Global versus regional warming of the tropical ocean basins and their impacts on Atlantic hurricane activity

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1. Introduction

There is considerable observational evidence that sea surface temperature (SST) changes in the tropical North Atlantic (TNA) affect and modulate the Atlantic hurricane activity. Saunders and Lea (2007), for example, showed from observational data that 0.5^{o}C increase of Atlantic SST in the main development region for hurricane (MDR) is associated with about 40% increase in Atlantic hurricane frequency during 1965 – 2005. According to the externally forced model simulations for the 21st century (SRESA1B scenario) used in the Intergovernmental Panel for Climate Change – 4th Assessment report (IPCC-AR4), the MDR SST may increase by about 2^{o}C between 2000 and 2100 due to anthropogenic global warming. Note that, the MDR SST anomaly barely reached 1^{o}C during the Atlantic hurricane season of June to November (JJASON) in 2005, but that the record-breaking fifteen hurricanes formed, of which four of them reached category 5 strength, causing many loss of human life and catastrophic property damage.

Are we really entering a new era of much elevated hurricane activity due to the rising global SST? Some studies argue that the increasing destructiveness of hurricanes due to rising global SST has been already occurring since 1980s (Emanuel 2005; Knutson and Tuleya 2004; Trenberth and Shea 2006; Webster et al. 2005). However, others point out that the recent increase can be attributed to multidecadal oscillations in hurricane activity associated with similar swings in the North Atlantic SSTs - the Atlantic Multidecadal Oscillation (AMO) (Bell and Chelliah 2006; Goldenberg et al. 2001). Furthermore, new studies using data and models suggest that the global warming has little impact on Atlantic hurricane activity or may even be associated with a weak downward trend in overall activity. For instance, Wang and Lee (2008) showed using observational data that the global warming of sea surface is associated with a secular increase of tropospheric vertical wind shear in the MDR, and that the increased vertical wind shear coincides with a weak but robust downward trend in U.S. landfalling hurricanes, a reliable measure of hurricanes over a long term (Landsea 2007). Vecchi and Soden (2007) also reported that an increase in the vertical wind shear over the TNA is a robust feature of the global climate model simulations for the 21st century used in IPCC-AR4.

Recent independent studies by Swanson (2008), Vecchi et al. (2008) and Wang and Lee (2008) provide a new insight as to why the observed correlation in the 20th century between the MDR SST and Atlantic hurricane cannot be used to project the future Atlantic hurricane activity of the 21st century. The main argument of these studies is that the tropical cyclones do not response to the absolute SST of MDR but to the relative SST of MDR to other tropical ocean basins. Under the anthropogenic global warming scenario, the MDR SST tends to increase along with other tropical ocean basins. Therefore, this hypothesis nicely fits to the notion that the global warming has little impact on Atlantic hurricane activity. For future reference, this hypothesis is referred to as "*regional warming hypothesis*", whereas the hypothesis that the global warming boosts the Atlantic hurricane activity is referred to as "*global warming hypothesis*". The main objective of this paper is to test and explore the dynamic and thermodynamic foundations of these two working hypotheses by performing a set of climate model experiments. Ultimately, we wish to examine if and how these hypotheses can be used to project tropical cyclone statistics of the 21st century.

2. Model Experiments

The NCAR community atmospheric model version 3 (CAM3) is used as a primary tool for this study. The CAM3 is setup as a global spectral model with a triangular spectral truncation of the spherical harmonics at zonal wave number 85 (T85) and with 26 hybrid sigma-pressure layers. The CAM3 is the atmospheric component of community climate system model version 3 (CCSM3), which is one of the 24 climate models used in IPCC-AR4. Model experiments are performed by prescribing various composites of global SST and sea ice fraction in the Atlantic and other ocean basins, taken from the externally forced CCSM3 simulation for the 21st century under SRESA1B scenario (IPCC-CCSM3 hereafter).

