The double-ITCZ bias and the nontraditional Coriolis terms

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Disclaimer: This work is independent from my host institution.

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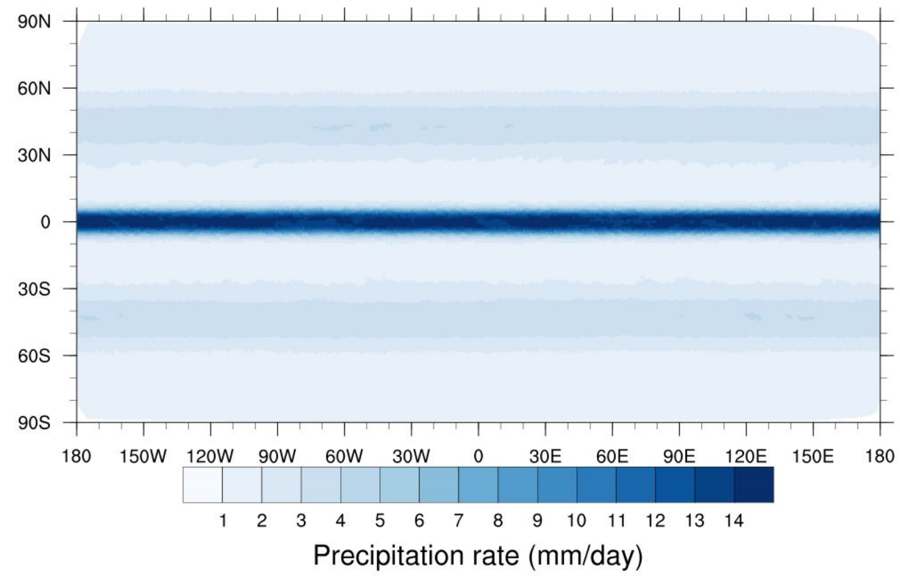
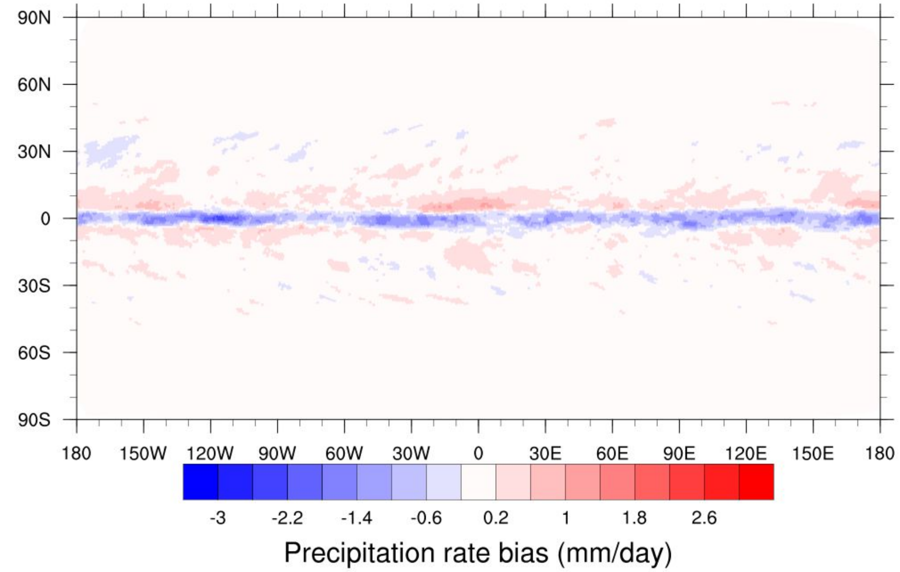
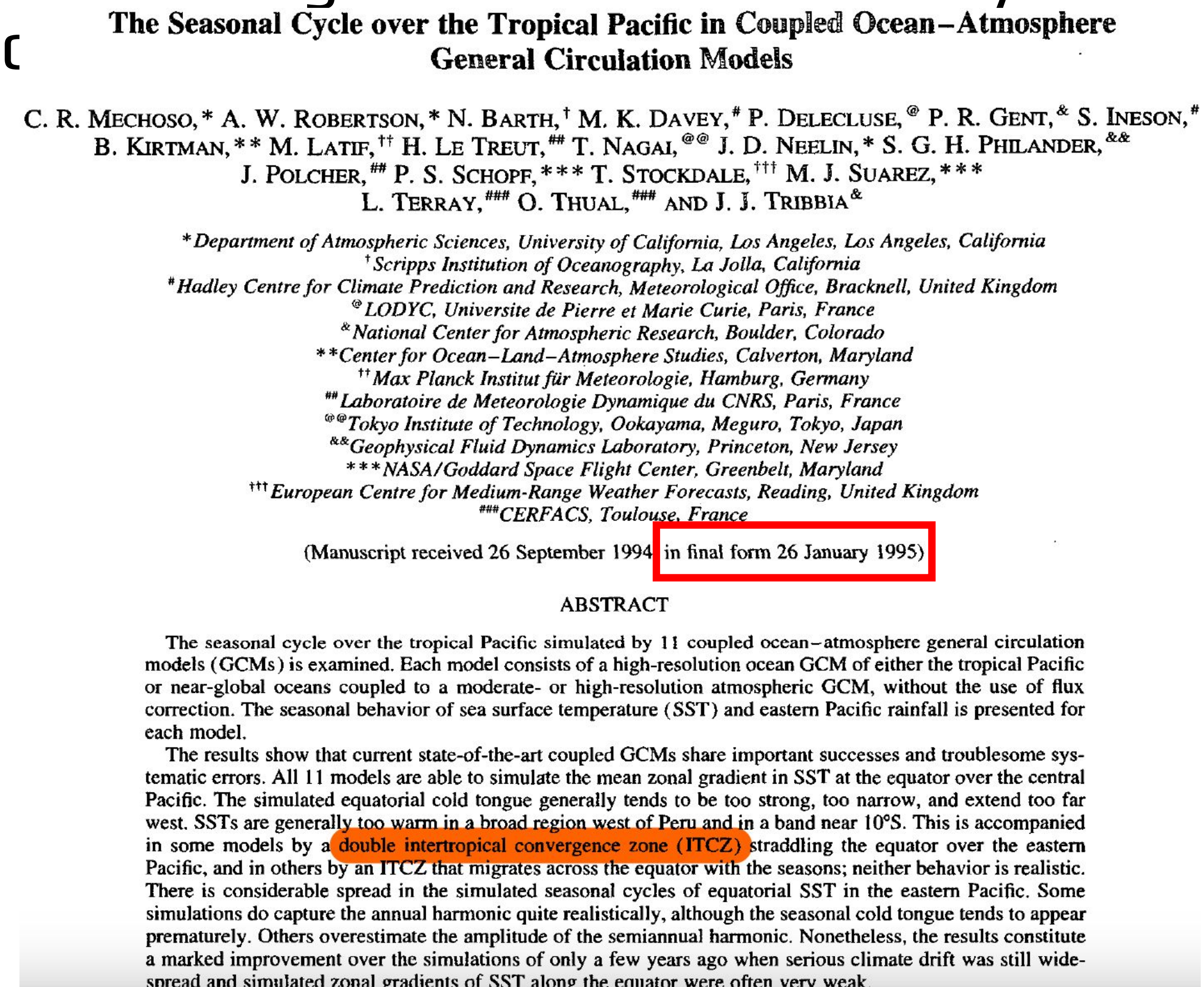




[Without NCTs] – [With NCTs]

The double-ITCZ (intertropical convergence zone) bias

has been a problem in generations of Earth system models and has been stuc



The Seasonal Cycle over the Tropical Pacific in Coupled Ocean–Atmosphere General Circulation Models

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ABSTRACT

The seasonal cycle over the tropical Pacific simulated by 11 coupled ocean–atmosphere general circulation models (GCMs) is examined. Each model consists of a high-resolution ocean GCM of either the tropical Pacific or near-global oceans coupled to a moderate- or high-resolution atmospheric GCM, without the use of flux correction. The seasonal behavior of sea surface temperature (SST) and eastern Pacific rainfall is presented for each model.

The results show that current state-of-the-art coupled GCMs share important successes and troublesome systematic errors. All 11 models are able to simulate the mean zonal gradient in SST at the equator over the central Pacific. The simulated equatorial cold tongue generally tends to be too strong, too narrow, and extend too far west. SSTs are generally too warm in a broad region west of Peru and in a band near 10°S. This is accompanied in some models by a double intertropical convergence zone (ITCZ) straddling the equator over the eastern Pacific, and in others by an ITCZ that migrates across the equator with the seasons; neither behavior is realistic. There is considerable spread in the simulated seasonal cycles of equatorial SST in the eastern Pacific. Some simulations do capture the annual harmonic quite realistically, although the seasonal cold tongue tends to appear prematurely. Others overestimate the amplitude of the semiannual harmonic. Nonetheless, the results constitute a marked improvement over the simulations of only a few years ago when serious climate drift was still widespread and simulated zonal gradients of SST along the equator were often very weak.

The double-ITCZ (intertropical convergence zone) bias

has been a problem in generations of Earth system models and has been studied for decades

Toward Improving the Simulation of Tropical Precipitation in E3SM

FUNDING PROGRAM AREA(S)

ESMD

PROJECT TYPE

University Grant

PROJECT TERM

2021-09 to 2025-08

PROJECT TEAM

Biases in tropical precipitation such as the double Intertropical Convergence Zone (ITCZ) are a long-standing problem in many global climate and Earth system models, including DOE's Exascale Energy Earth System Model (E3SM). The E3SM has large positive precipitation biases across the tropical Pacific south of the equator and an excessive equatorial cold tongue compared to observations. In this project, the team aims to improve the simulation of tropical precipitation and associated sea surface temperature (SST) in E3SM by addressing the following questions: (1) How and to what extent does convective parameterization contribute to tropical precipitation biases? (2) How do coupled atmosphere-ocean feedback processes affect the double ITCZ developed in E3SM? (3) How can tropical precipitation and SST simulations in E3SM be improved?

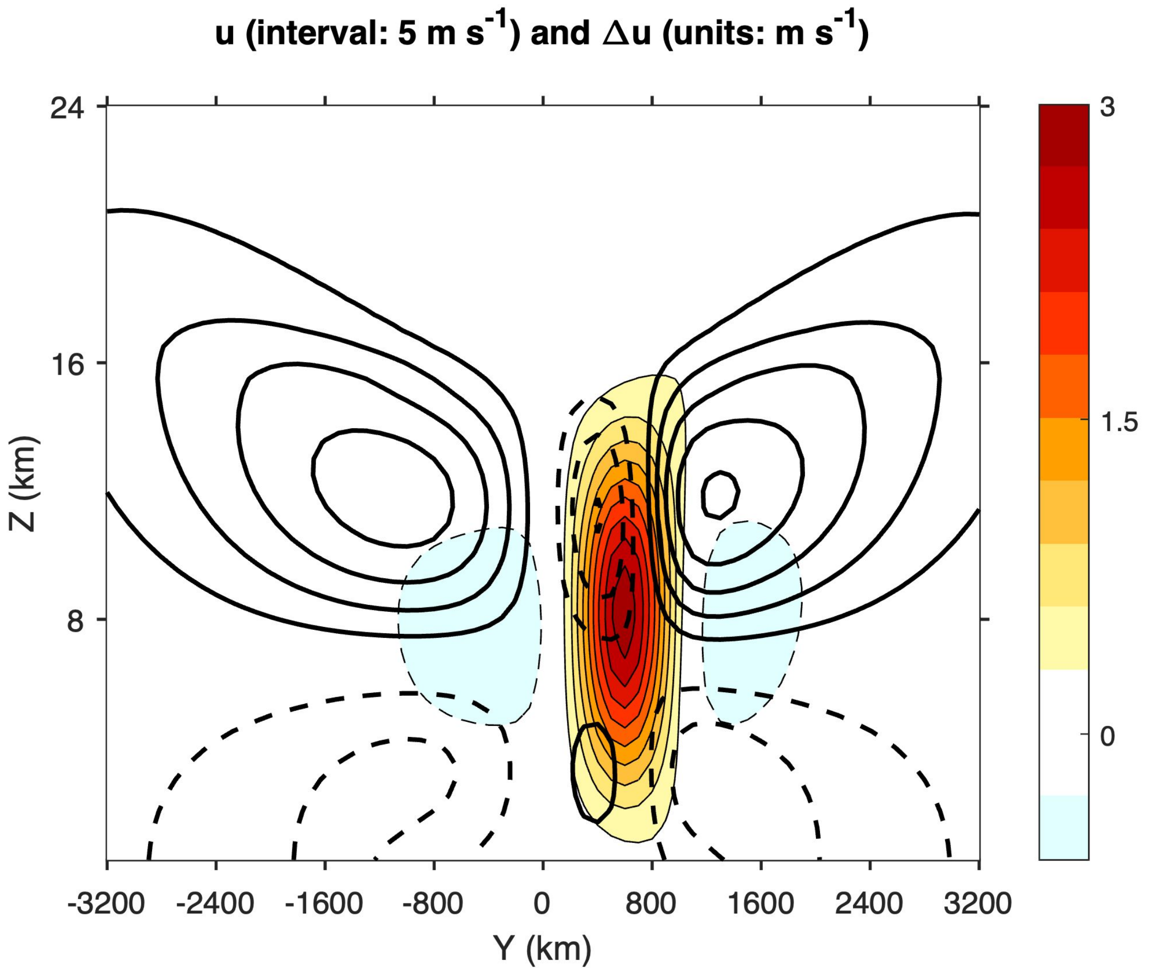
NCTs (nontraditional Coriolis terms)

Most global atmospheric models* share a common approximation: the traditional shallow-atmosphere approximation, which neglects the NCTs.

NCTs arise from planetary rotation. NCTs turn eastward motion upward and upward motion westward, and vice versa.

*A notable exception lies in UK Met Office. The dynamical core of HadGEM relaxes this approximation.

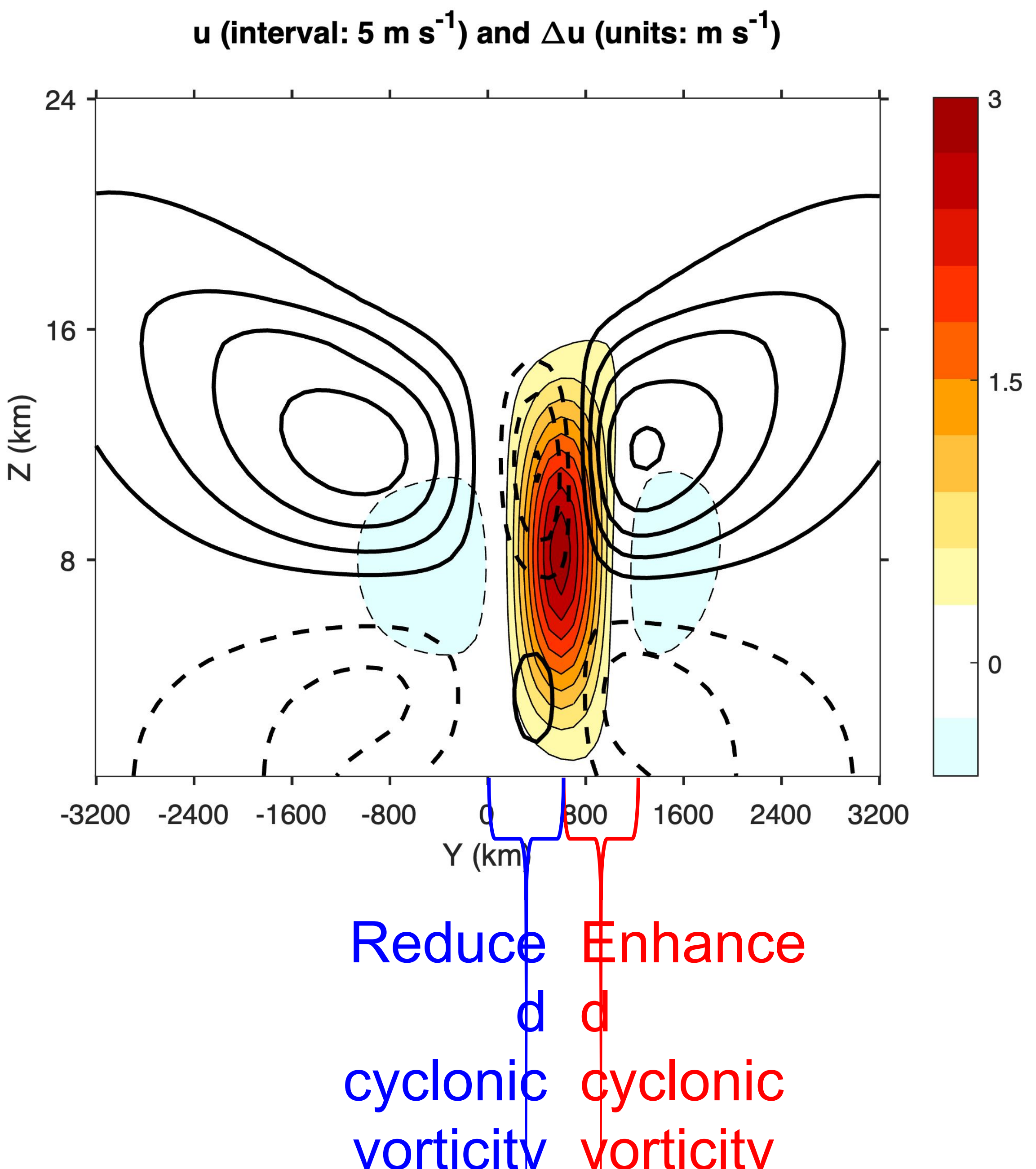
Omitting NCTs yields a westerly wind bias in an ITCZ-like heating region



