rockies. On the other hand, CFSR (Fig. 7b) seems consistent over the eastern Pacific north of the equator but indicates a negative trend over south and southeast United States. This region has been affected by long-term droughts (Samanta et al. 2011) and CFSR has an improved data assimilation and higher resolution to identify these regional patterns. All CMIP5 models show an expansion

of areas with $Q850_{p85}$ over the NAMS domain and Florida (Figs. 7c–l). The CMIP5 patterns of decadal variability of $Q850_{p85}$ over NAMS are quite consistent with NCEP–NCAR.

CMIP5 multiannual variations of $Q850_{p85}$ over NA in JJA along with the two reanalyses are shown in Fig. 8a. CFSR and NCEP–NCAR differ in magnitude and interannual variability. The CFSR 85th percentile is about 0.5 g kg^{-1} greater than NCEP–NCAR. CFSR shows a decrease in the 9-yr moving average of $Q850_{p85}$ after 1996, while NCEP–NCAR shows a positive trend during the same period. CSIRO Mk3.6.0 has the largest positive bias ($>1 \text{ g kg}^{-1}$), whereas IPSL-CM5A-LR has the largest negative bias ($<1 \text{ g kg}^{-1}$) with respect to the two reanalyses (not shown). Interesting enough, MIROC4h and CanESM2 show ranges of magnitudes that are similar to NCEP–NCAR, in spite of the relatively large positive biases in $T850_{p85}$. The CMIP5 ensemble mean agrees quite well with NCEP–NCAR but underestimates CFSR. The fraction of NA with $Q850 \geq Q850_{p85}$ in JJA is shown in Fig. 8b. The CMIP5 ensemble mean is consistent with NCEP–NCAR after 1979 and indicates an increase of about 2% in the area with $Q850 \geq Q850_{p85}$ from 1955 to 2001. CFSR shows a decrease in $Q850_{p85}$ that is not identified by NCEP–NCAR. It is worth noticing that the decrease in the extent of the moist regions over NA identified with CFSR does not reflect the trend in $T850_{p85}$ (Figs. 6a,b).

c. RCP8.5 future projections: South America

The future projections in the decadal variation of $T850_{p85}$ and $Q850_{p85}$ in the RCP8.5 scenario were investigated in a common framework using the same thresholds of $T850_{p85}$ and $Q850_{p85}$ obtained for the historic runs. Figure 9 shows CMIP5 projections of decadal variations of $T850_{p85}$ for SA in DJF during 2006–95. A 15-yr average was used to simplify the results. All CMIP5 models project a continued expansion of $T850_{p85}$ toward eastern tropical SA and the equatorial Atlantic and Pacific. These trends follow the patterns of warming that have been observed in the historic runs and for NCEP–NCAR and CFSR reanalyses (Fig. 1). Notice that no CMIP5 model projects the extension in area of $T850_{p85}$ south of 40°S over SA and south of 30°S over the South Atlantic. The spatial patterns of the trends suggest a decrease in temperature gradients near the equator and an increase in subtropical latitudes. These projections critically impact SAMS characteristics by modifying ocean–land temperature contrasts and low-level moisture convergence. In fact, Seth et al. (2010) have projected an increase in the integrated moisture flux convergence in the A2 scenario relatively to the historic run (twentieth-century

FIG. 7. As in Fig. 3, but for NA during JJA.

climatology) over southeastern South America using CMIP3 models. These features seem consistent with the changes in temperature gradients examined in the present study.

Figure 10a shows the projections of the anomalies using the same methodology discussed in Fig. 2a. NCEP-NCAR and CFSR 9-yr moving averages have been extended until 2005. The ensemble mean is consistent with

FIG. 7. (Continued)

NCEP–NCAR, whereas the ensemble maximum seems to be closer to CFSR. The ensemble mean projects that $T850_{p85}$ will be 2.5°C (4.7°C) above the values observed in 1955 by 2050 (2095). Considering that the maximum projected anomalies are more consistent with CFSR, one might expect $T850_{p85}$ anomalies of about 4.5°C over SA by 2050 under the RCP8.5 scenario.