We have performed three sets of model experiments as summarized in Table 1. In the control experiment (EXP_CTR), the global SST and sea ice fraction are prescribed with twelve monthly climatological values of IPCC-CCSM3 for 2001-2020 periods. The CO_2 level is fixed to 380ppm, which is the averaged CO_2 level for 2001-2020 under SRESA1b scenario. In the global warming experiment (EXP_GLB), the climatological values of IPCC-CCSM3 global SST and sea ice fraction for 2081-2100 are used as the boundary conditions. The CO_2 level is fixed to 675ppm following SRESA1b scenario. The next experiment (EXP_ATL) is designed to represent Atlantic-only warming. This is identical to EXP_GLB except that SSTs outside of the Atlantic Ocean basin (from Antarctic continent to 60^oN) are those of EXP_CTR. In each model experiment, the model is integrated for 25 years. The first 5 years of model output are discarded to exclude any possible transient spinup effects. To suppress internal atmospheric variability, the remaining 20 years of model output are averaged for all analyses in the next sections. EXP_GLB is designed to test "*global warming hypothesis*", whereas EXP_ATL is designed to test "*regional warming hypothesis*". To isolate the effects of global versus regional warming of the tropical ocean basins on Atlantic hurricane activity, the difference between EXP_GLB and EXP_CTR, and between EXP_ATL and EXP_CTR are described in the next sections.

3. Results

Here, we focus on the atmospheric response of the vertical wind shear because it is a relevant environmental factor for Atlantic hurricane activity. Figure 1a shows the vertical wind shear difference in JJASON between EXP_GLB and EXP_CTR, while Figure 1b shows the same between EXP_ATL and EXP_CTR. The global warming experiment (EXP_GLB - EXP_CTR) is characterized by a weak increase in the vertical wind shear over the Gulf of Mexico and Caribbean Sea, consistent with Vecchi and Soden (2007). In the Atlantic-only warming experiment (EXP_ATL – EXP_CTL), on the other hand, the vertical wind shear over the Caribbean Sea is weakened substantially. Note that the absolute MDR SSTs in the two experiments (EXP_GLB and EXP_ATL) are identical. Nevertheless, the MDR vertical wind shear response is much stronger when the SSTs of other two ocean basins are relatively colder than the MDR SST. Since a decrease (increase) in MDR vertical wind shear supports (inhibits) the organization of deep convection required for a hurricane development, this model result indeed supports *regional warming hypothesis* - the hurricane activity responses primary to the relative SST of MDR to other two tropical ocean basins, not to the absolute SST of MDR (Swanson 2008; Vecchi et al. 2008; Wang and Lee 2008). On the other hand, since the MDR vertical wind shear response in the global warming experiment (EXP_GLB) is fairly weak and positive, our model result disqualifies "*global warming hypothesis*".

4. Importance of regional warming on MDR vertical wind shear

Our model experiments show that a relative warming of the tropical Atlantic Ocean to other tropical ocean basins decreases the MDR vertical wind shear but that a uniform warming of the global tropical oceans has a little impact on the MDR vertical wind shear. Now, we want to explore why a regional warming, not a global ocean warming, is important for the MDR vertical wind shear. To answer this question, it is helpful to examine the upper and lower tropospheric geopotential heights and winds. Figure 2a clearly shows that the dynamic response of the upper troposphere (200mb) to global warming is relatively weak and more prominent over mid- and high-latitudes. There is, however, a weak cyclonic circulation centered over the TNA with strengthened westerly winds over the Gulf of Mexico. In the case of Atlantic-only warming, on the other hand, the TNA is characterized by an intense cyclone in the upper troposphere (200mb), causing a substantial weakening of the westerly upper tropospheric wind over the MDR.