- Contour: u (w/ NCTs)
- Shading: Δu (w/o minus w/)
- Flow response to the following prescribed heat source:
  - ITCZ width = 1000 km
  - ITCZ location = 600 km

$$\frac{max.\,westerly\;bias}{max.\,westerly\;wind} = 12\%$$

Ong & Roundy (2019)



Hypothesis

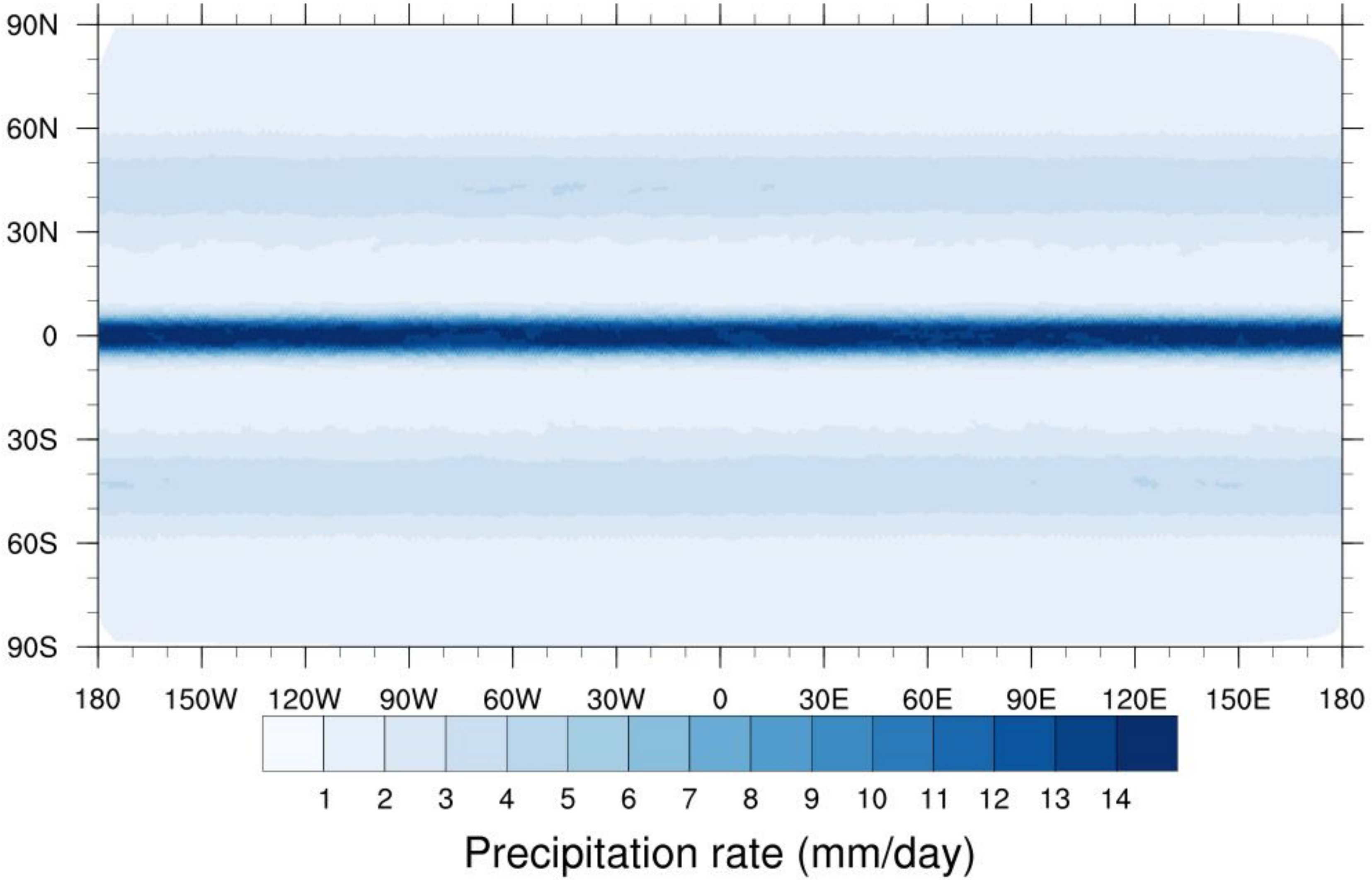
- On the poleward side of ITCZ:
  - Neglecting NCTs
  - ➡️ enhances cyclonic vorticity
  - ➡️ enhances Ekman pumping
  - ➡️ enhances precipitation
- On the equatorward side of ITCZ, the opposite is true.

We hypothesize neglecting NCTs

- reduces equatorial precipitation,
- enhances off-equatorial precipitation, and thus
- promotes a double-ITCZ pattern

Methods: Aquaplanet experiment

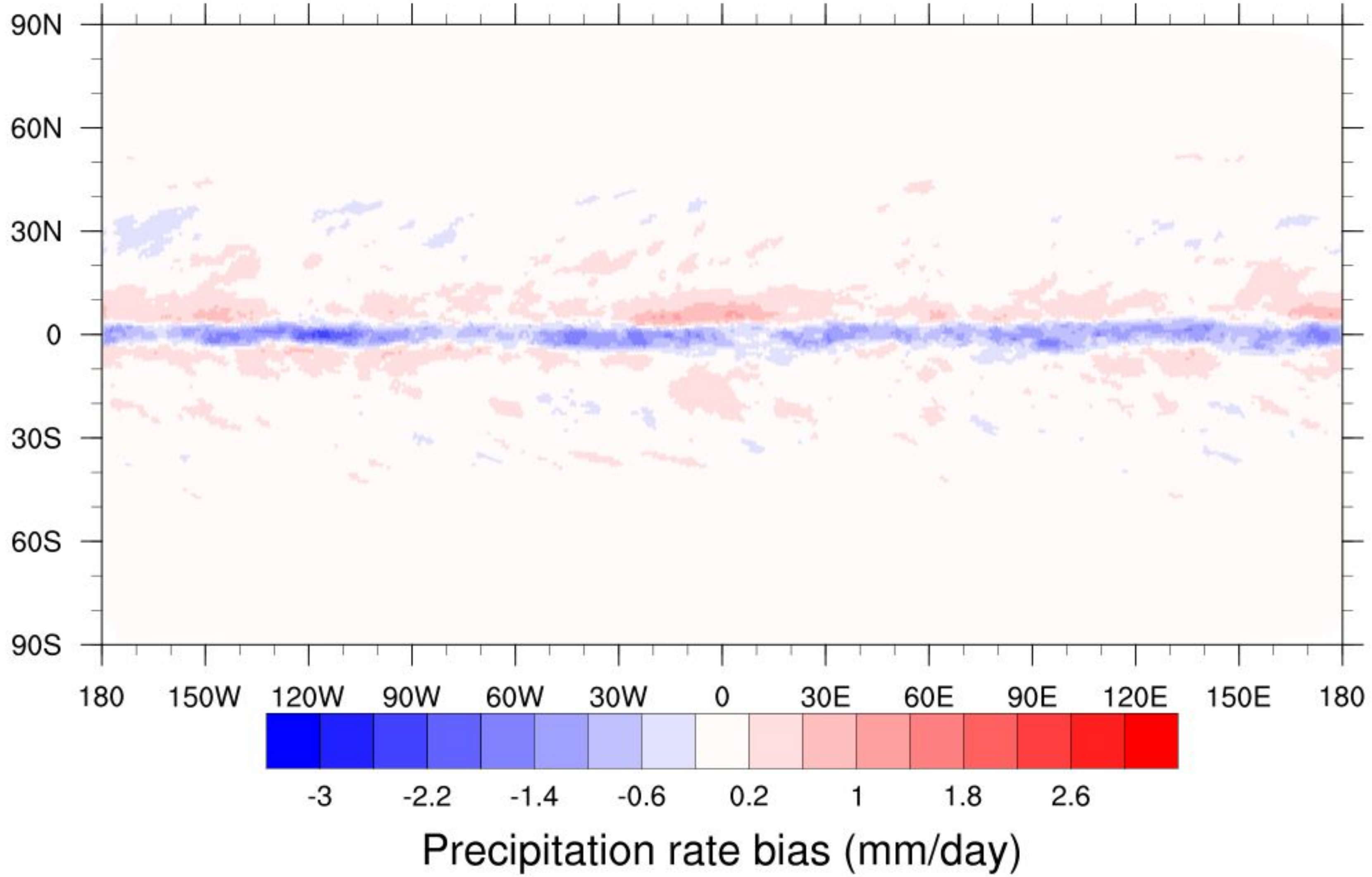
- Model used:
  - CAM (Community Atmosphere Model) development version (cam6_4_044) with the
  - deep-atmosphere MPAS (Model for Prediction Across Scales) dynamical core (Skamarock, Ong, & Klemp, 2021) with 120-km mesh.
- ‘QPC6’ Configuration:
  - Aquaplanet with fixed sea-surface temperature
  - Perpetual equinox forcing
- Simulation setup:
  - Spin up for one year from motionless US standard atmosphere state with the deep-atmosphere option, and then
  - Branch into two 16-year simulations:
    - continue to solve the deep-atmosphere equations (with NCTs)
    - switch to solve the shallow-atmosphere equations (without NCTs)



Results

Precipitation climatology

With NCTs



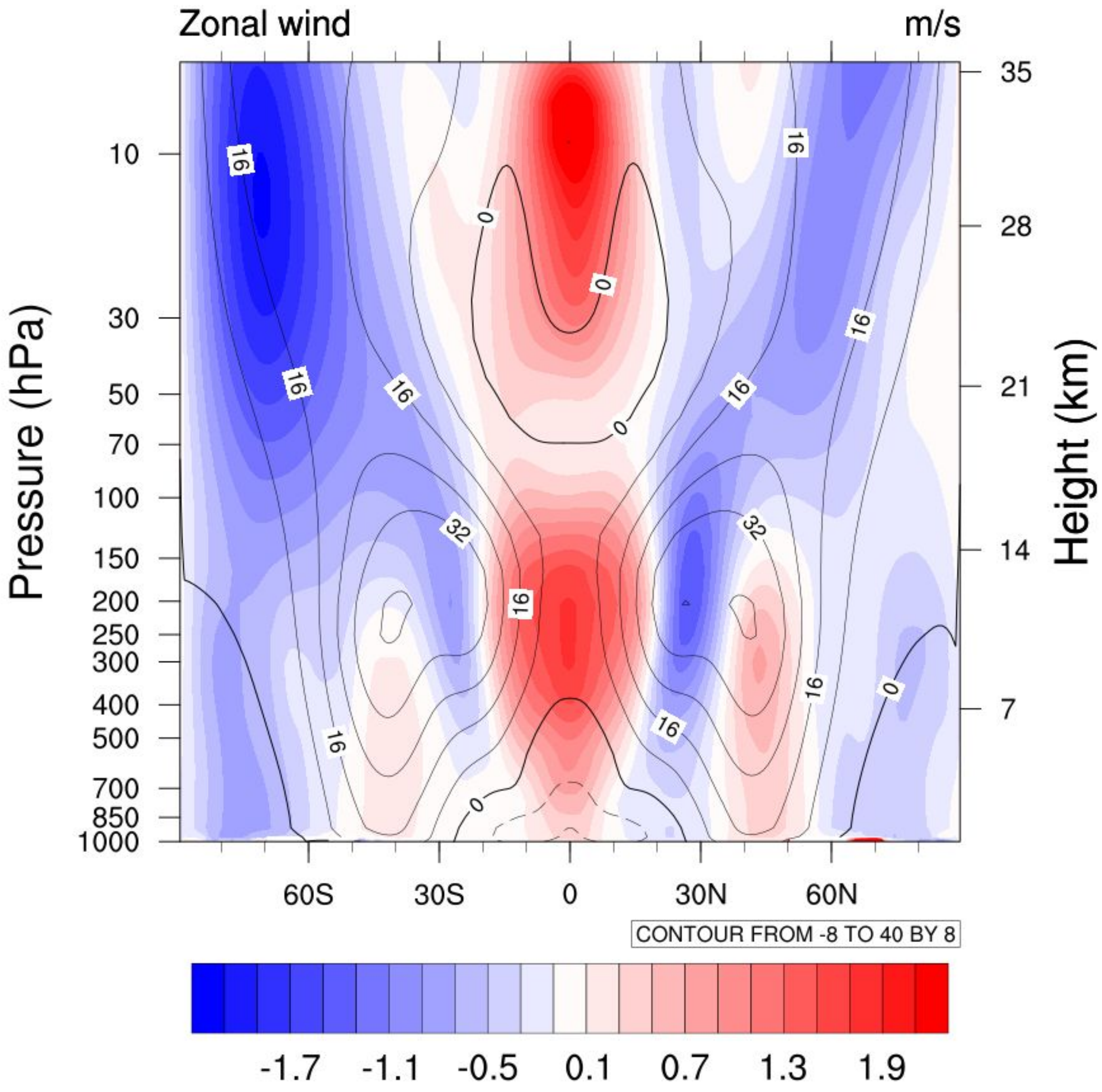
[Without NCTs] – [With NCTs]

Results

Bias of precipitation climatology due to the traditional approximation

Note:

- Reduced equatorial precipitation
- Enhanced off-equatorial precipitation



[Without NCTs] – [With NCTs]

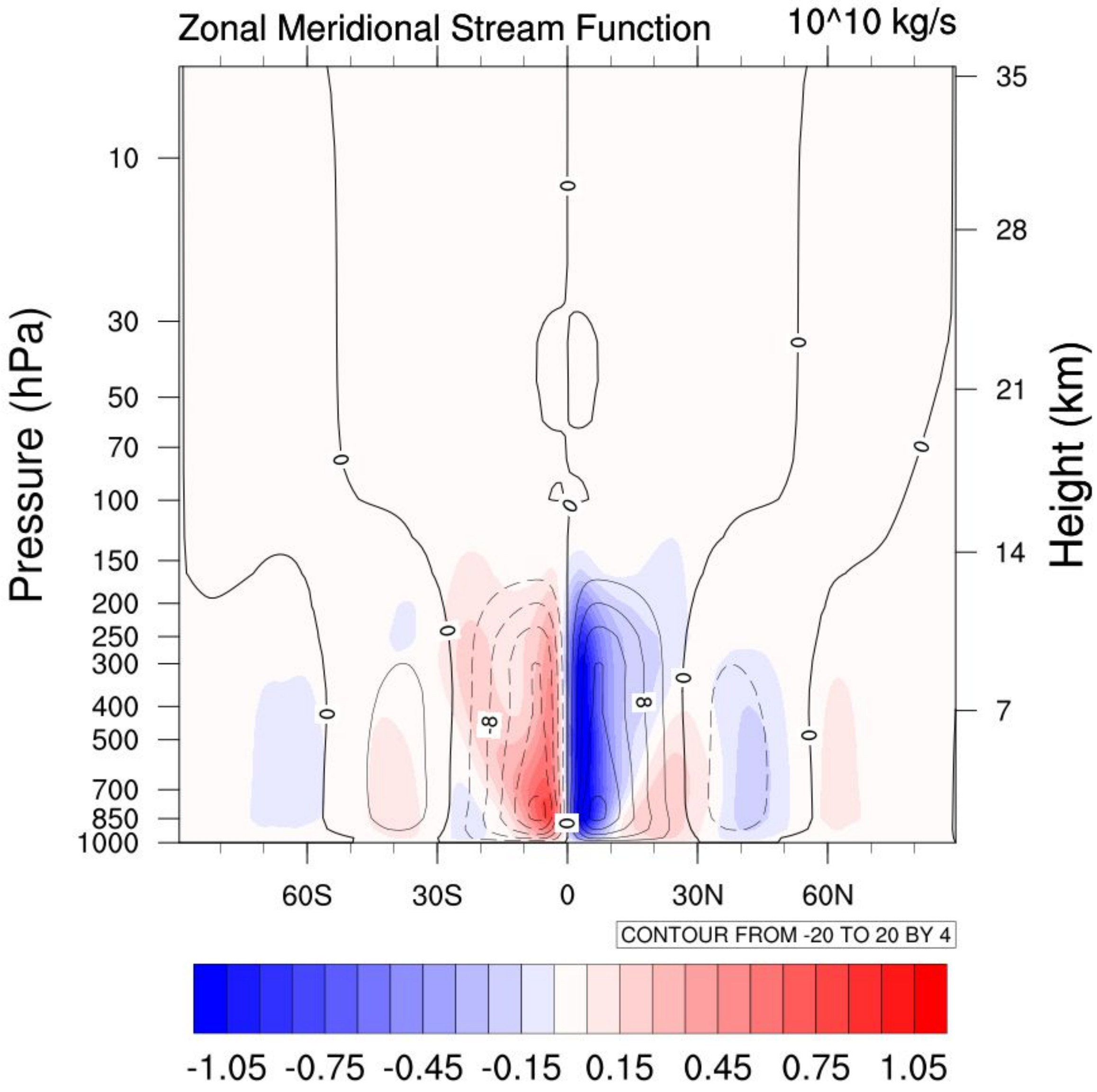
Results

Zonal mean zonal wind climatology (contoured)

