

Earth and Space Science

RESEARCH ARTICLE

10.1029/2020EA001296

Special Section:

Community Earth System Model version 2 (CESM2) Special Collection

Characteristics of Future Warmer Base States in CESM2

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Key Points:

- CESM2(CAM6) and CESM2(WACCM6) have higher equilibrium climate sensitivity (ECS) but about the same transient climate response (TCR) compared to CESM1
- Future global warming diverges around 2050, with greater warming by end of century in the higher forcing scenarios and in both versions of CESM2 compared to CESM1
- There is more future warming (and greater precipitation increase) in the tropics in the CESM2 versions compared to CESM

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Citation:

Meehl, G. A., Arblaster, J. M., Bates, S., Richter, J. H., Tebaldi, C., Gettelman, A., et al. (2020). Characteristics of future warmer base states in CESM2. *Earth and Space Science*, 7, e2020EA001296. <https://doi.org/10.1029/2020EA001296>

Received 11 JUN 2020

Accepted 15 JUN 2020

Accepted article online 13 JUL 2020

Abstract Simulations of 21st century climate with Community Earth System Model version 2 (CESM2) using the standard atmosphere (CAM6), denoted CESM2(CAM6), and the latest generation of the Whole Atmosphere Community Climate Model (WACCM6), denoted CESM2(WACCM6), are presented, and a survey of general results is described. The equilibrium climate sensitivity (ECS) of CESM2(CAM6) is 5.3°C, and CESM2(WACCM6) is 4.8°C, while the transient climate response (TCR) is 2.1°C in CESM2(CAM6) and 2.0°C in CESM2(WACCM6). Thus, these two CESM2 model versions have higher values of ECS than the previous generation of model, the CESM (CAM5) (hereafter CESM1), that had an ECS of 4.1°C, though the CESM2 versions have lower values of TCR compared to the CESM1 with a somewhat higher value of 2.3°C. All model versions produce credible simulations of the time evolution of historical global surface temperature. The higher ECS values for the CESM2 versions are reflected in higher values of global surface temperature increase by 2,100 in CESM2(CAM6) and CESM2(WACCM6) compared to CESM1 between comparable emission scenarios for the high forcing scenario. Future warming among CESM2 model versions and scenarios diverges around 2050. The larger values of TCR and ECS in CESM2(CAM6) compared to CESM1 are manifested by greater warming in the tropics. Associated with a higher climate sensitivity, for CESM2(CAM6) the first instance of an ice-free Arctic in September occurs for all scenarios and ensemble members in the 2030–2050 time frame, but about a decade later in CESM2(WACCM6), occurring around 2040–2060.

Plain Language Summary The new Earth system model versions CESM2(CAM6) and CESM2(WACCM6) have higher equilibrium climate sensitivity than the previous model version CESM1. While this higher climate sensitivity produces greater warming by the end of the 21st century in CESM2(CAM6) and CESM2(WACCM6) compared to CESM1 for the high forcing scenario, prior to midcentury the warming is comparable among all model versions and scenarios. The higher climate sensitivity in CESM2(CAM6) and CESM2(WACCM6) compared to CESM1 produces greater tropical warming and precipitation increases in those regions. CESM2(CAM6) does not warm as much in the tropics as CESM2(WACCM6), though CESM2(CAM6) shows the first instance of an ice-free Arctic in September for all scenarios and ensemble members about a decade earlier than in CESM2(WACCM6).

1. Introduction

A number of previous versions of the Community Earth System Model version 1 (CESM1) were described by Hurrell et al. (2013, CESM1), Kay et al. (2015, CESM1.1, the large ensemble), and Meehl et al. (2019, CESM1.3). Here we describe future climate characteristics of a new generation of the CESM, the CESM2. As presented in the general model description with extensive details (Danabasoglu et al., 2020), the new model versions here are “CESM2(CAM6)” (Community Atmosphere Model Version 6, CAM6) and “CESM2(WACCM6)” (Whole Atmosphere Community Climate Model Version 6, WACCM6). The latter is more fully described by Gettelman, Mills, et al. (2019) and is the high-top version to accompany the low-top CESM2(CAM6). Both use the same ocean, land, and sea ice components, as well as the same tropospheric atmospheric physics (with a few differences, see discussion below) and dynamical core. To provide context for the future warmer base states in the different scenario simulations, we will review general

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Table 1
Number of Ensemble Members for the Historical and Future Scenario Runs to 2100 for CESM2(CAM6) and CESM2(WACCM6)

Model	Historical	SSP1–2.6	SSP2–4.5	SSP3–7.0	SSP5–8.5
CESM2(CAM6)	11 (3 each for single forcings)	3	3	3	3
CESM2(WACCM6)	3	1	5 ^a	3 ^b	5 ^a

Note. Three members are used for all CESM1 simulations.