In the lower troposphere, the dynamic response to global warming is also very weak (Figure 3a). In particular, the global warming has a little influence in the Gulf of Mexico and Caribbean Sea regions. Therefore, the vertical wind shear enhancement over these regions, shown in Figure1a, is largely due to the strengthening of the westerly wind in the upper troposphere (Figure 2a). In the Atlantic-only warming case (Figure 3b), on the other hand, there is a substantial weakening of the easterly lower-level wind over the MDR. The outgoing long-wave radiation response shown in Figure 4b further indicates that the atmospheric response to the Atlantic-only warming and associated vertical wind shear reduction in the MDR are due to a baroclinic response to a diabatic heating local to the TNA. The baroclinic model response in this case is largely consistent with the Gill's (1980) solution to a heating anomaly slightly north of the equatorial region (Heckley and Gill 1984). In the global warming case (Figure 4a), the tropical diabatic heating is slightly enhanced overall. But, the increase is relatively smaller in the TNA and larger in the western Pacific warmpool region. Since the TNA is not a significant source of diabatic-heating anomaly in the global warming experiment, the atmosphere aloft the TNA is relatively undisturbed, and thus the MDR vertical wind shear is relatively unchanged.

In summary, the vertical wind shear reduction in the MDR requires a diabatic heating local to the MDR. A localized regional warming of the Atlantic Ocean basin increases the diabatic heating in the MDR. But, a uniform warming of the global oceans, as in the global warming experiment, does not increase the diabatic heating in the MDR.

5. Discussions

This study shows that the most relevant factor for projecting the future Atlantic hurricane activity under global warming scenarios is the relative warming rate of the Atlantic Ocean basin to that of the Indo-Pacific Ocean basins, in agreement with Swanson (2008), Vecchi et al. (2008) and Wang and Lee (2008). Under anthropogenic global warming scenarios, the tropical Atlantic SST tends to increase more or less uniformly along with other tropical ocean basins. Therefore, the global warming has little impact on Atlantic hurricane activity.

As discussed earlier, Vecchi and Soden (2007) showed that an increase in the vertical wind shear over the TNA is a robust feature of the global climate model simulations for the 21st century used in IPCC-AR4. Our conclusion may be also applicable for understanding this behavior of the IPCC-AR4 models. According to the externally forced model simulations for the 21st century used in the IPCC-AR4, the Atlantic Meridional Overturning Circulation (AMOC) may slow down by about 25% between 2000 and 2100 due the anthropogenic CO_2 emission to the atmosphere. Enfield et al. (unpublished manuscript) showed that the North Atlantic warms more slowly than other oceans as the AMOC decreases in the IPCC-AR4 multi-model sets. They further argued that the relatively cold North Atlantic SST could result in a reduction of the MDR vertical wind shear and thus decrease the Atlantic hurricane activity. Our study suggests that the hypothesis proposed by Enfield et al. is indeed a plausible explanation for the increase in the vertical wind shear over the TNA in the IPCC-AR4 model simulations for the 21st century.