Its bias due to the traditional approximation (shaded)

Note:

- Enhanced cyclonic wind shear in 5° to 20° latitudes



[Without NCTs] – [With NCTs]

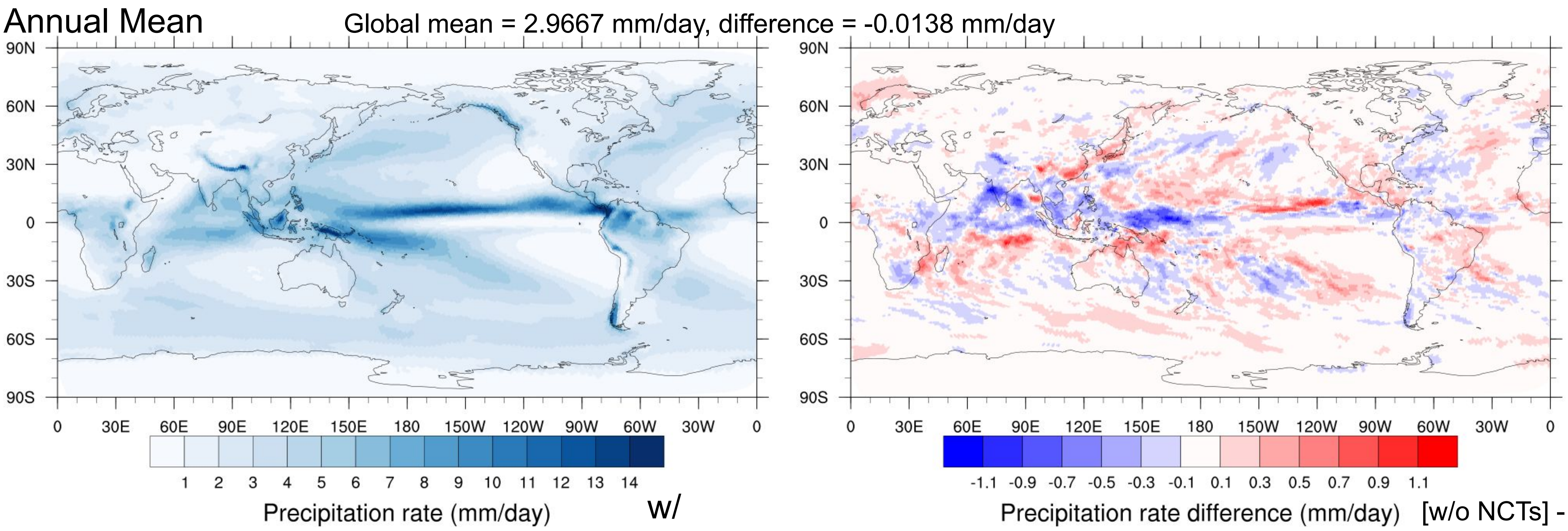
Results

Zonal mean streamfunction climatology (contoured)

Its bias due to the traditional approximation (shaded)

Note:

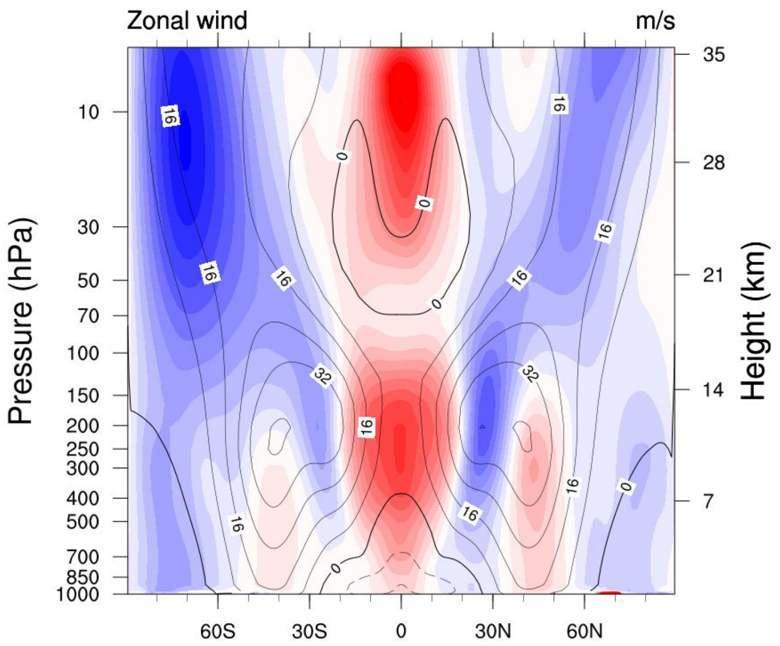
- Enhanced cyclonic wind shear in 5° to 20° latitudes

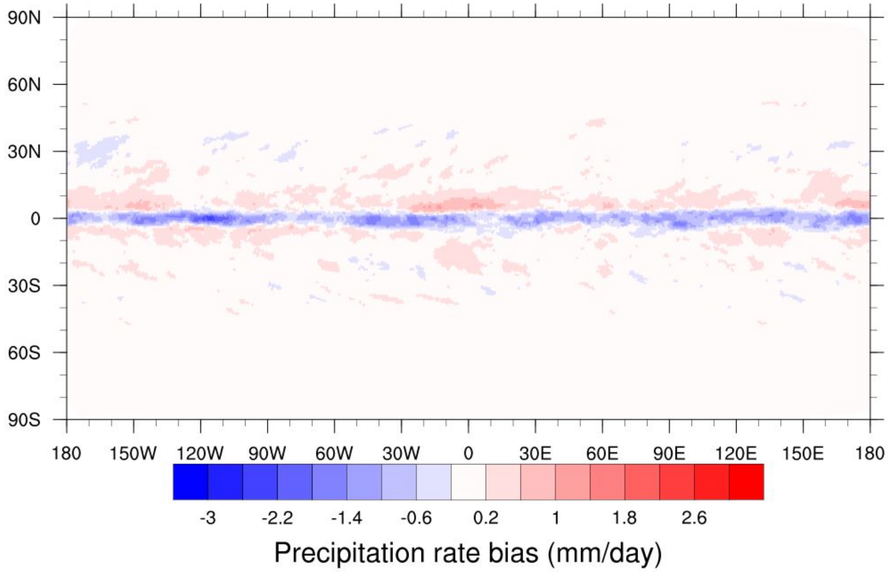


w/ NCTs

[w/o NCTs] - [w/ NCTs]

- AMIP experiment also shows a double-ITCZ pattern in the difference between results with and without NCTs.
- 'F2000climo' Configuration
  - Climatological seasonal sea-surface temperature around 2000
  - Climatological seasonal forcing around 2000





[Without NCTs] – [With NCTs]

Conclusion

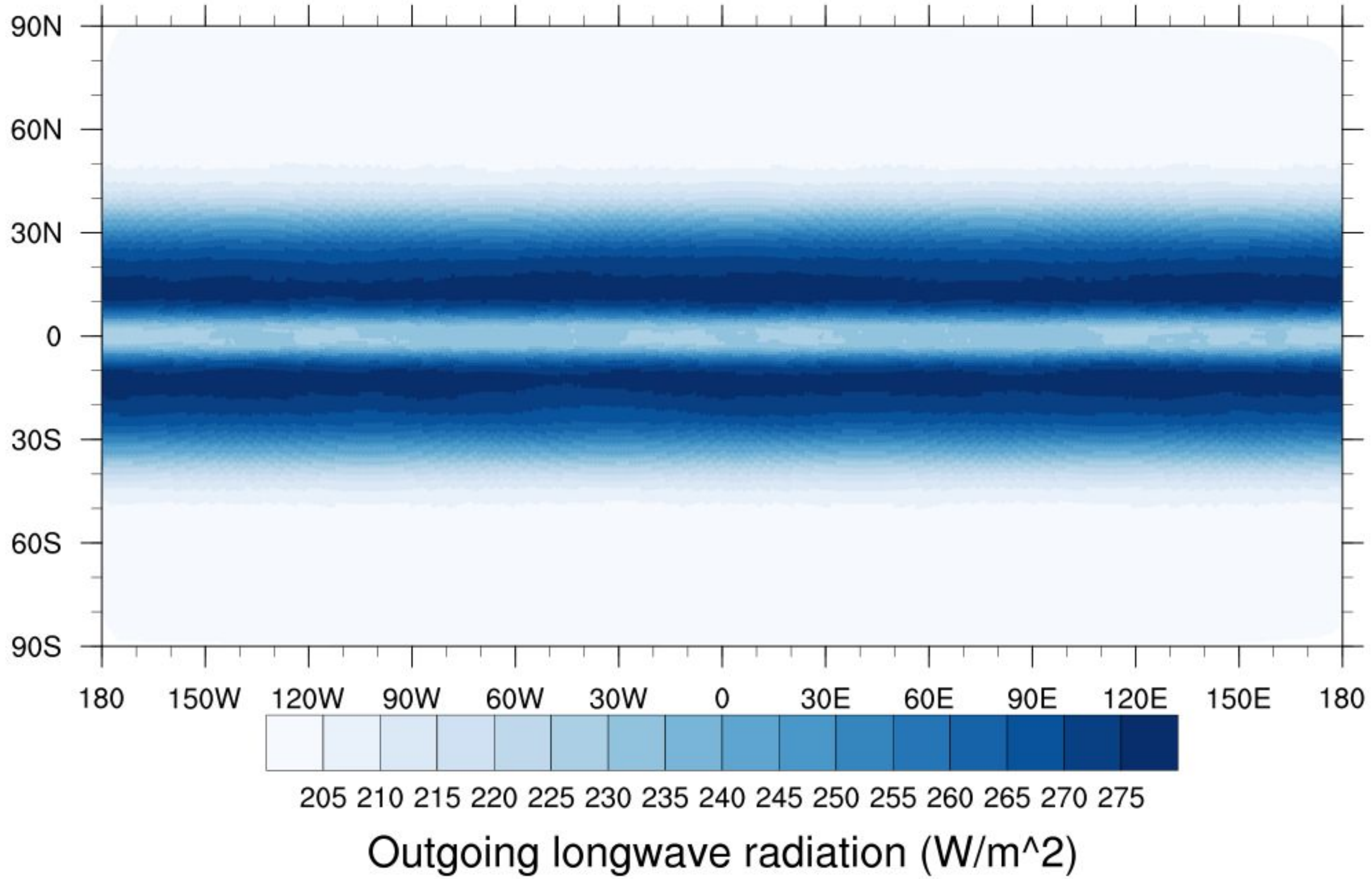
- Climate models have suffered from the double-ITCZ bias for decades.
- Climate models have neglected NCTs for decades with only few exceptions
- This study shows that neglecting NCTs promotes a double-ITCZ pattern through the following pathway:
  - On the poleward side of ITCZ:
    - Neglecting NCTs

    ➡️ enhances cyclonic vorticity

    ➡️ enhances Ekman pumping

    ➡️ enhances precipitation
  - The opposite is true on the equatorward side of ITCZ:

Supplementary

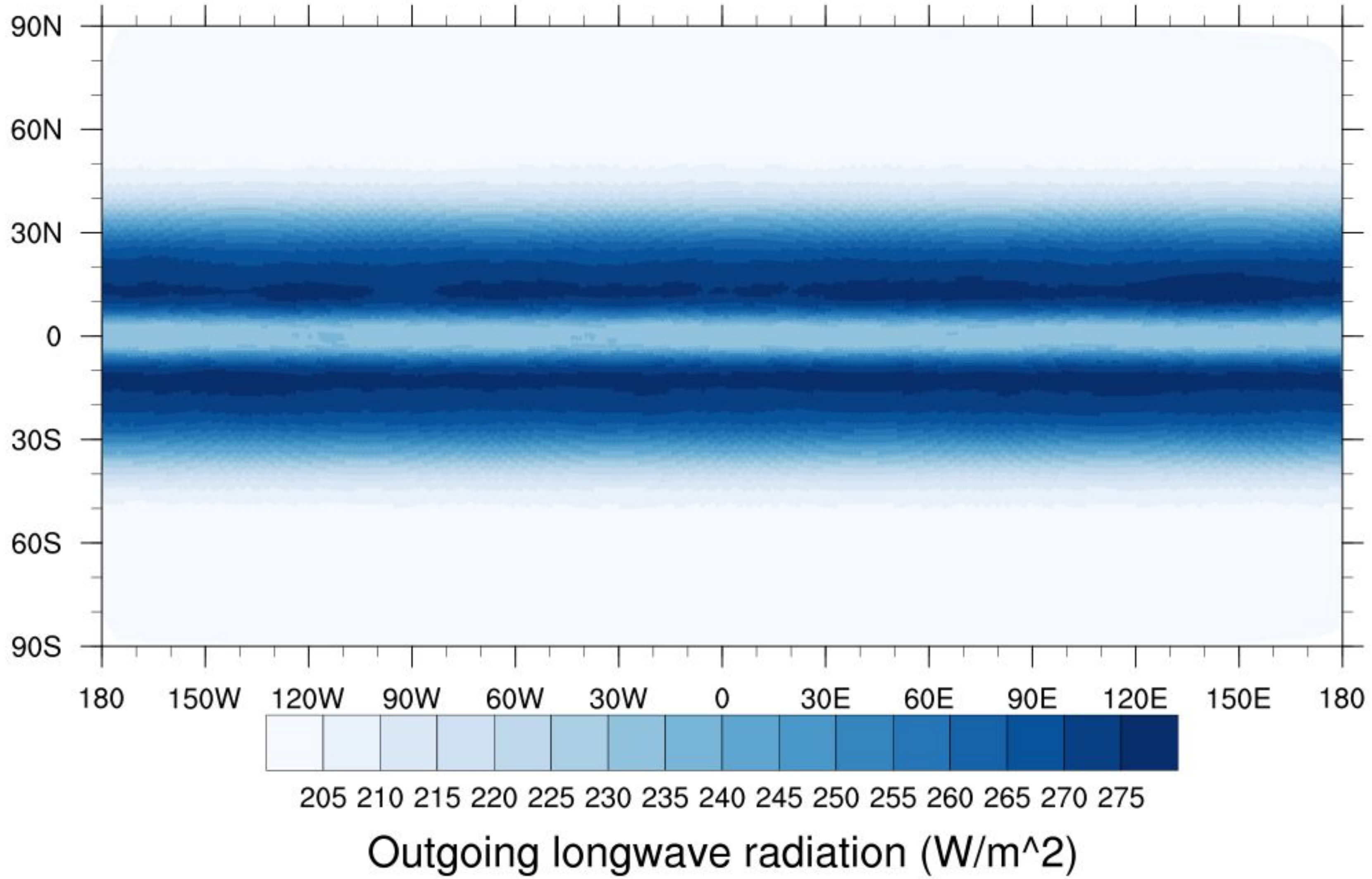


Results

Outgoing longwave radiation (all-sky) climatology

With NCTs

Global mean = 238.551 W/m^2

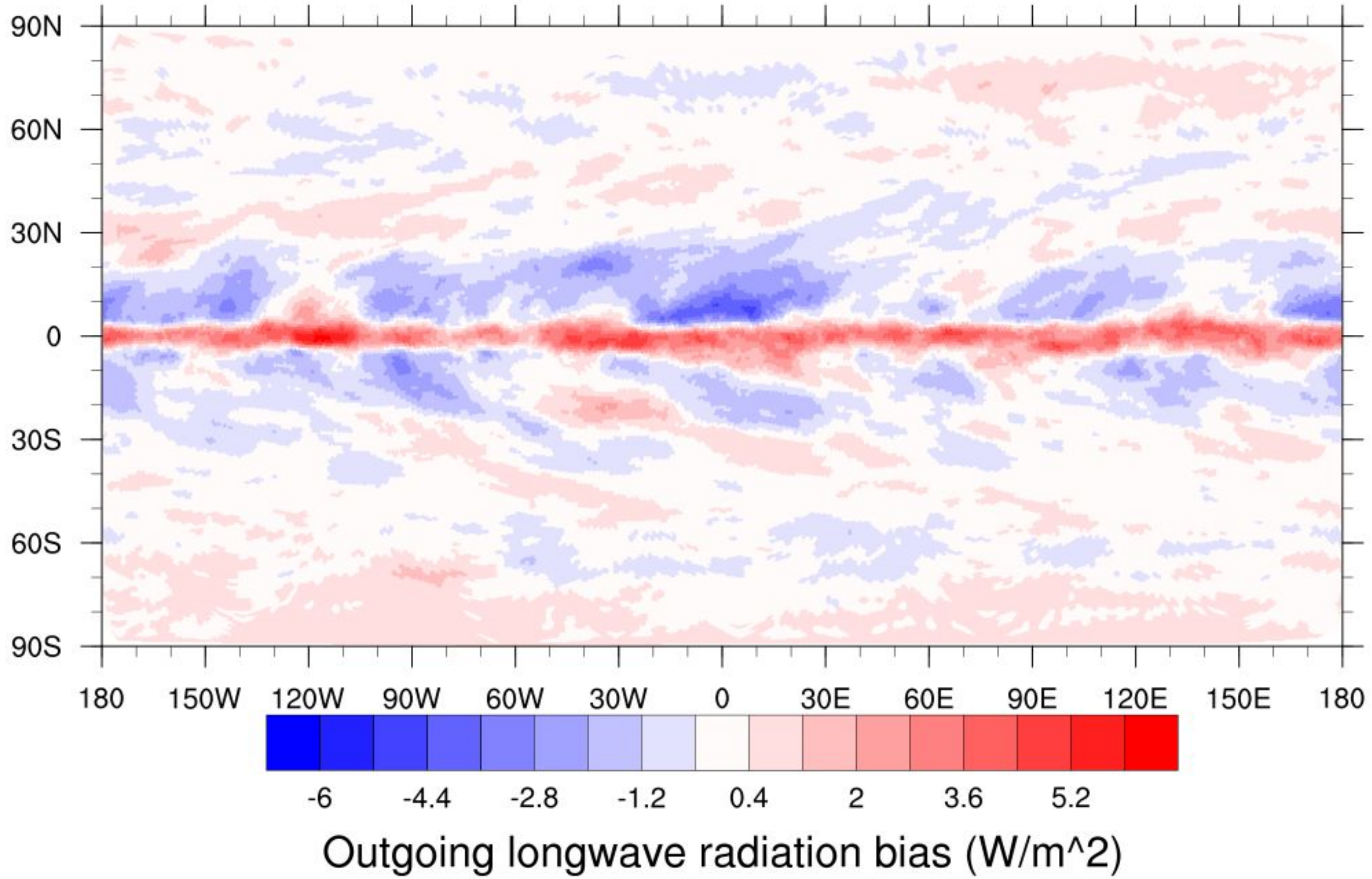


Results

Outgoing longwave radiation (all-sky) climatology

Without NCTs

Global mean = 238.485 W/m^2

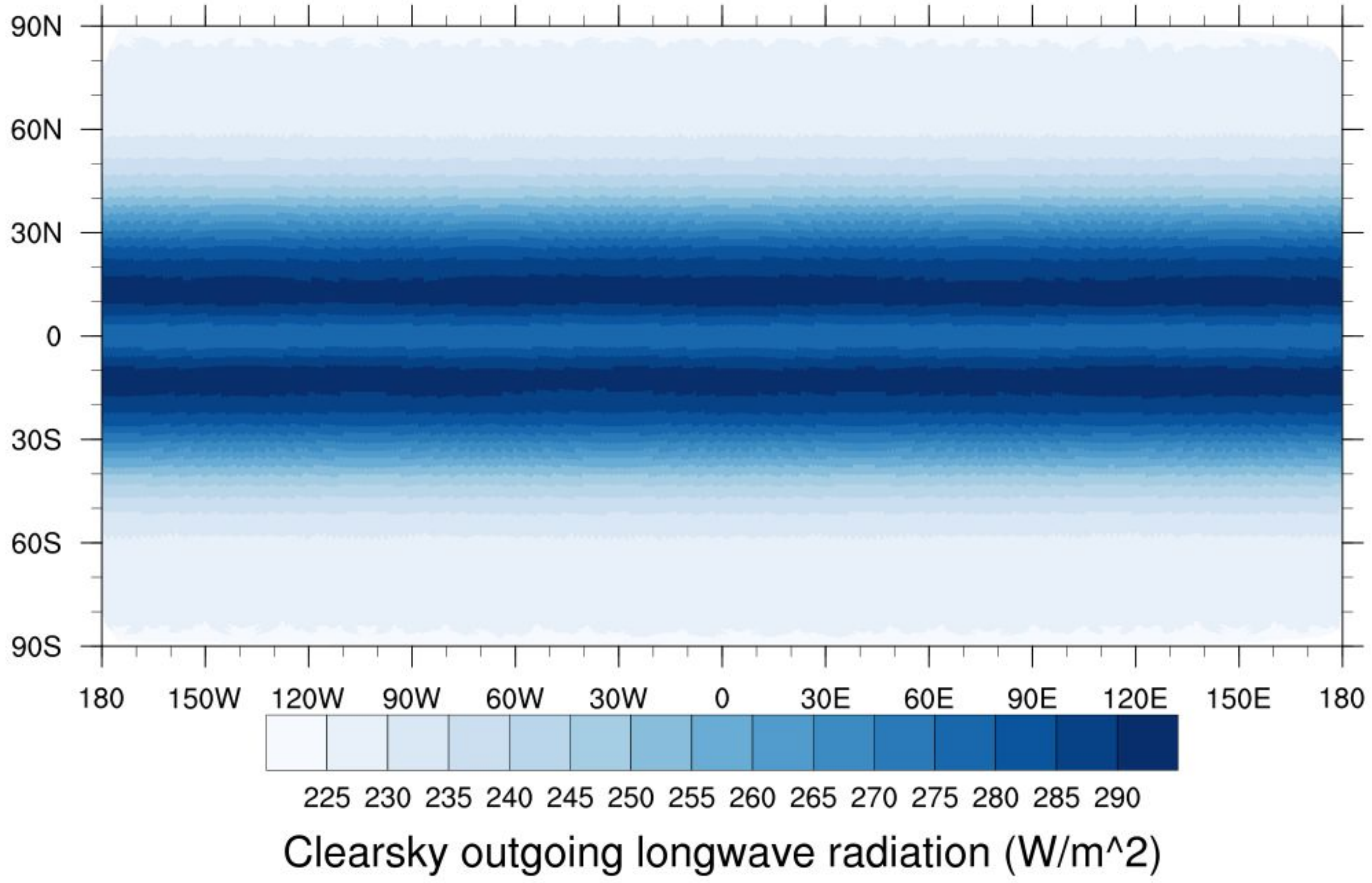


[Without NCTs] – [With NCTs]

Results

Bias of outgoing longwave radiation (all-sky) climatology

Global mean = 0.066 W/m^2

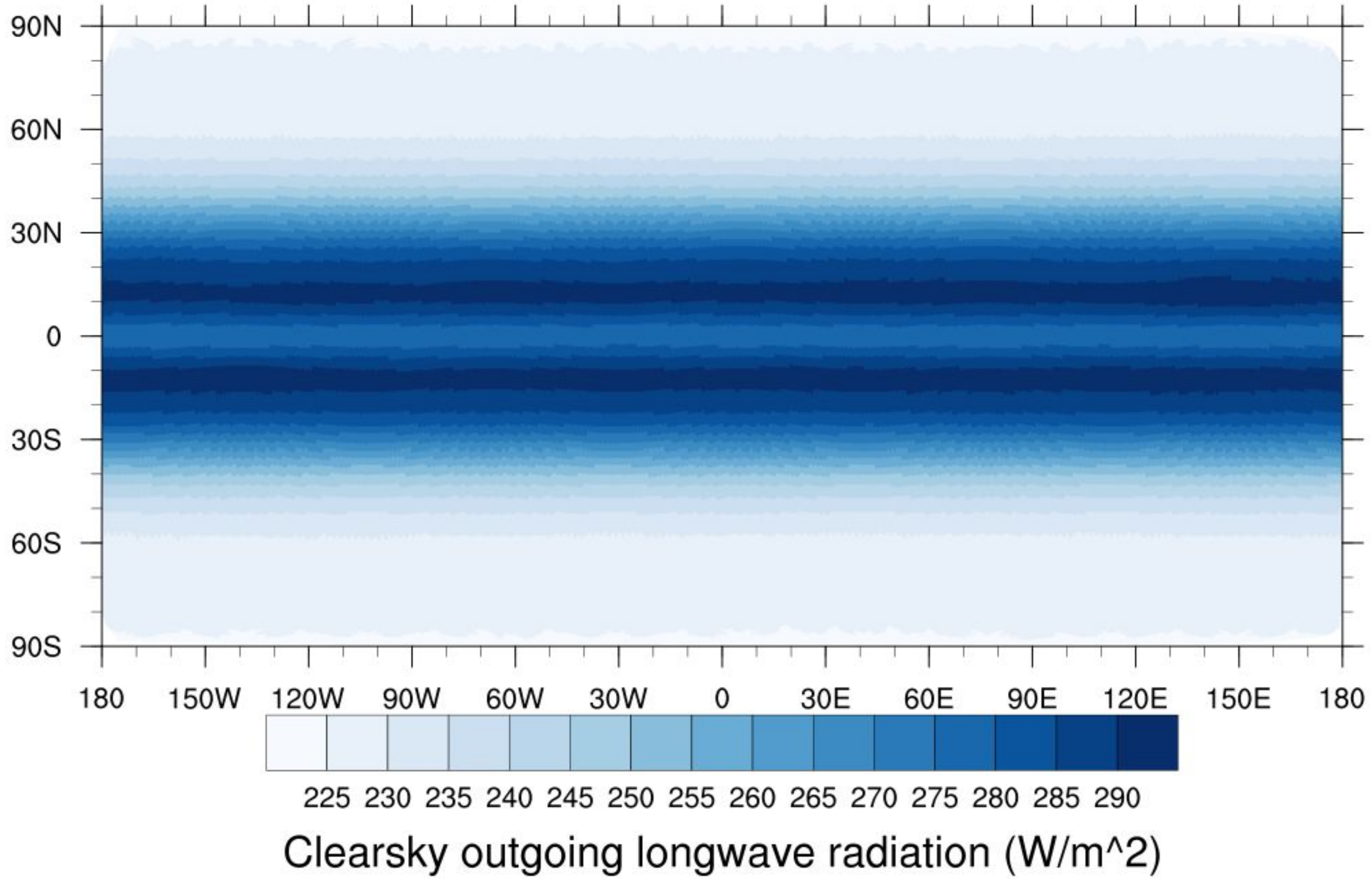


Results

Outgoing longwave radiation (clear-sky) climatology

With NCTs

Global mean = 263.428 W/m^2

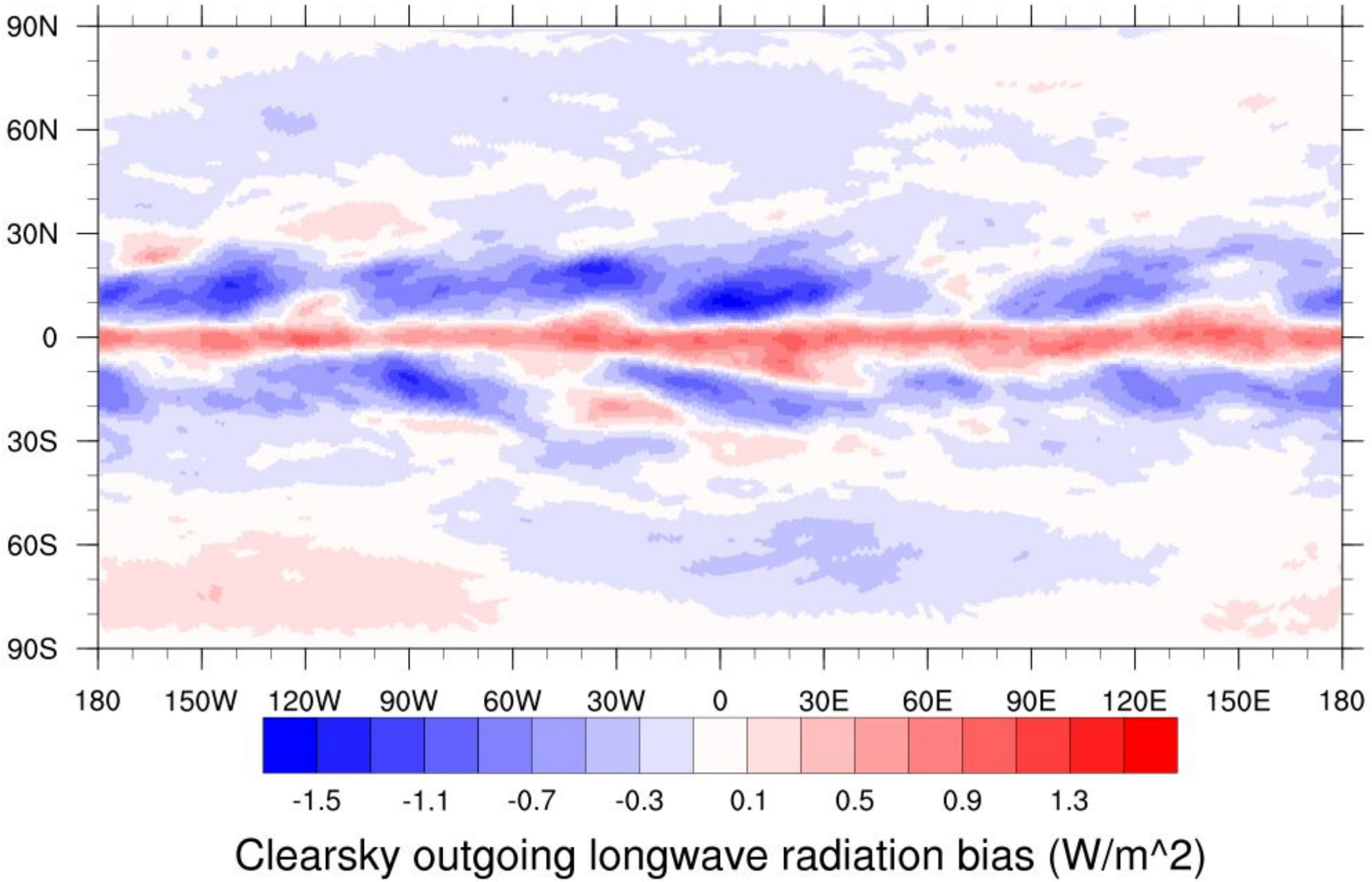


Results

Outgoing longwave radiation (clear-sky) climatology

Without NCTs

Global mean = 263.283 W/m^2

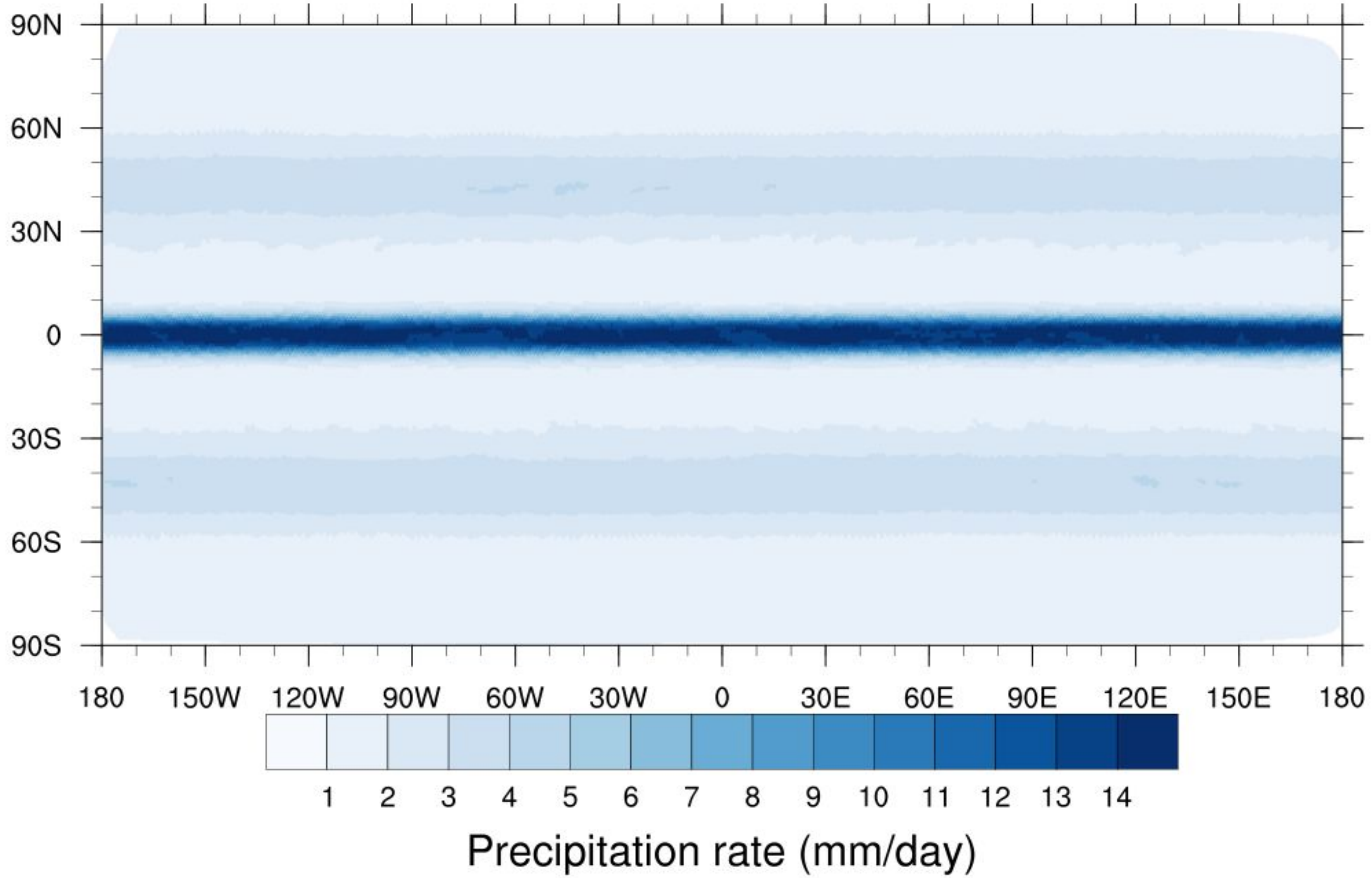


[Without NCTs] – [With NCTs]