^aThe first three ensemble members continue from the three corresponding historical simulations; Ensemble Member 004 initial state uses historical member 002 for atmosphere, and Historical Member 001 for all other components; Ensemble Member 005 uses Historical Member 003 for atmosphere and Historical Member 002 for all other components. ^bOnly one member with output post-2055.

climate sensitivity metrics, the ECS (derived from the “Gregory method”; Gregory et al., 2004, from an instantaneous 4xCO₂ simulation), and the TCR (the global average surface warming in a 1% per year CO₂ increase experiment at the time of CO₂ doubling around year 70). We also will show how CESM1 and CESM2 produce somewhat different patterns of surface temperature and precipitation change in a future warmer climate, as well as differences between the responses of CESM2(CAM6) and CESM2(WACCM6) including the sea ice changes that occur in the Arctic and Antarctic in the future warmer base states in the model versions. The intention here is to provide a survey of general model response characteristics and point to other studies in the CESM2 virtual special issue that explore various features in more detail.

2. Model Characteristics

There have been a number of changes implemented in CESM2 compared to previous versions of CESM1 noted above. These are described in detail in Danabasoglu et al. (2020) and briefly summarized here. The CESM2 uses a nominal 1° (1.25° in longitude and 0.95° in latitude) horizontal resolution configuration with 32 vertical levels and a model top at 3.6 hPa (about 40 km, termed “low top”) with a finite volume dynamical core and limited chemistry. In the atmosphere, the separate representations of the boundary layer, shallow convection and large-scale condensation (e.g., the boundary layer in the University of Washington, UW, scheme and Park scheme for shallow convection and macrophysics in CESM1) have been replaced by the Cloud Layers Unified By Binormals parameterization (CLUBB, Golaz et al., 2002). CLUBB is a high-order turbulence closure scheme and uses simple PDFs to describe the subgrid-scale distributions of key humidity, saturation, temperature, and vertical velocity quantities. The previous version of the Morrison-Gettleman (MG1) microphysics scheme in CESM1 has been updated to MG2 in CESM2. The MG2 scheme now predicts rather than diagnoses precipitating hydrometeors (Gettelman & Morrison, 2015) and links mixed phase ice nucleation to aerosols, rather than just temperature as in CESM1. Direct modifications to the Zhang-McFarlane deep convection scheme (Neale et al., 2008; Zhang & McFarlane, 1995) act to further increase humidity sensitivity, and the near-surface stress scheme of Beljaars and Wood (2004) acts to reduce excessive drag seen in CESM1. The final major change was to advance the modal aerosol scheme from 3 to 4 modes (MAM4, Liu et al., 2016) including an improved aging process for black carbon.

The ocean model in CESM2 is a version of POP used in CESM1 but with many improvements to the physics (Danabasoglu et al., 2020). It has a nominal 1° horizontal resolution and enhanced resolution in the equatorial tropics, and 60 levels in the vertical. Other features of CESM2

involving land and sea ice are described in detail by Danabasoglu et al. (2020).

WACCM6 is a “high top” chemistry and climate model with 70 levels in the vertical which extend up to ~140 km in the upper atmosphere, coupling the same nominal 1° latitude-longitude grid spacing in the atmosphere and ocean to form CESM2(WACCM6) as in CESM2(CAM6). WACCM6 simulations differ from CAM6 simulations only in (a) the higher vertical lid, (b) full stratospheric and tropospheric chemistry instead of fixed oxidants in CAM6, and (c) additional nonorographic gravity wave drag parameterization in

Table 2
ECS and TCR Values for CESM2(CAM6), CESM2(WACCM6), and CESM1 (°C)

Model	ECS	TCR
CESM2(CAM6)	5.3°C	2.0°C
CESM2(WACCM6)	4.8°C	1.9°C
CESM1	4.1°C	2.3°C

Note. Slightly different values calculated by ESMValTool in Meehl et al. (2020), which is based on surface air temperature, with ECS for CESM2(CAM6) of 5.2°C, and TCR for CESM2(WACCM6) of 2.0°C. Methods for calculating these values are discussed in the text.