The expansion in area of the $T850_{p85}$ calculated for the historic runs are shown in Fig. 10b. The ensemble mean is very consistent with both reanalyses, particularly in recent decades, suggesting high confidence in the projected trends. CMIP5 ensemble mean, CFSR, and NCEP–NCAR indicate that the $T850_{p85}$ extends over an area that represents approximately between 25% and 30% of SA. By 2050 this area might double (i.e., reach 60% of SA) according to the CMIP5 RCP8.5 ensemble mean projections. This trend would continue until the end of the century when it would reach $\sim 80\%$ of the continent, extending largely over tropical SA and likely affecting SAMS characteristics.

Projections of decadal variations in $Q850_{p85}$ are displayed in Fig. 11. All CMIP5 models indicate an increase in $Q850$ over the tropics, extending from central South America toward the Pacific and Atlantic ITCZ regions. The CFSR average of $Q850 \geq Q850_{p85}$ in recent years (2006–10; not shown) indicates that $Q850_{p85}$ has largely expanded over the Amazon basin and

southeastern Brazil, supporting the CMIP5 projected trends in $Q850_{p85}$.

Figure 12a summarizes the projected CMIP5 ensemble mean of $Q850_{p85}$ over SA. In spite of differences in spatial patterns, there is an extraordinary agreement between the ensemble mean and CFSR. The ensemble mean suggests that $Q850_{p85}$ would increase 1 g kg^{-1} from the present value ($\sim 12.4\text{ g kg}^{-1}$) by 2050 and $\sim 3.0\text{ g kg}^{-1}$ by 2095. The fraction of SA with $Q850_{p85}$ (Fig. 12b) would increase from approximately 30% in the 2000–10 decade to about 58% around 2050. This fraction might increase to about 70% in 2095.

Changes in daily precipitation rate were investigated between two 30-yr periods: 2071–2100 and 1951–81 (Fig. 13). We highlighted differences in daily precipitation using a common threshold of $\pm 0.5\text{ mm day}^{-1}$. A preliminary analysis of the statistical significance in the difference of the means indicated that 0.5 mm day^{-1} is statistically significant for all models at 5% significance level (not shown). Some models, however, show statistically significant differences with lower thresholds. All CMIP5 models indicate intensification in daily precipitation in the ITCZ in DJF, particularly in the east Pacific ITCZ. Large discrepancies among models are observed over tropical South America, with some models suggesting an intensification in daily precipitation over tropical and subtropical SA (MRI-CGCM3 and

FIG. 8. As in Fig. 4, but for NA during JJA.

NorESM1-M), whereas others project a decrease in daily precipitation over the Amazon basin and eastern Brazil (MPI-ESM-LR and CanESM2). Some models project a decrease in daily precipitation in the SACZ (GFDL-ESM2M), whereas others seem to project the opposite (MRI-CGCM3).

The increase in the lower-tropospheric moisture in convergence zones and the intensification of precipitation in these regions as well as the decrease in precipitation in areas dominated by subsidence under global warming has been associated with the so-called rich-get-richer mechanism (Chou et al. 2009). Chou and Neelin (2004) argue that, in order to compensate for the tropospheric warming, moisture in the atmospheric boundary layer (BL) must increase to maintain positive convective available potential energy (CAPE) in convective regions. In contrast, in regions dominated by subsidence the atmospheric BL moisture is controlled by different balances and does not increase as much, creating a spatial gradient of moisture anomalies. This spatial pattern of the atmospheric BL moisture anomalies creates two main mechanisms responsible for the anomalous tropical precipitation. In some areas increases in the atmospheric BL moisture are opposed by dry air imported from nonconvective regions over the margins of convective areas resulting in decreased

precipitation. On the other hand, over convective regions the gross moist stability is reduced because of increased atmospheric BL moisture. As a result, convection is enhanced and precipitation becomes heavier over convective regions. Chou and Neelin (2004) suggest that the variation in gross moist stability, which is likely to differ among climate models, is a potential factor causing discrepancies in the predicted regional tropical precipitation changes. These mechanisms can potentially explain the large model-to-model variability of the signal of changes in daily precipitation in the vicinity of the convergence zones where $Q850_{p85}$ have increased due to global warming.