Results

Bias of outgoing longwave radiation (clear-sky) climatology

Global mean = 0.144 W/m^2

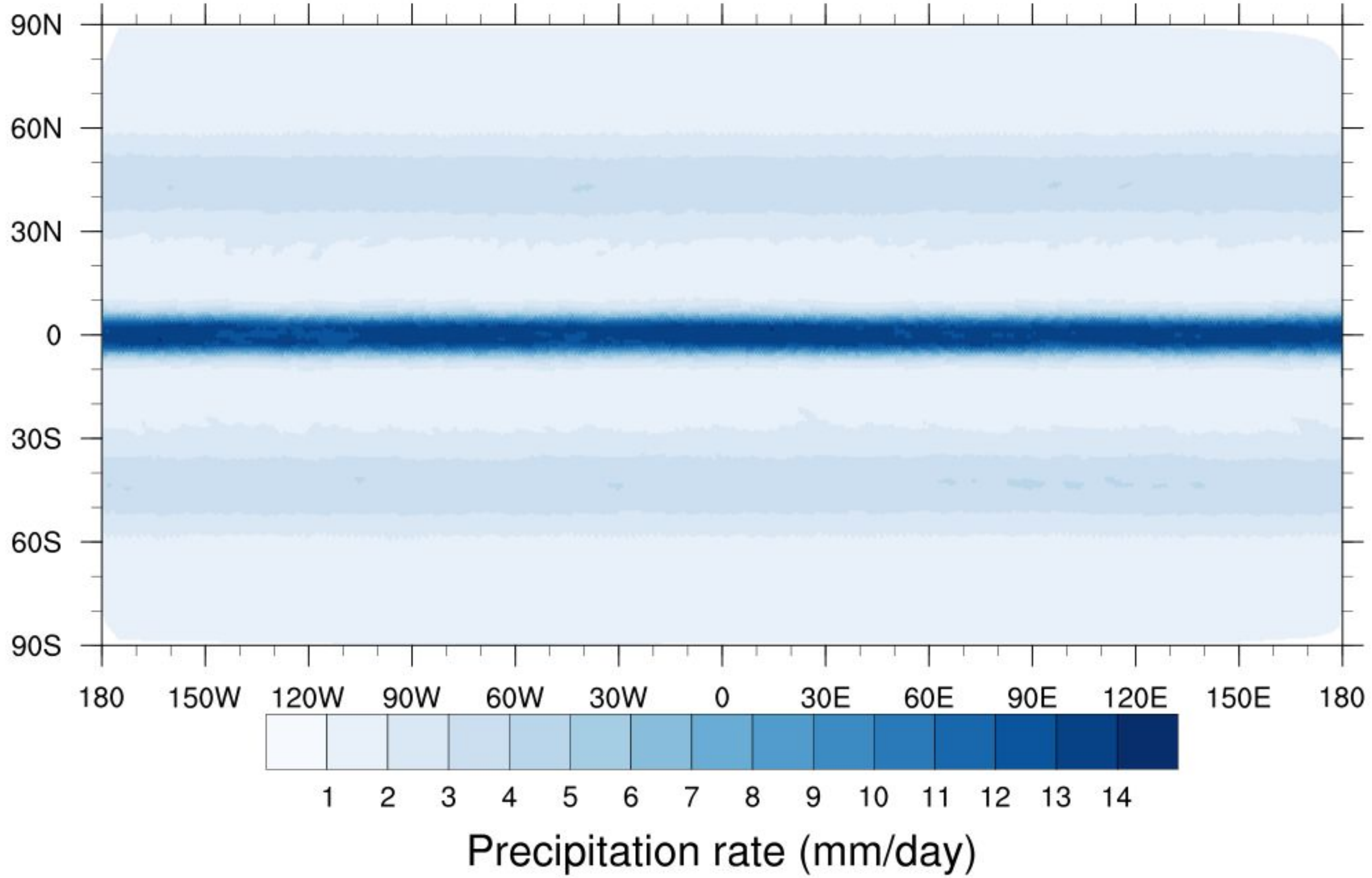


Results

Precipitation climatology

With NCTs

Global mean = 3.3153 mm/day

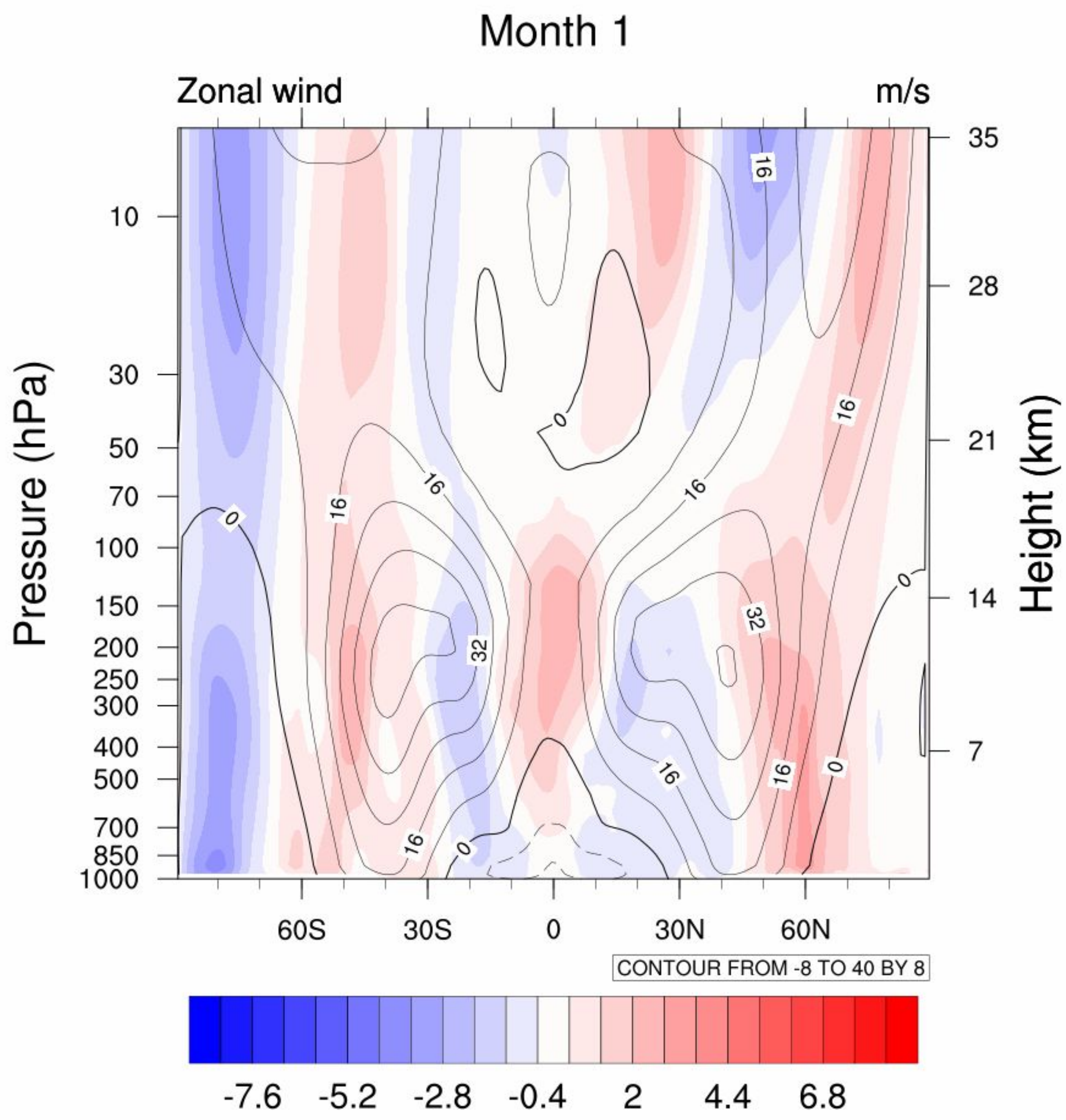


Results

Precipitation climatology

Without NCTs

Global mean = 3.3180 mm/day



[Without NCTs] – [With NCTs]

Results

Zonal mean zonal wind climatology (contoured)

Its bias due to the traditional approximation (shaded)

Note:

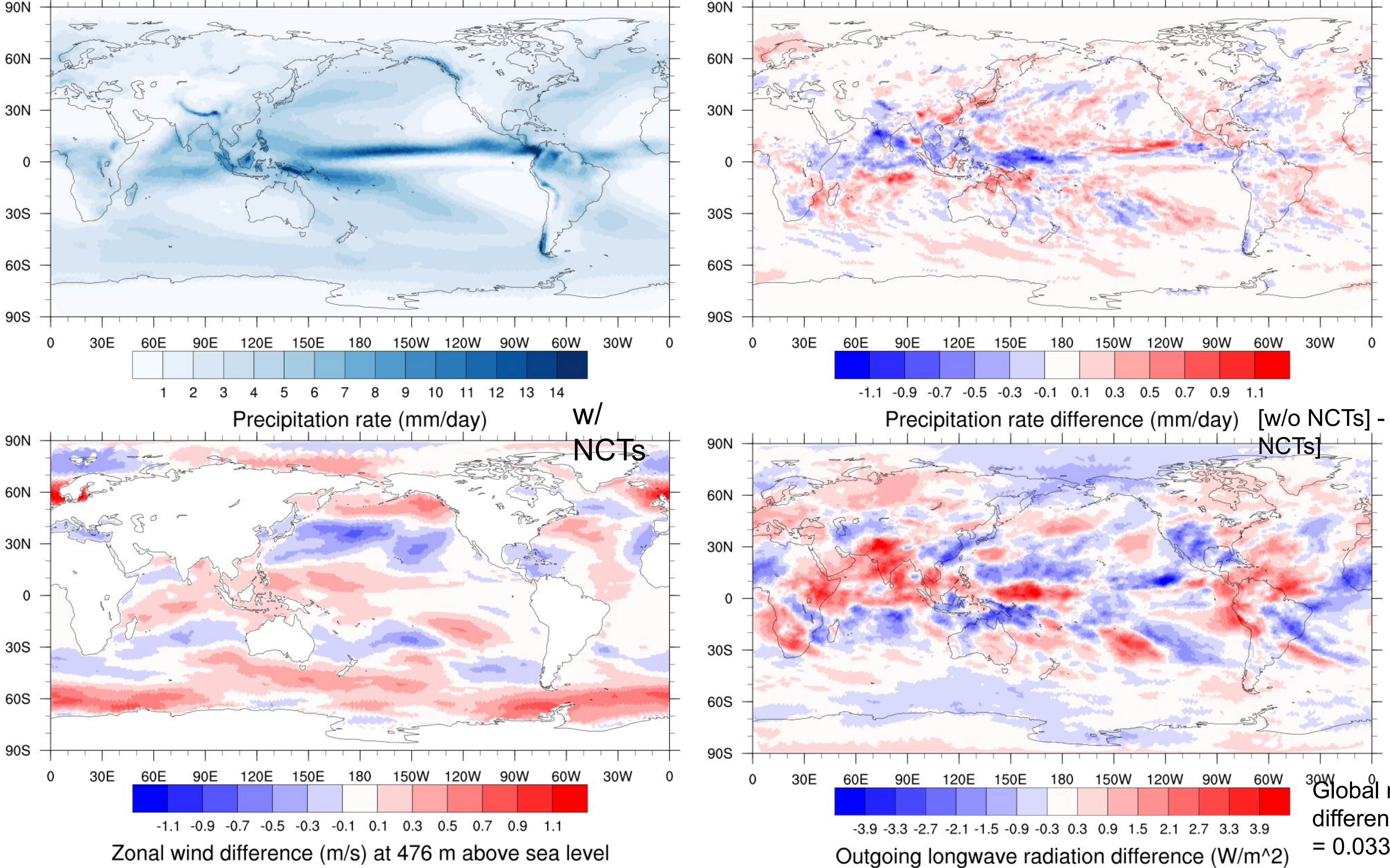
- Enhanced cyclonic wind shear in 5° to 20° latitudes

Methods: AMIP experiment

- Model used:
  - CAM (Community Atmosphere Model) development version (cam6_4_044) with the
  - deep-atmosphere MPAS (Model for Prediction Across Scales) dynamical core (Skamarock, Ong, & Klemp, 2021) with 120-km mesh.
- ‘F2000climo’ Configuration:
  - Climatological seasonal sea-surface temperature around 2000
  - Climatological seasonal forcing around 2000
- Simulation setup:
  - From 2000-01-01, run two 16-year simulations:
    - solve the deep-atmosphere equations (with NCTs)
    - solve the shallow-atmosphere equations (without NCTs)

Annual Mean

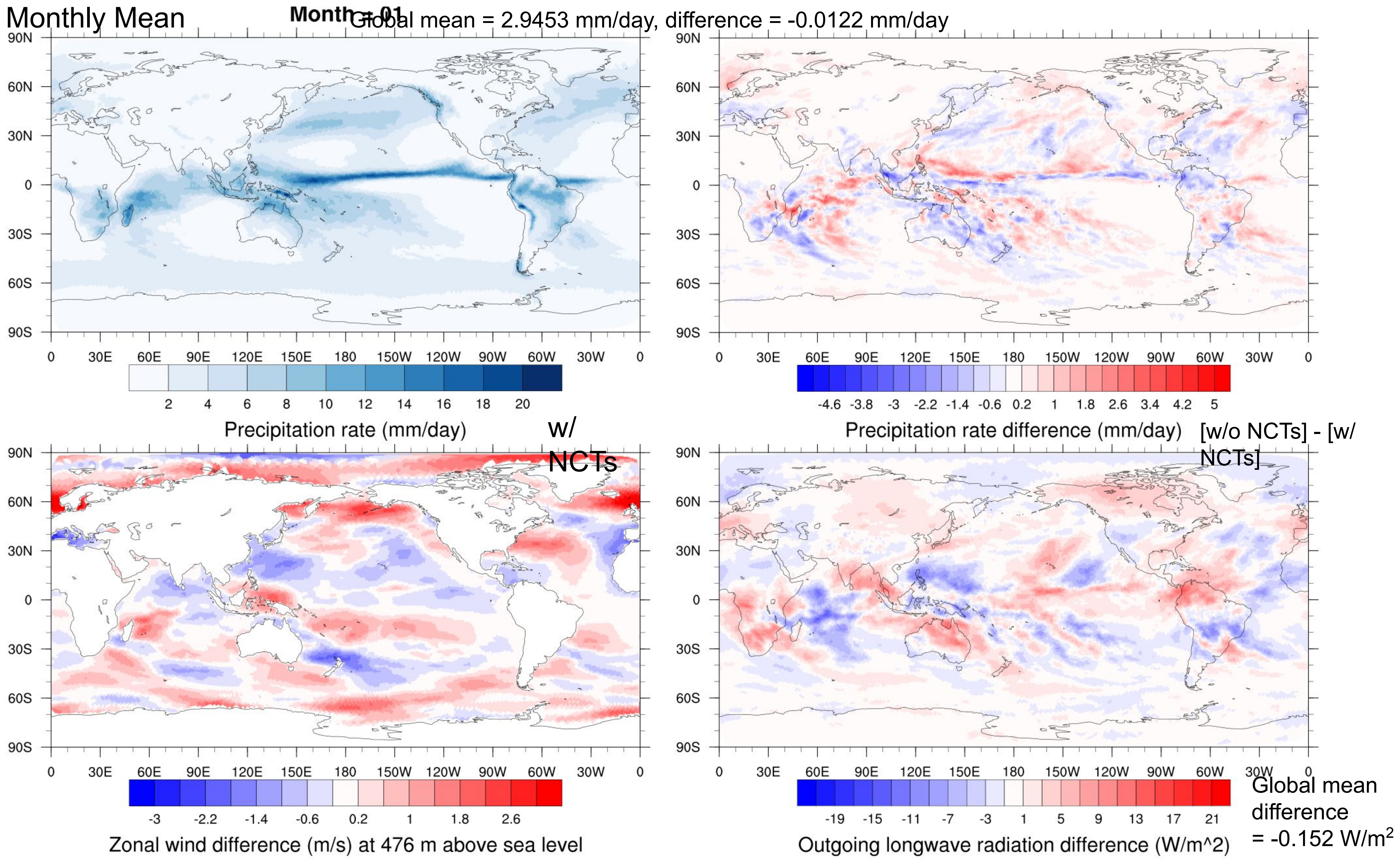
Global mean = 2.9667 mm/day, difference = -0.0138 mm/day