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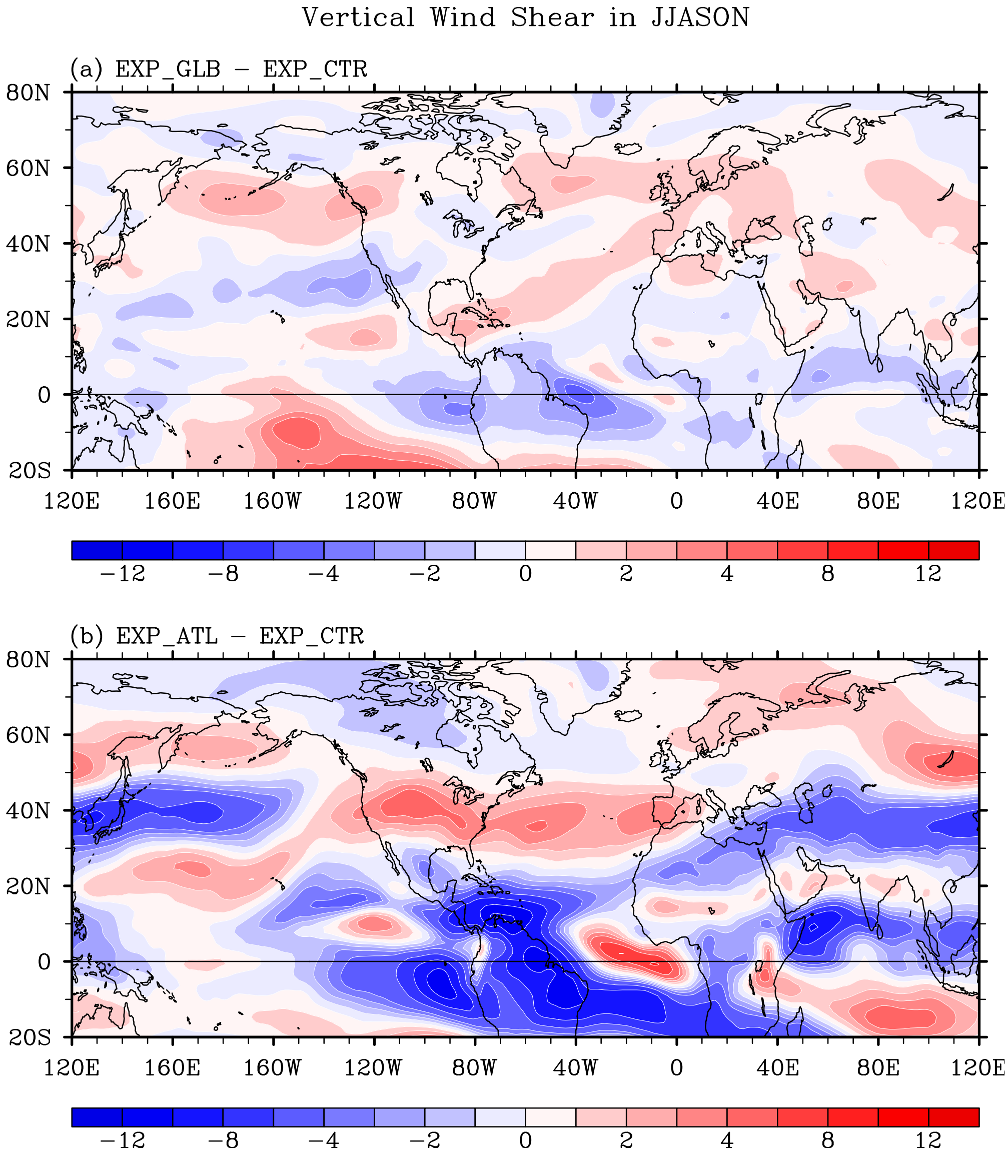
Table 1. Three CAM3 experiments are summarized. See text for detail.

Experiments	Atlantic SSTs	SSTs in Indo-Pacific Oceans	Sea Ice Fraction	CO_2 Level
EXP_CTR	2000-2007	2000-2007	2000-2010	381ppm
EXP_GLB	2090-2100	2090-2100	2000-2010	675ppm
EXP_ATL	2090-2100	2000-2007	2090-2100	675ppm



Vertical Wind Shear in JJASON
(a) EXP_GLB − EXP_CTR
80N
60N
40N
20N
0
20S
120E
160E
160W
120W
80W
40W
0
40E
80E
120E
−12
−8
−4
−2
0
2
4
8
12
(b) EXP_ATL − EXP_CTR
80N
60N
40N
20N
0
20S
120E
160E
160W
120W
80W
40W
0
40E
80E
120E
−12
−8
−4
−2
0
2
4
8
12

Figure 1.