d. RCP8.5 future projections: North America

CMIP5 projections of decadal variations in $T850_{p85}$ and $Q850_{p85}$ over NA in JJA are shown in Figs. 14 and 15, respectively. All CMIP5 models project progressive increases in the area with $T850 \geq T850_{p85}$ that extends beyond NA, including tropical SA (Fig. 14). Moreover, the warm temperatures (Fig. 14) observed poleward of the areas with large daily precipitation in JJA extend progressively toward the NAMS domain in Mexico and Central America. These are remarkable findings, given that it is winter in SA and the 85th percentile for NA is higher than the respective percentiles in SA during

FIG. 9. Decadal variation of the T850 85th percentile ($T850_{p85}$) during DJF (values are indicated at the top of each frame) for the RCP8.5 simulations (2006–95). Values of $T850_{p85}$ were calculated over SA for the historic run (see Table 2): (a) GFDL-ESM2M, (b) MRI-CGCM3, (c) MPI-ESM-LR, (d) INM-CM4, (e) NorESM1-M, and (f) CanESM2. Colors and line patterns represent different decades as indicated in the legend at the top right of the figure. Green shade indicates topography above 1500 m and gray shades are daily precipitation differences. The solid thick gray line encloses regions with positive anomalies.

summer (see Table 2). Another significant feature is the progressive expansion of the warming toward eastern United States and high latitudes, suggesting the expansion of tropical temperatures toward the extratropics of NA. The resulting changes in temperature gradients are consistent with the projected changes in the baroclinicity and resulting increase in precipitation over the extratropics of NA shown in E. Maloney et al. (2012, personal communication) (indicated in Fig. 18).

Figure 15a shows future projections of $T850_{p85}$ anomalies over NA in JJA. To compare the historic with the

RCP8.5 simulations, the CMIP5 ensemble mean, maximum, and minimum were obtained after removing the intercept of the linear trends fitted for the historic run (Fig. 6a). It can be noticed that the CMIP5 minimum values seem consistent with NCEP–NCAR, whereas the maximum values follow CFSR. The ensemble mean projects an increase of $\sim 2.8^{\circ}\text{C}$ (5.5°C) from 1955 to 2050 (1955 to 2095). Projections of changes in the fraction of NA with $T850 \geq T850_{p85}$ in JJA are shown in Fig. 15b. There is a remarkable agreement among the reanalyses and the ensemble mean. The ensemble mean indicates

FIG. 10. (a) CMIP5 historic simulations and RCP8.5 ensemble mean, maximum, and minimum projections of $T850_{p85}$ anomalies (intercept of the linear fit removed) over SA during DJF. (b) Fraction of SA (%) with $T850 \geq T850_{p85}$ in the historic and RCP8.5 simulations (CMIP5 ensemble mean, maximum, and minimum) during DJF. NCEP–NCAR and CFSR are also included (1955–2006). Curves are 9-yr moving averages.

that the warming could expand approximately 15% by 2050 and would reach 50% of NA by the end of the century. Most of this expansion would take place in the low troposphere of the United States.

Projections of decadal changes in $Q850_{p85}$ are shown in Fig. 16. The most consistent projection among models is the progressive expansion of $Q850_{p85}$ from the tropics toward higher latitudes over the central–eastern United States. Changes are much less pronounced in the west coast of the United States. MRI-CGCM3 (Fig. 16b), MPI-ESM-LR (Fig. 16c), NorESM1-M (Fig. 16d), and CanESM2 (Fig. 16e) show an expansion of $Q850_{p85}$ over the eastern North Atlantic, suggesting the intensification of the warming in this region that is not necessarily identified from decadal changes in $T850_{p85}$ (cf. Fig. 16 with Fig. 14).