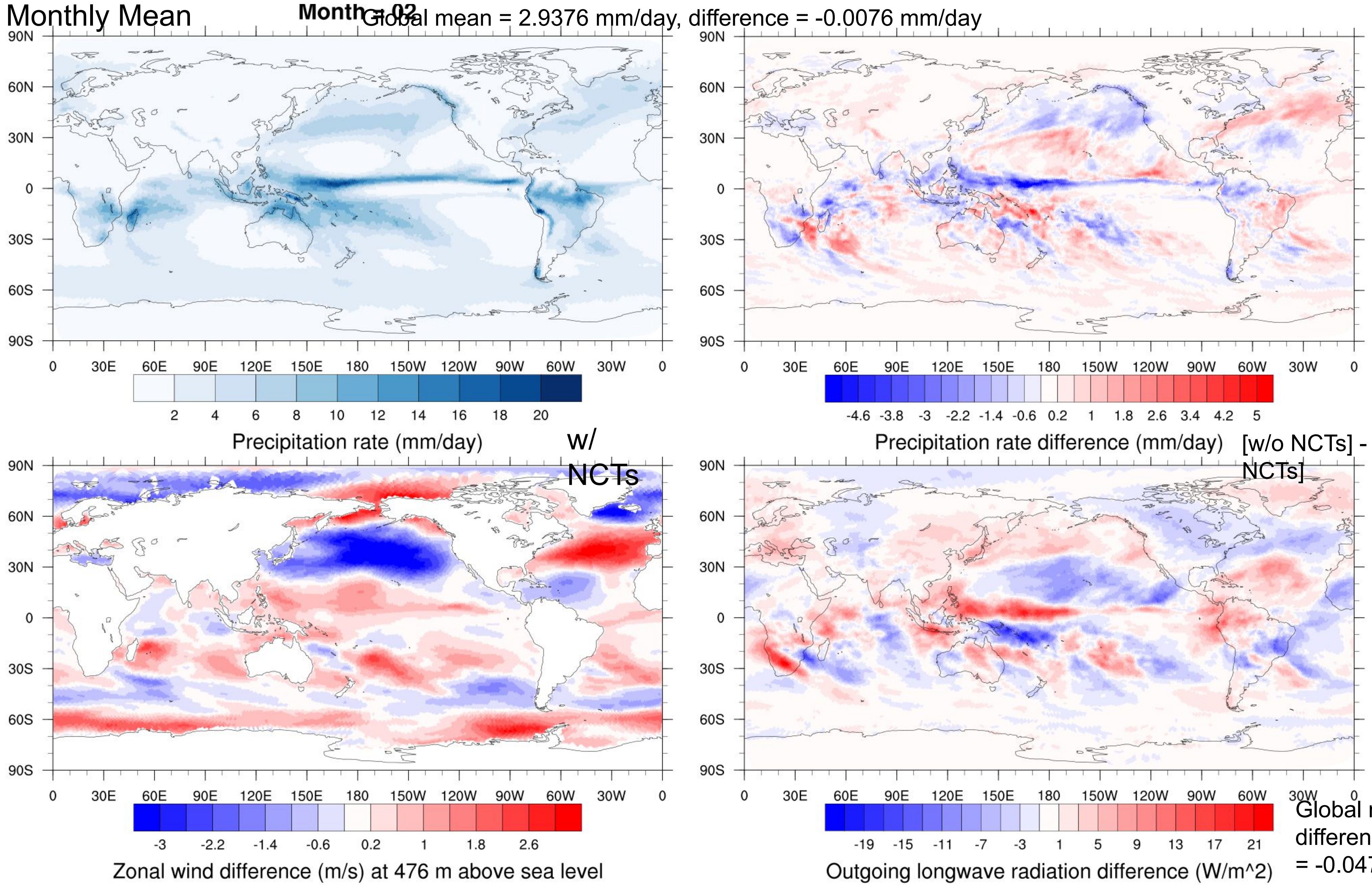
w/ NCTs

[w/o NCTs] - [w/ NCTs]

Global mean difference = 0.033 W/m^2


Monthly Mean
Month = 01
Global mean = 2.9453 mm/day, difference = -0.0122 mm/day
Precipitation rate (mm/day)
w/ NCTs
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
Zonal wind difference (m/s) at 476 m above sea level
Outgoing longwave radiation difference (W/m^2)
Global mean difference = -0.152 W/m^2

Monthly Mean

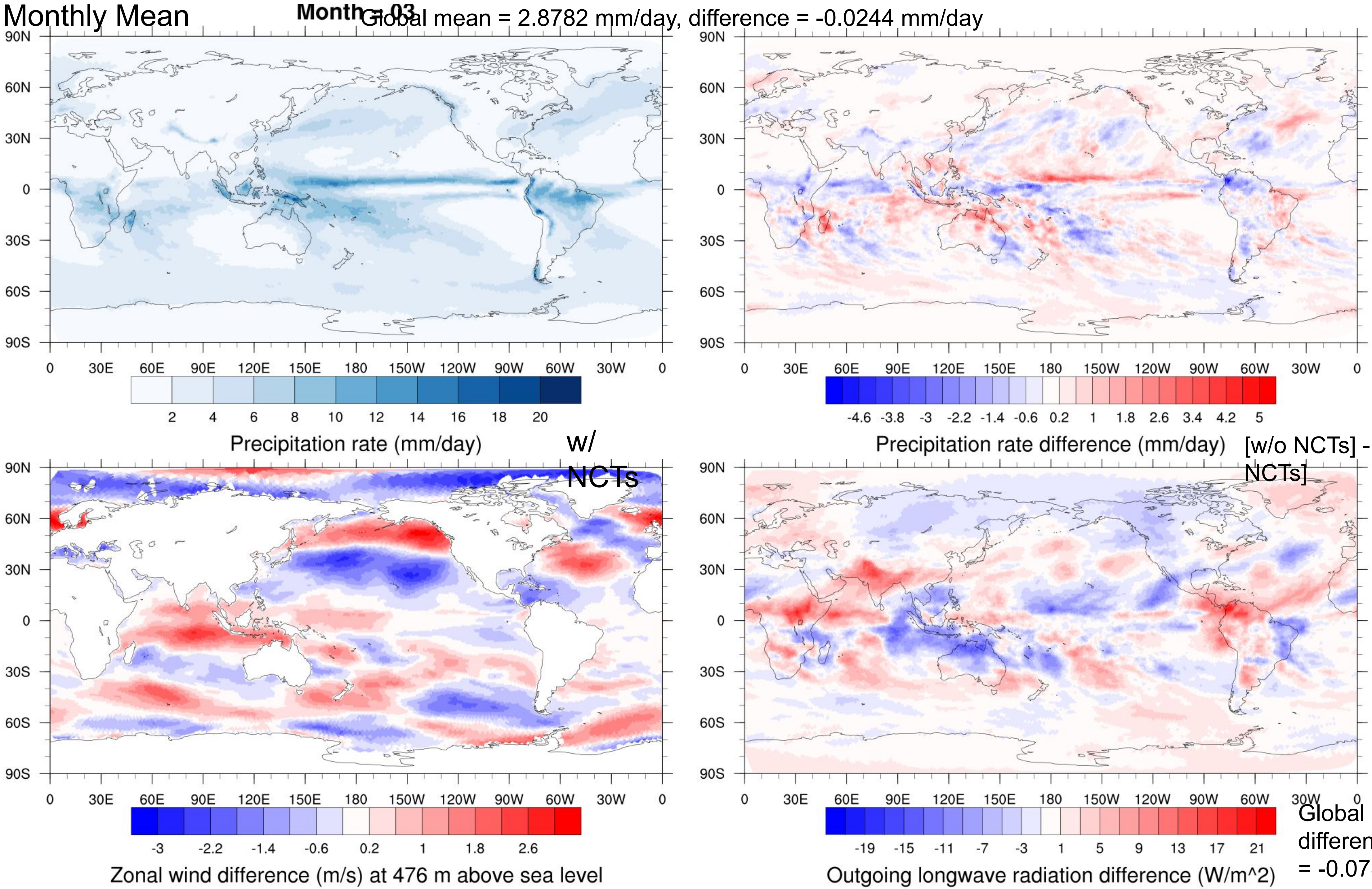


w/ NCTs

[w/o NCTs] - [w/ NCTs]

Global mean difference = -0.047 W/m^2

Monthly Mean



w/ NCTs

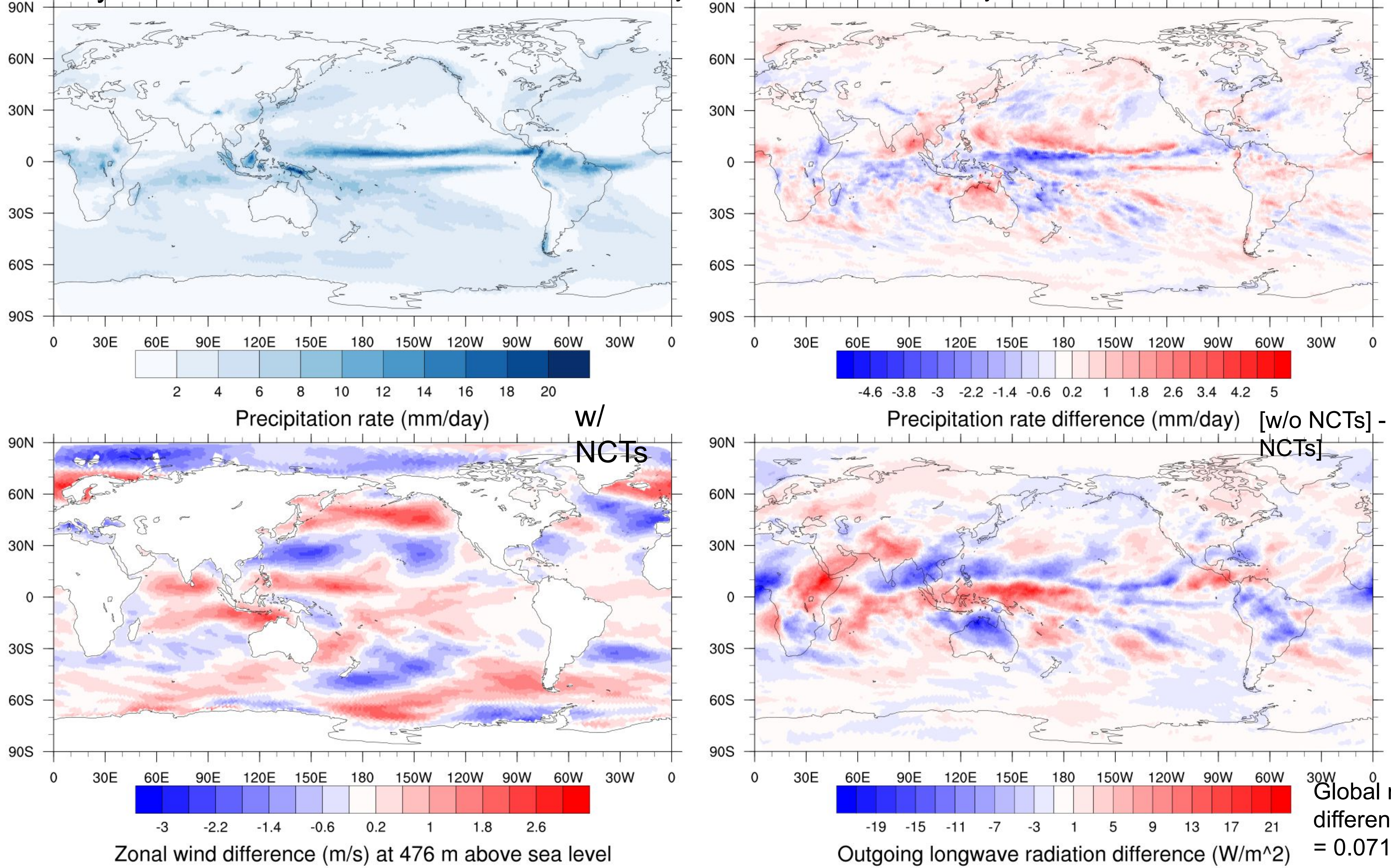
[w/o NCTs] - [w/ NCTs]

Global mean difference = -0.078 W/m^2

Monthly Mean

Month = 04

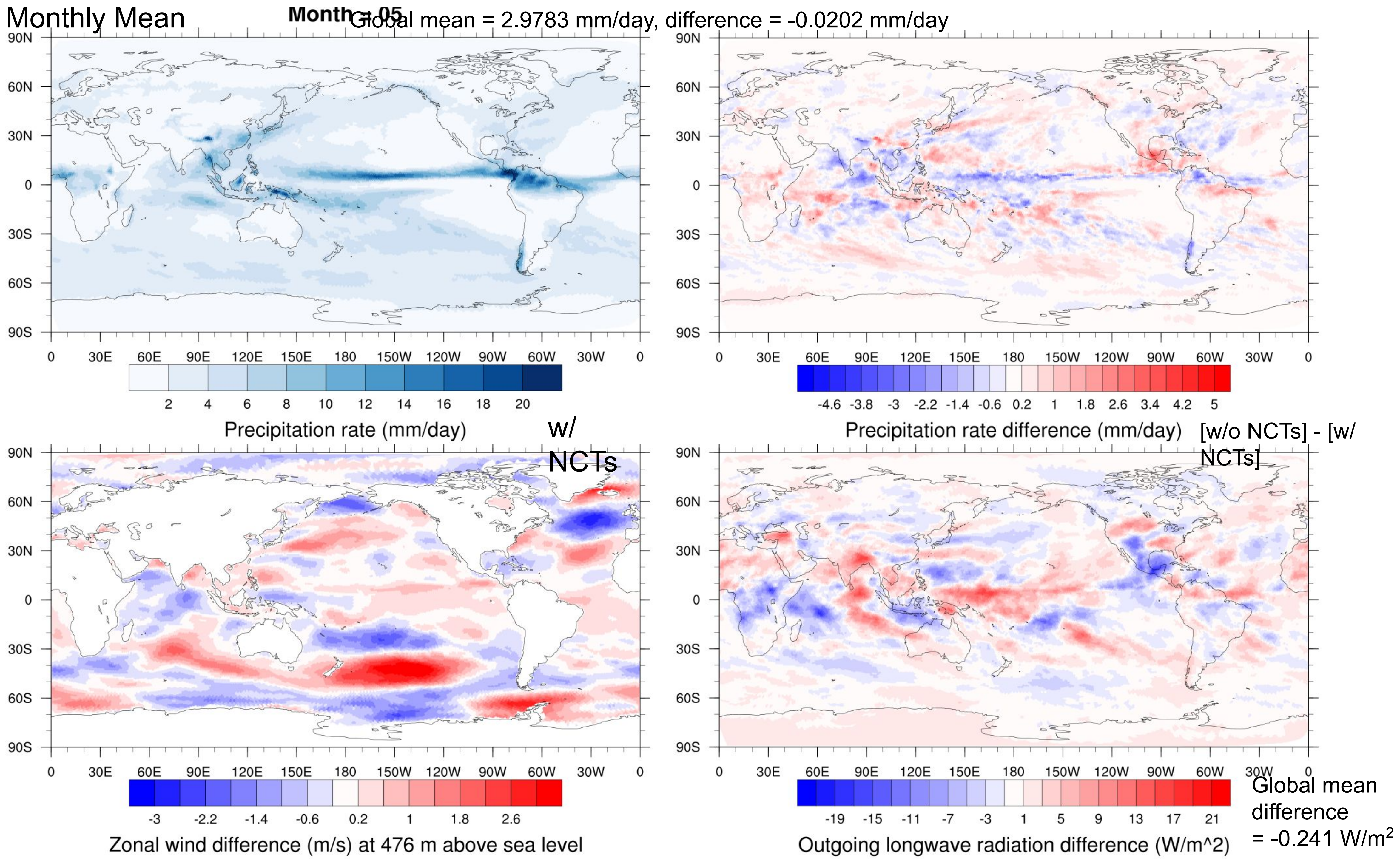
Global mean = 2.9044 mm/day, difference = -0.0030 mm/day