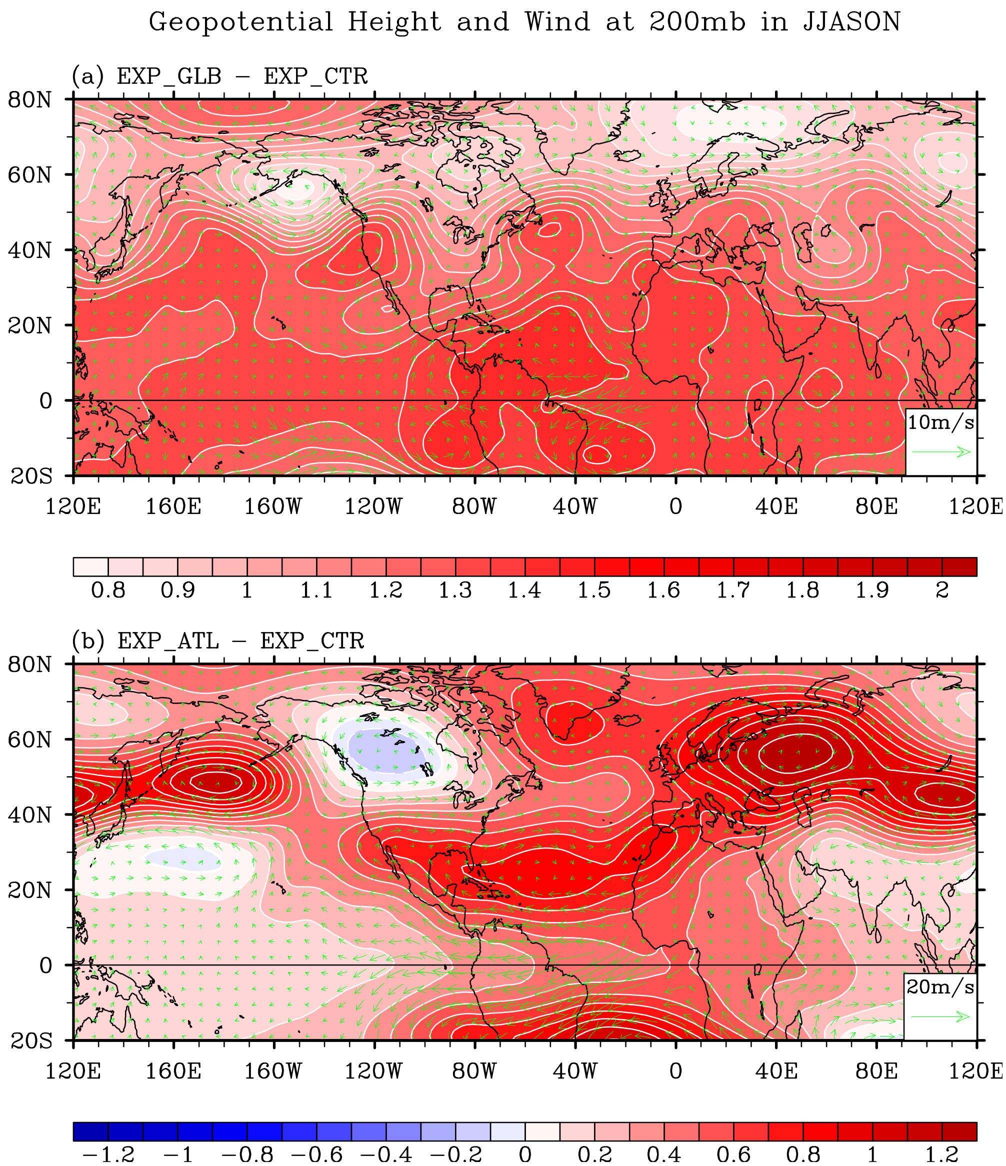

Geopotential Height and Wind at 200mb in JJASON
(a) EXP_GLB – EXP_CTR
80N
60N
40N
20N
0
20S
120E 160E 160W 120W 80W 40W 0 40E 80E 120E
10m/s
0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
(b) EXP_ATL – EXP_CTR
80N
60N
40N
20N
0
20S
120E 160E 160W 120W 80W 40W 0 40E 80E 120E
20m/s
−1.2 −1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1 1.2

Figure 2.