Multiannual variations and changes in the magnitude of $Q850_{p85}$ over NA in JJA are shown in Fig. 17a. As discussed before, there is good agreement between the

ensemble mean and NCEP–NCAR. CFSR varies more consistently with the CMIP5 maximum projections. The ensemble mean indicates that $Q850_{p85}$ would increase from $\sim 10 \text{ g kg}^{-1}$ by 2006 to $\sim 11 \text{ g kg}^{-1}$ (12.5 g kg^{-1}) by 2050 (2095). The ensemble mean projections of expansion in the fraction of NA with $Q850 \geq Q850_{p85}$ (Fig. 17b) suggest an increase in 15% of the area by 2050 and 50% by 2095.

Changes in daily precipitation between the 30-yr periods 2071–2100 and 1951–81 in JJA are shown in Fig. 18. All CMIP5 models agree well in projecting an increase in daily precipitation over the Pacific ITCZ, consistent with the mechanism described in Chou and Neelin (2004) and Held and Soden (2006). The change in the ITCZ would affect precipitation regimes over northern SA and Central America and likely over southern Mexico. Nevertheless, northern Mexico and the southern United States would experience drier conditions according to MPI-ESM-LR (Fig. 18c), NorESM1-M

FIG. 11. As in Fig. 9, but for $Q850_{p85}$ and with (d) NorESM1-M and (e) CanESM2.

(Fig. 18d), and CanESM2 (Fig. 18e). However, given the coarse resolution of the CMIP5 models, the exact extent of the projected dry and wet regimes over NAMS is unknown. Interestingly, another consistent feature in these models is the increase in precipitation over southwestern South Atlantic in subtropical latitudes during JJA, which could be also associated with changes in temperature and pressure gradients resulting from the progressive warming of tropical South America.

4. Conclusions

This study examines the warming and moistening of tropical SA and NA and relationships with daily

precipitation with emphasis in the tropical regions under the influence of SAMS and NAMS. The focus of this analysis is on the multiannual to decadal variations and changes of the 85th percentiles of temperature and specific humidity in 850 hPa. The 85th percentiles were calculated separately for NA and SA during the respective peaks of the summer seasons. It is shown that the 85th of specific humidity is largely associated with daily precipitation above 5 mm day^{-1} in the SAMS and NAMS domains.

This study investigates 11 CMIP5 model simulations of the “historic” run and 6 models for the RCP8.5 projections. Two reanalyses are examined: NCEP–NCAR (1951–2010) and CFSR (1979–2010). These two reanalyses

FIG. 12. As in Fig. 10, but for $Q850_{p85}$ (without intercept of the linear fit removed).

differ in resolution and data assimilation. CFSR has a positive bias in temperature and moisture with respect to NCEP–NCAR. In spite of existing biases in T850, the two reanalyses are well correlated over time. Large differences are observed in spatial and temporal patterns of Q850 and these differences may have largely resulted from differences in data assimilation schemes. In addition, the CFSR mean daily precipitation (magnitude and spatial variability) is comparatively more realistic than the respective NCEP–NCAR precipitation climatology (Carvalho et al. 2012).

NCEP–NCAR and CFSR show progressive increases in the area with $T850_{p85}$ over SA, with a remarkable extension over eastern Brazil. All CMIP5 simulations of the historic run show similar increases in $T850_{p85}$ over SA and are consistent among themselves and with the two reanalyses in the last 1–2 decades. The CMIP5 ensemble mean underestimates the observed anomalies in $T850_{p85}$ over SA. The maximum simulated anomalies seem to better represent the magnitude of the warming estimated with NCEP–NCAR and CFSR in the present climate. The CMIP5 ensemble mean, maximum, and

minimum of the fraction of $SA \geq T850_{p85}$ is in the expected range of variations indicated by the two reanalyses. The trends in the ensemble mean are consistent with the trends of the two reanalyses, particularly in the last decade. A large discrepancy is observed in the CMIP5 spatial variability of the mean daily rainfall. The most remarkable issues are the incorrect simulations of the SACZ and ITCZ and the misplacement of the maximum daily precipitation rate. These features affect to some extent the performance of the CMIP5 models in simulating the observed patterns of warming and moistening.