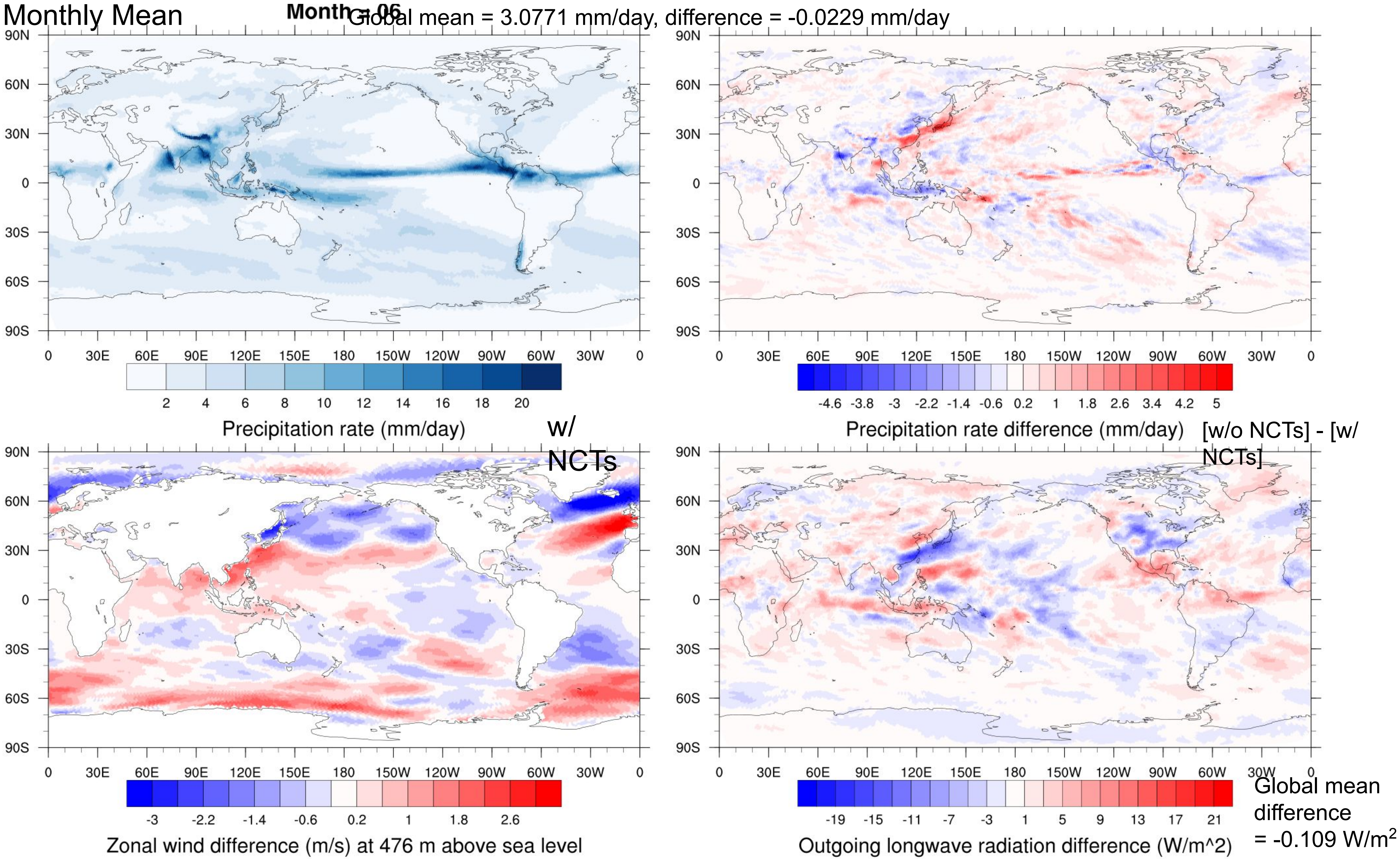


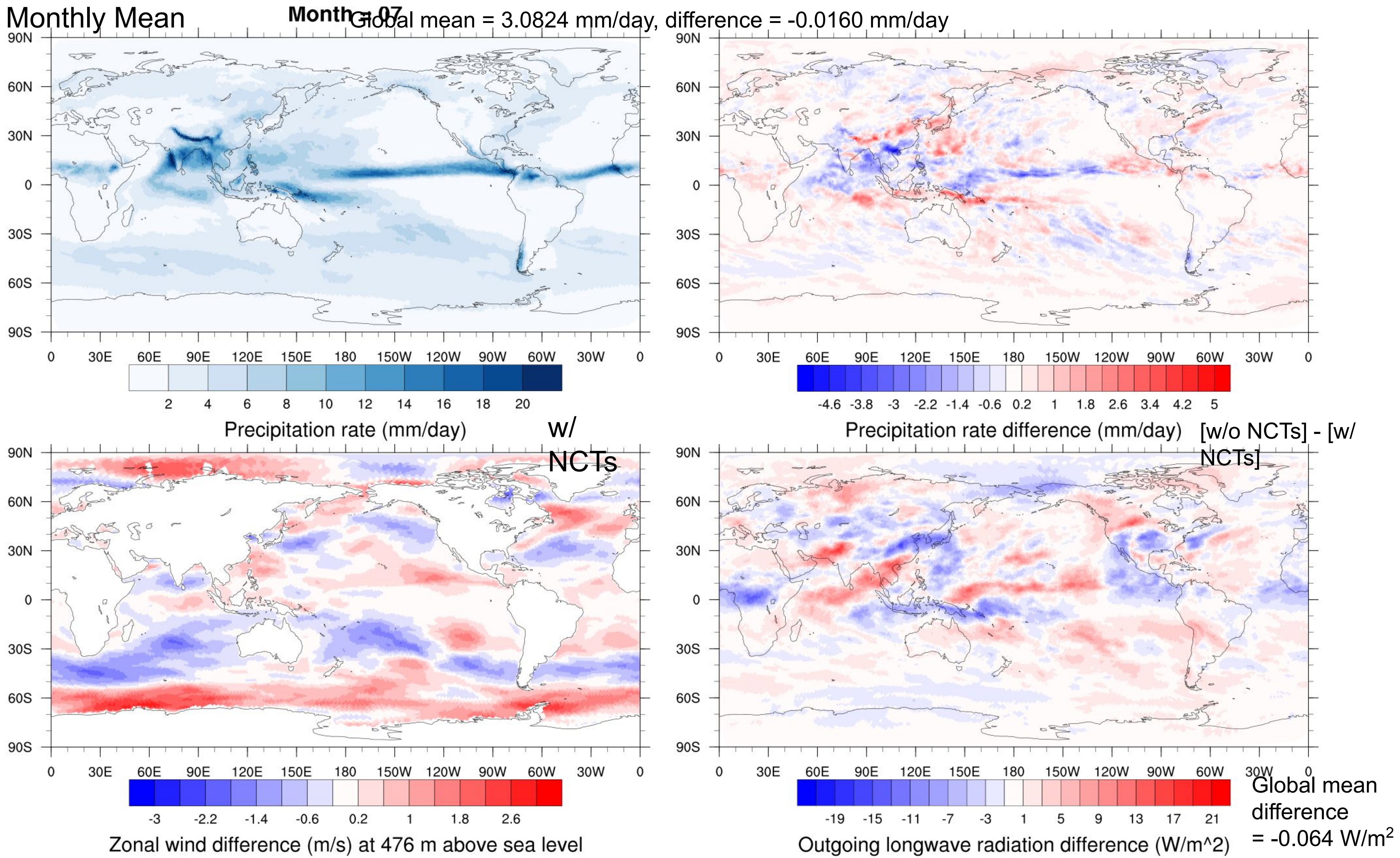
w/ NCTs

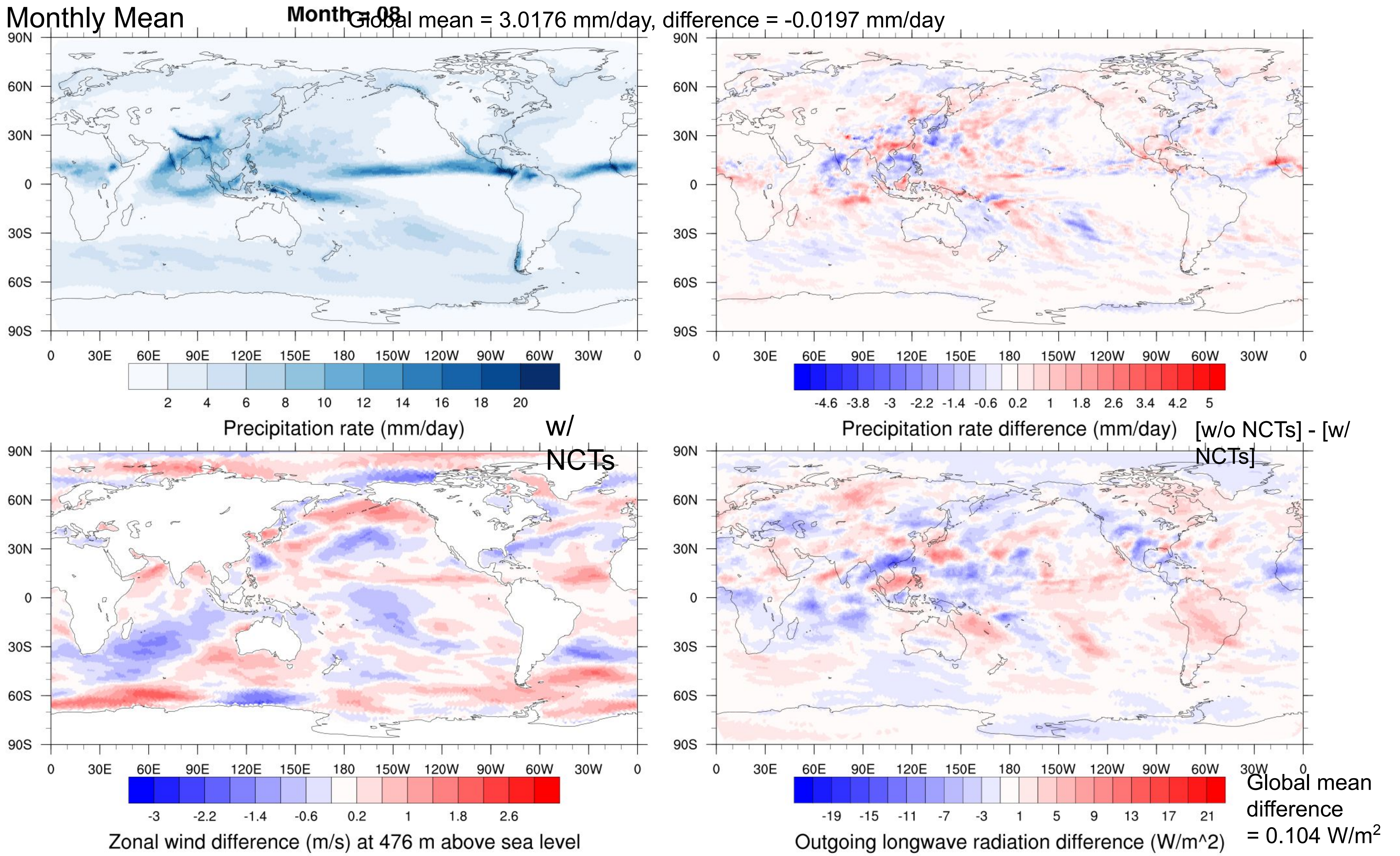
[w/o NCTs] - [w/ NCTs]

Global mean difference = 0.071 W/m^2

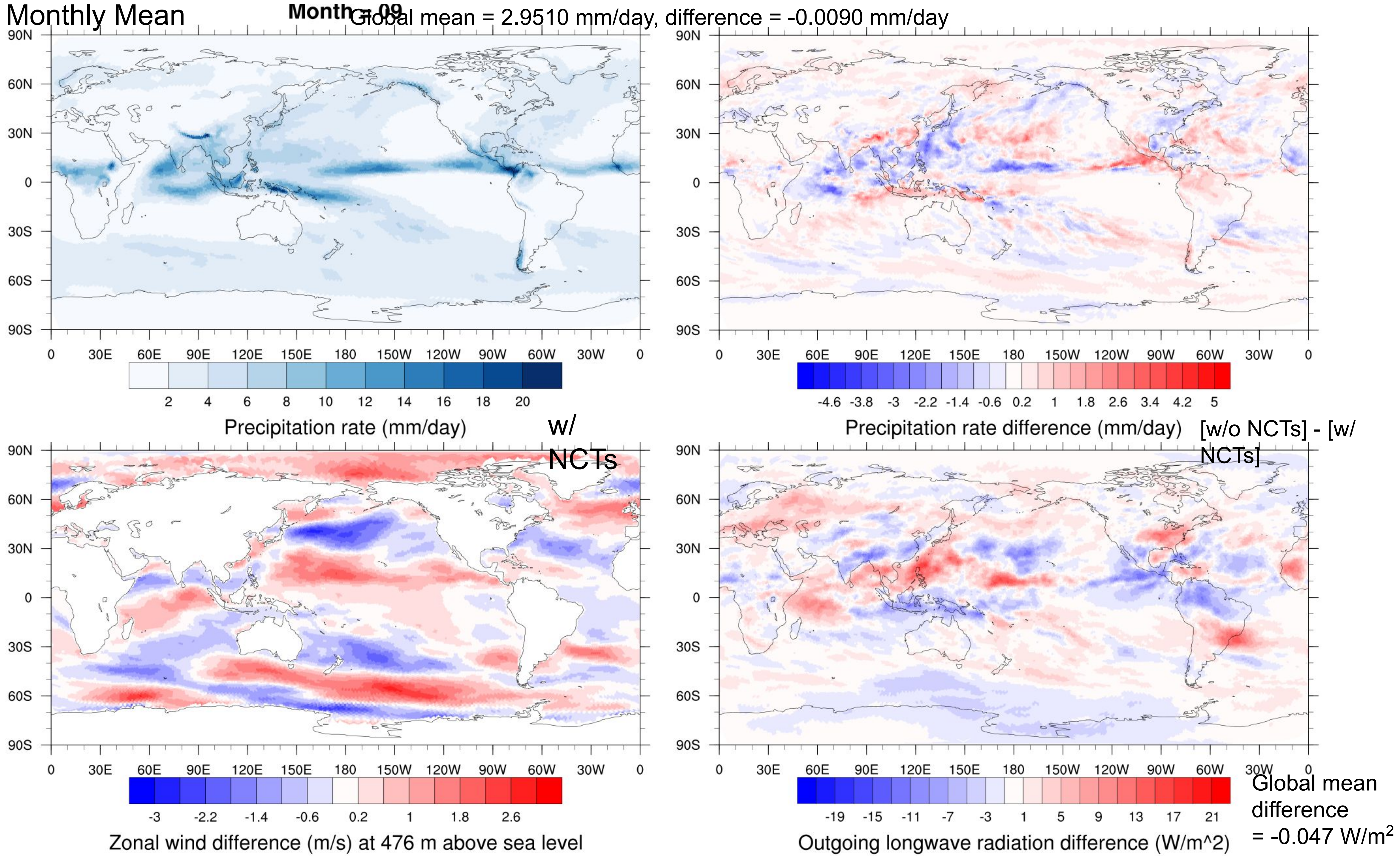

Monthly Mean
Month = 05
Global mean = 2.9783 mm/day, difference = -0.0202 mm/day
Precipitation rate (mm/day)
w/ NCTs
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
Zonal wind difference (m/s) at 476 m above sea level
Outgoing longwave radiation difference (W/m^2)
Global mean difference = -0.241 W/m2


Monthly Mean
Month = 06
Global mean = 3.0771 mm/day, difference = -0.0229 mm/day
90N 60N 30N 0 30S 60S 90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0
2 4 6 8 10 12 14 16 18 20
Precipitation rate (mm/day)
w/ NCTs
-4.6 -3.8 -3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6 3.4 4.2 5
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
-3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6
Zonal wind difference (m/s) at 476 m above sea level
-19 -15 -11 -7 -3 1 5 9 13 17 21
Outgoing longwave radiation difference (W/m^2)
Global mean difference = -0.109 W/m^2