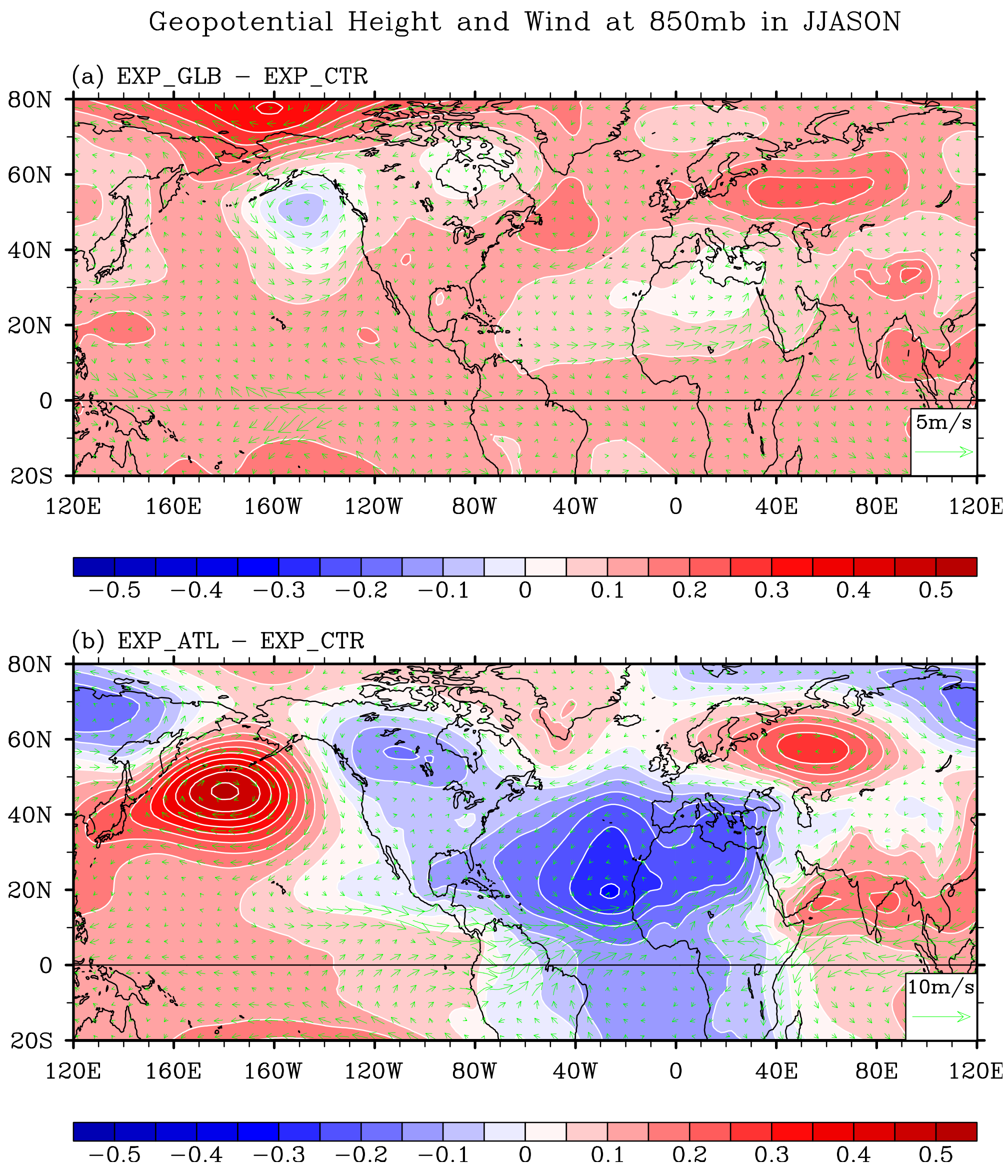

Geopotential Height and Wind at 850mb in JJASON
(a) EXP_GLB − EXP_CTR
80N
60N
40N
20N
0
20S
120E
160E
160W
120W
80W
40W
0
40E
80E
120E
5m/s
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
(b) EXP_ATL − EXP_CTR
10m/s

Figure 3.