The RCP8.5 CMIP5 projects a continuous expansion of $T850_{p85}$ over eastern tropical SA in DJF with important impacts to low-level moisture and precipitation. CMIP5 RCP8.5 simulations indicate that the maximum projected anomalies are more realistic when compared to CFSR, whereas the ensemble mean represents NCEP–NCAR quite well. The maximum projected anomaly for the RCP8.5 scenario indicates an increase in $T850_{p85}$ of about 4°C by 2050 and about 8°C by 2095 with respect to the beginning of the historic simulation. If one

FIG. 13. Difference in daily mean precipitation (mm day^{-1}) during DJF between the following 30-yr periods: 2071–2100 (RCP85) minus 1951–2005 (historic simulation). Only differences above (below) 0.5 (-0.5) mm day^{-1} are shown. Dotted (solid) lines indicate negative (positive) anomalies and are plotted every 1 mm day^{-1} : (a) GFDL-ESM2M, (b) MRI-CGCM3, (c) MPI-ESM-LR, (d) NorESM1-M, and (e) CanESM2. Dark gray shade indicates topography $>1500 \text{ m}$.

considers the ensemble mean projection, which is more consistent with NCEP–NCAR, the anomalies would be about 2.5°C by 2050 and 4.8°C by 2095, with a projected range between 3.0° and 8.0°C based on the six models investigated here. Less uncertainty is observed for the area with $T850 \geq T850_{p85}$ for SA when comparing the CMIP5 ensemble mean with the two reanalysis. The RCP8.5 scenario projects that about 60% of the area of SA would experience $T850 \geq T850_{p85}$ by 2050, which is

double of the present area and 6 times larger than the area observed in the beginning of the historic period. The expansion in area is largely concentrated in the tropics and north of 30°S .

Large discrepancies are observed in the patterns of $Q850_{p85}$ over SA in the two reanalyses. CFSR shows $Q850_{p85}$ extending over the monsoon region in a spatial pattern that resembles the SACZ, whereas NCEP–NCAR shows that the 85th percentile is essentially

FIG. 14. As in Fig. 9, but for NA and JJA.

observed over the northern Amazon. CFSR shows a large increase in $Q850_{p85}$ over the Amazon basin in recent decades. Similar increase is also simulated by most CMIP5 models in the historic run. The $Q850_{p85}$ has progressively expanded toward the geographical regions with enhanced climatological precipitation (1951–2005). There is remarkable good agreement between the interannual variation of $Q850_{p85}$ from the CMIP5 ensemble mean and CFSR, which is of great value for future projections of climate change. The CMIP5 models overestimate the area with $Q850_{p85}$ based on CFSR. However, the trend in area in the last two decades is well simulated by the CMIP5 models. CMIP5 RCP85 runs project a continuous expansion of the $Q850_{p85}$ toward

low latitudes of SA during DJF. By 2050 this area should extend toward low latitudes of the NH and the Atlantic and Pacific ITCZ. The augmentation of moisture in tropical regions in a warming climate results in remarkable spatial changes in daily precipitation with large intermodel variability. The rich-get-richer mechanism dominates the patterns of change in daily precipitation in the CMIP5 convergence zones, especially the ITCZ. However, over the core of SAMS (e.g., Gan et al. 2004; Carvalho et al. 2011a,b; Silva and Carvalho 2007; Raia and Cavalcanti 2008) and in the SACZ (Carvalho et al. 2002) there is a large uncertainty in the signal of the changes in daily precipitation rate by the end of the twenty-first century. The discrepancy could

FIG. 15. As in Fig. 10, but for NA and JJA.

result from model-to-model variability in moist static energy, among other factors (Chou et al. 2009). Changes in daily precipitation intensity in DJF should not be mistaken for total seasonal precipitation during the summer monsoon season, which will depend on the length of the monsoon season and frequency of intense events, among other factors.