Monthly Mean
Month = 07
Global mean = 3.0824 mm/day, difference = -0.0160 mm/day
Precipitation rate (mm/day)
w/ NCTs
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
Zonal wind difference (m/s) at 476 m above sea level
Outgoing longwave radiation difference (W/m^2)
Global mean difference = -0.064 W/m^2
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
2
4
6
8
10
12
14
16
18
20
-4.6
-3.8
-3
-2.2
-1.4
-0.6
0.2
1
1.8
2.6
3.4
4.2
5
-3
-2.2
-1.4
-0.6
0.2
1
1.8
2.6
-19
-15
-11
-7
-3
1
5
9
13
17
21

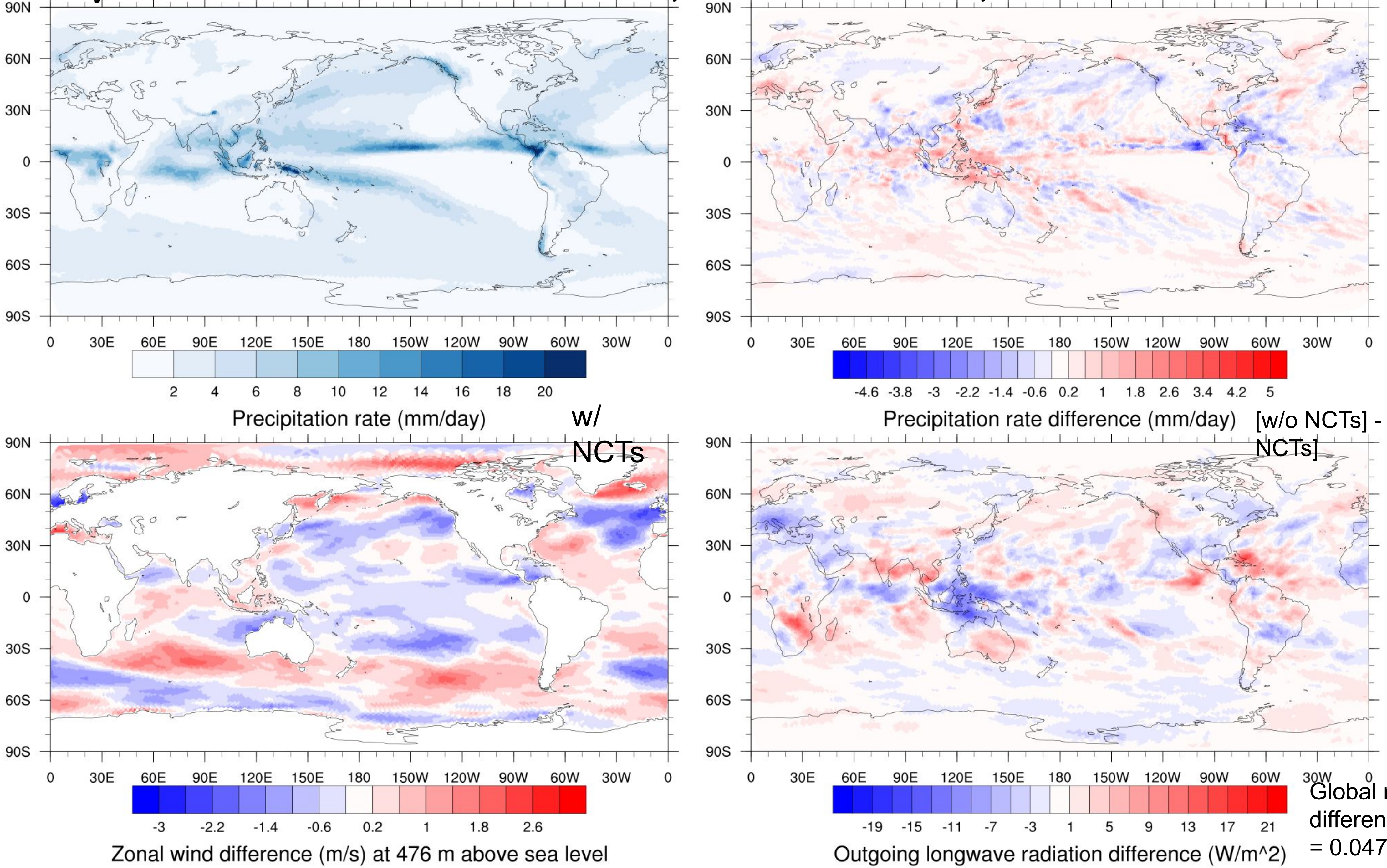


Monthly Mean
Month = 08
Global mean = 3.0176 mm/day, difference = -0.0197 mm/day
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
2 4 6 8 10 12 14 16 18 20
Precipitation rate (mm/day)
w/ NCTs
-4.6 -3.8 -3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6 3.4 4.2 5
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
-3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6
Zonal wind difference (m/s) at 476 m above sea level
-19 -15 -11 -7 -3 1 5 9 13 17 21
Outgoing longwave radiation difference (W/m^2)
Global mean difference = 0.104 W/m2


Monthly Mean
Month = 09
Global mean = 2.9510 mm/day, difference = -0.0090 mm/day
Precipitation rate (mm/day)
w/ NCTs
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
Zonal wind difference (m/s) at 476 m above sea level
Outgoing longwave radiation difference (W/m^2)
Global mean difference = -0.047 W/m^2

Monthly Mean

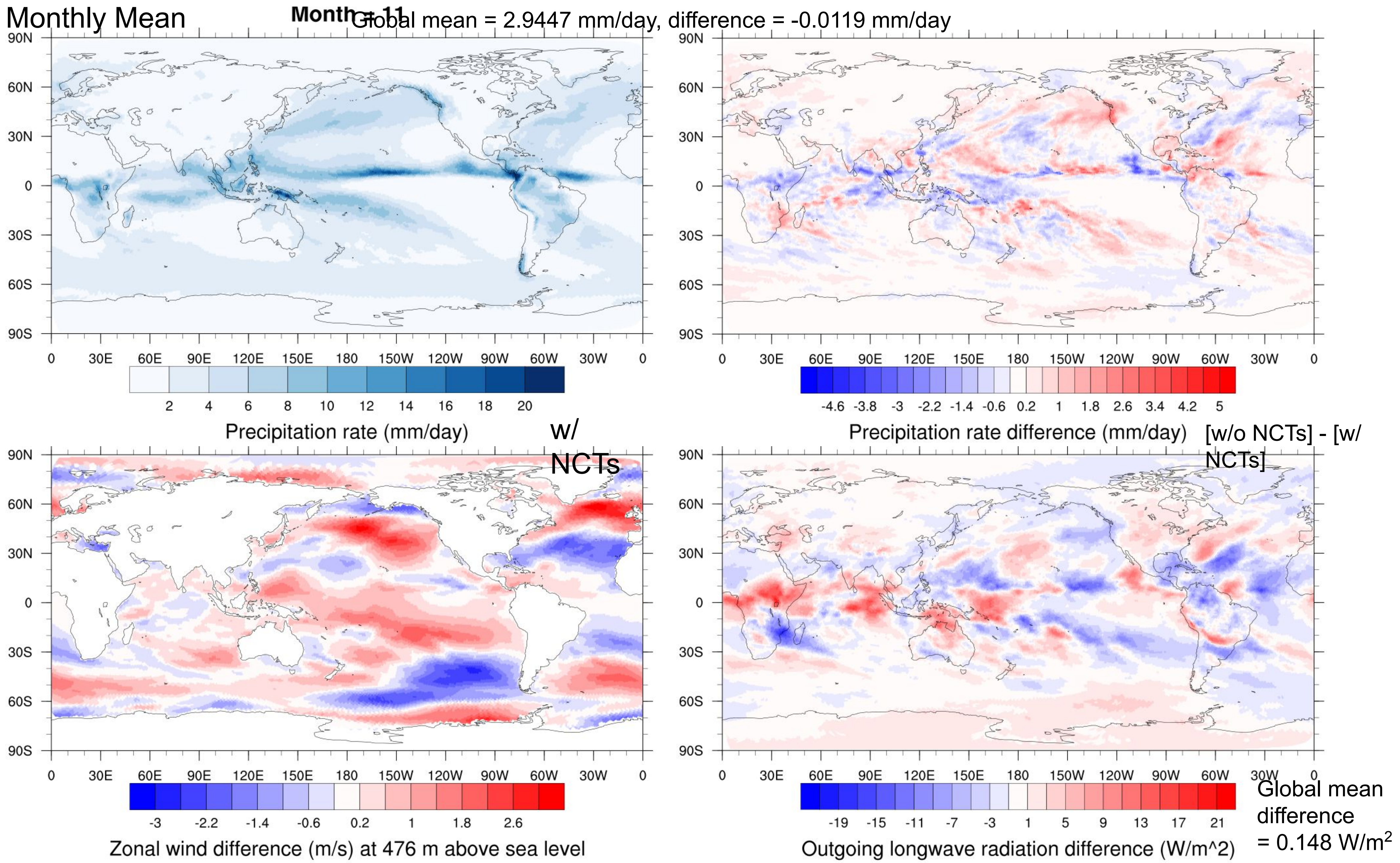
Month = 10 Global mean = 2.9167 mm/day, difference = -0.0171 mm/day

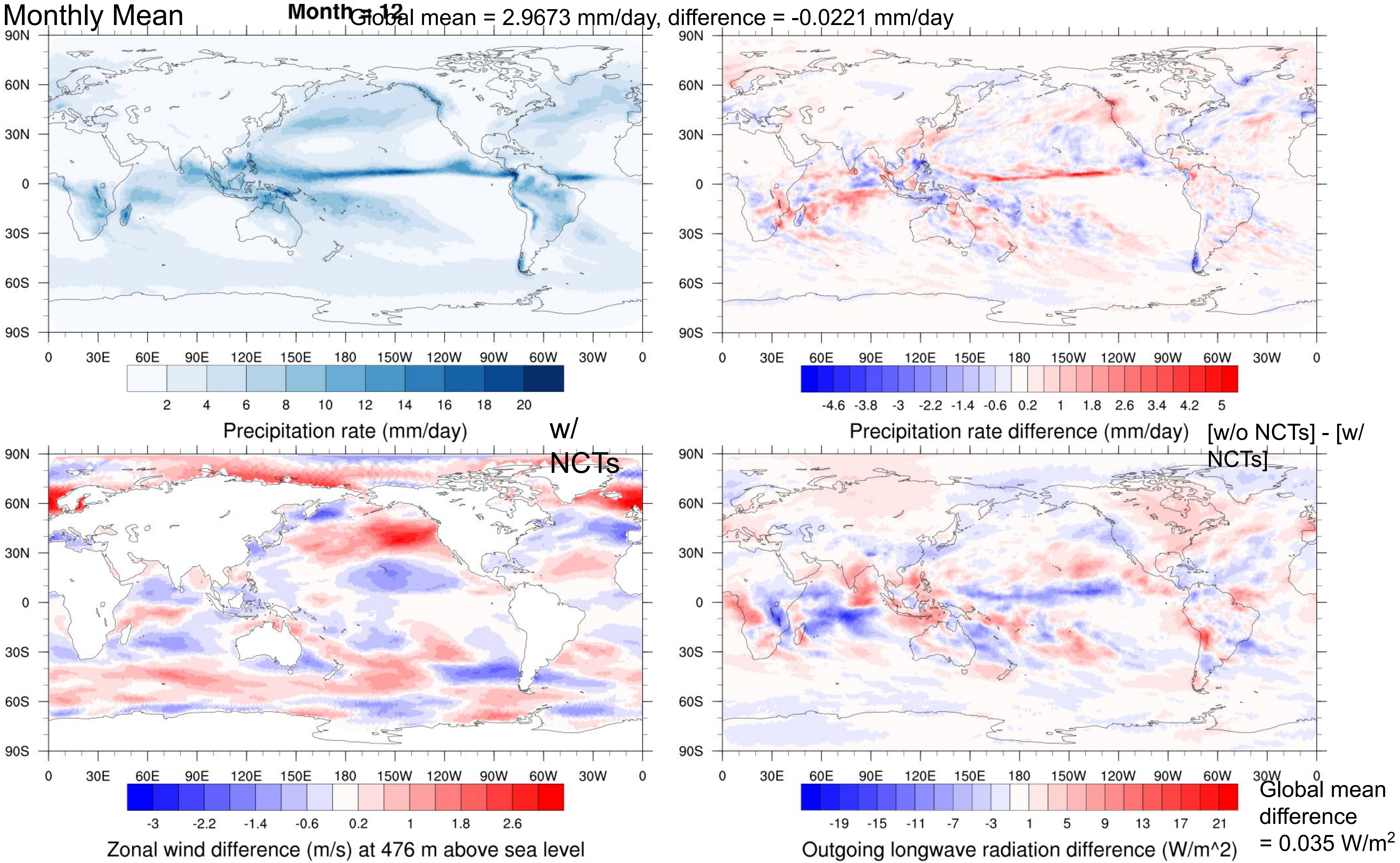


w/ NCTs

[w/o NCTs] - [w/ NCTs]

Global mean difference = 0.047 W/m^2


Monthly Mean
Month = 11
Global mean = 2.9447 mm/day, difference = -0.0119 mm/day
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
2
4
6
8
10
12
14
16
18
20
Precipitation rate (mm/day)
w/ NCTs
-4.6
-3.8
-3
-2.2
-1.4
-0.6
0.2
1
1.8
2.6
3.4
4.2
5
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
-3
-2.2
-1.4
-0.6
0.2
1
1.8
2.6
Zonal wind difference (m/s) at 476 m above sea level
-19
-15
-11
-7
-3
1
5
9
13
17
21
Outgoing longwave radiation difference (W/m^2)
Global mean difference = 0.148 W/m2


Monthly Mean
Month = 12
Global mean = 2.9673 mm/day, difference = -0.0221 mm/day
90N
60N
30N
0
30S
60S
90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0
2 4 6 8 10 12 14 16 18 20
Precipitation rate (mm/day)
w/ NCTs
-4.6 -3.8 -3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6 3.4 4.2 5
Precipitation rate difference (mm/day)
[w/o NCTs] - [w/ NCTs]
-3 -2.2 -1.4 -0.6 0.2 1 1.8 2.6
Zonal wind difference (m/s) at 476 m above sea level
-19 -15 -11 -7 -3 1 5 9 13 17 21
Outgoing longwave radiation difference (W/m^2)
Global mean difference = 0.035 W/m^2

Ongoing efforts introducing NCTs to E3SM

Introducing a Deep-Atmosphere Version of E3SM's Dynamical Core to Reduce Climate Model Biases

FUNDING PROGRAM AREA(S)	PROJECT TYPE	PROJECT TERM
ESMD	University Grant	2022-09 to 2025-08

PROJECT TEAM

Recent work has created controversy around the validity of a pair of simplifying assumptions that are often made in representing (a) the strength of the gravitational force and (b) the form of the Coriolis force in the dynamical cores of weather and climate models. They are called the Shallow-Atmosphere Approximation (SA) and Traditional Approximation (TA) which together form the basis of the dynamical core design of the Department of Energy's (DOE) Energy Exascale Earth System Model version 2 (E3SMv2). E3SMv2's shallow-atmosphere (SA & TA) dynamical core is called the "High-Order Methods Modeling Environment" (HOMME) which is accompanied by a new software design in DOE's latest "Simple Cloud-Resolving E3SM Atmosphere Model" (SCREAM). The HOMME dynamical core supports non-hydrostatic and hydrostatic configurations as well as Fortran-based (HOMME) and C++/Kokkos-based software architectures for SCREAM. Recent increases in computational capacity have now allowed high-resolution (25 km) and even cloud-permitting (3 km) assessments of the climate system with the E3SM/HOMME and SCREAM configurations. At these high resolutions the validity of the shallow-atmosphere configuration is especially questionable, as diabatic effects become better represented. In fact, there are indications that the neglect of the cosine-based Coriolis accelerations in the momentum budget can cause biases on the order of 10% for diabatically driven tropical and planetary-scale flows. In addition, the neglect of the gravitational variations needs to be questioned as models raise the position of the model lid (60-65 km for E3SM). These biases are systematic, and while they might be less relevant for short weather simulations, they accumulate over time in long-term climate simulations. It is therefore hypothesized that long-standing "stubborn" climate model biases like the position and strength of the Intertropical Convergence Zone (ITCZ) in E3SM are connected to E3SM's shallow-atmosphere design, and a deep-atmosphere extension of HOMME is proposed to test this hypothesis. The expectation is that the deep-atmosphere configuration of E3SM has the potential to reduce climate model biases, especially in the tropics.