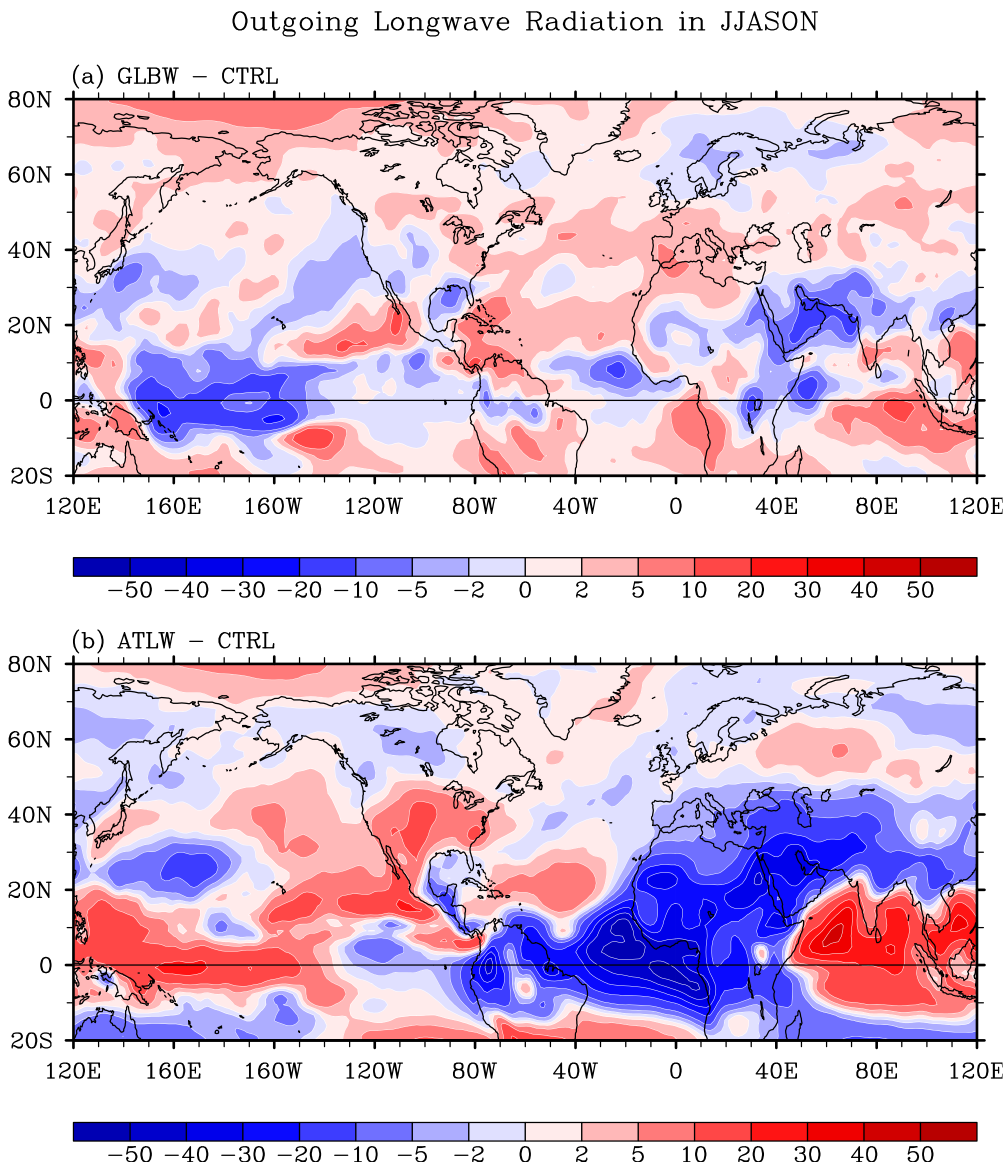

Outgoing Longwave Radiation in JJASON
(a) GLBW − CTRL
80N
60N
40N
20N
0
20S
120E
160E
160W
120W
80W
40W
0
40E
80E
120E
−50 −40 −30 −20 −10 −5 −2 0 2 5 10 20 30 40 50
(b) ATLW − CTRL
80N
60N
40N
20N
0
20S
120E
160E
160W
120W
80W
40W
0
40E
80E
120E
−50 −40 −30 −20 −10 −5 −2 0 2 5 10 20 30 40 50

Figure 4.