The NCEP–NCAR and CFSR reanalyses do not show large decadal increases in the area with $T850_{p85}$ over the NAMS region. Most CMIP5 models are consistent with these observations and some show modest warming over central–western United States during JJA in the historic simulations. However, comparisons among the reanalyses and the CMIP5 historic simulations of the multiannual variation of the magnitudes of the $T850_{p85}$ indicate large uncertainty, with the maximum anomalies more consistent with CFSR and minimum anomalies consistent with NCEP–NCAR. The ensemble mean captures well the overall trend of $T850_{p85}$ over NAMS, specially the trends in the last three decades of the historic period. Furthermore, there is very good agreement between CFSR, NCEP–NCAR, and the CMIP5 ensemble mean of the multiannual variability of the area of NA

with $T850 \geq T850_{p85}$. Although the positive trends in area and in the magnitude of $T850_{p85}$ are much less pronounced in the NAMS domain comparatively with the SAMS domain, the RCP85 scenario indicates that changes between 1° and 4°C in the magnitude may likely occur by 2050. The large anomalies are more consistent with CFSR in the CMIP5 historic simulations. We recall that, because of the coarse resolution of most CMIP5 models and also the reanalyses (in particular NCEP–NCAR), there is an underrepresentation of the contribution of valleys and other areas located in complex terrain to the warming of the NAMS region.

Nonetheless, the RCP85 simulations show remarkable and consistent expansions of the warm areas eastward of the present domain. Given the large extent of NA toward the extratropics, all models indicate that the $T850_{p85}$ (as calculated for the historic runs) would expand to midlatitudes of NA. The CMIP5 RCP8.5 ensemble mean projects that the fraction of NA with $T850 \geq T850_{p85}$ would increase from about 15% in 2001 to approximately 35% by 2050 and will reach about 50% by 2095. These changes could largely affect the climate variability of the subtropics and extratropics of the United States.

FIG. 16. As in Fig. 11, but for NA and JJA.

As observed for SA, there is a large discrepancy in $Q850_{p85}$ between the two reanalyses over NA in JJA. These differences seem to be particularly relevant over southern U. S. The CMIP5 ensemble mean shows multiannual variations that are more consistent with NCEP–NCAR reanalysis, whereas CFSR is more consistent with CMIP5 maximum values. These discrepancies increase the uncertainties in the RCP8.5 projections of $Q850_{p85}$ area and magnitude. The RCP8.5 CMIP5 ensemble mean projects an increase of about 1 g kg^{-1} in $Q850_{p85}$ by 2050 and 2.5 g kg^{-1} by 2095. Increased moisture in the lower troposphere would extend to the extratropics of NA as well as low latitudes of SA during JJA. The increase in tropical moisture and temperatures

over the NAMS domain are observed along with increased precipitation in a narrow band in the ITCZ around 5°N and dry conditions north and south of this convective area by the end of the century. Some models project dry conditions also in the Atlantic ITCZ and northern South America. These patterns of rainfall variability are consistent with the overall weakening of the Walker circulation discussed in Vecchi and Soden (2007). They analyzed the CMIP3 dataset for the twenty-first century and indicated that the large-scale convective overturning must slow to compensate for the fact that atmospheric water vapor increases more than precipitation in a warmer planet. The projected response is the enhancement in the upward motion in the

FIG. 17. As in Fig. 12, but for NA and JJA.

eastern tropical Pacific and reduction in the western tropical Pacific, resembling the warm phase of the El Niño–Southern Oscillation (ENSO). These findings are consistent with the patterns of change in daily precipitation over the tropical Americas in JJA.

Although future emissions and the adequate atmospheric radiative forcing to represent future scenarios of climate change are still debatable, the historic runs and reanalyses examined in this study have provided consistent evidence that critical changes in the climate over the tropical Americas are likely to occur. These analyses showed evidence that over the SAMS domain these projections are already in place. Analyses similar to the ones discussed here were carried out for the CMIP5 preindustrial experiment (labeled as “picontrol”) (not shown). The picontrol experiment prescribed preindustrial atmospheric CO₂ concentrations and unperturbed land use. They provided additional confirmation that the expansion of the warming over tropical SA and trends in area and magnitude of the 85th percentiles observed in the historic runs and reanalyses are not spurious and are of anthropogenic origin.

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FIG. 18. As in Fig. 13, but for JJA.

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