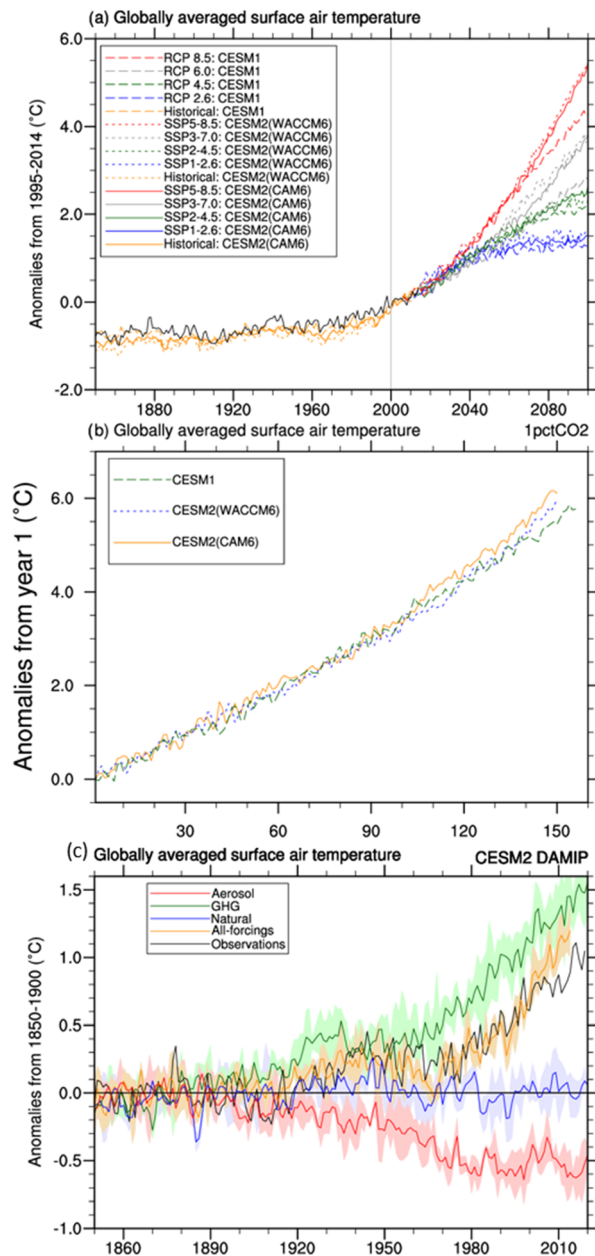


Figure 1. (a) Time series of global mean annual mean surface air temperature anomalies (°C, computed relative to the 1995–2014 base period) for late 19th, 20th, and 21st centuries from CESM1, CESM2(CAM6), and CESM2(WACCM6), for the ensemble averages (see Figure 2 for spread of ensemble members) of the four RCP scenarios for CESM1, and the four SSP scenarios for CESM2(CAM6) and CESM2(WACCM6) as denoted in the text box in the figure (see Table 2 for list of ensemble members); black line denotes observations from HadCRUT4; ensemble averages for the historical runs compared to observations are described in detail by Danabasoglu et al. (2020); (b) same as (a) except for the 1% per year CO₂ increase experiments (°C, anomalies computed relative to each model's first year) where CO₂ doubles around year 70; (c) single-forcing DAMIP experiments with CESM2(CAM6) as defined in the text box, observations as in (a); solid colored lines are three-member ensemble averages for each experiment with the shading representing the minimum and maximum values across the ensemble, anomalies are computed relative to the 1850–1900 period.

WACCM6. The other coupled components (ocean, sea ice, and land) are identical in CESM2(WACCM6) and CESM2(CAM6). Full details of the WACCM6 configuration are described in Gettelman, Mills, et al. (2019).

Here we show results for 21st century simulations with four future emission scenarios (Shared Socioeconomic Pathways: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, see O'Neill et al., 2016, for descriptions) for CESM2(CAM6) and CESM2(WACCM6). Several forcing data sets for the CESM2(CAM6) were obtained from the CESM2 (WACCM6), as described by Danabasoglu et al. (2020). For the SSP experiments, volcanic aerosol emissions are set at constant averaged PI control values, resulting in different effects on radiative forcing under each SSP. Solar and geomagnetic forcing follows the CMIP6 recommendations (Gettelman, Mills, et al., 2019). We use all available ensemble members for the CESM2 versions (see Table 1), and three each for the previously-documented Representative Concentration Pathways (RCP) scenarios for CESM1. Statistical significance is assessed via a *t* test, taking into account the varying number of members in each ensemble. For differences between the model versions, we use nonoverlapping 20 year averages from the multicentury PI control simulations as a measure of the variance.

The ECS, calculated with the standard “Gregory method” as noted above (Gregory et al., 2004), of CESM2(CAM6) is 5.3°C, and that of CESM2(WACCM6) is 4.8°C, while the TCR of 2.0°C in CESM2 and 1.9°C in WACCM6 (Table 2). Here, TCR is calculated as the difference between the Years 60 and 79 average in surface temperature in a 1% CO₂ increase experiment (where CO₂ doubles around Year 70) minus the linear fit to the piControl runs for the 140 years overlapping the 1% CO₂ runs. Another variant is to form the difference relative to the comparable Years 61–80 in the piControl run (as in Meehl et al., 2013, with the cited value here for CESM1 from that paper). Differences in TCR between these methods are slight, usually only on the order of ~0.1°C. For example, values calculated directly by ESMValTool cited in Meehl et al. (2020) show ECS for CESM2(CAM6) of 5.2°C and TCR for CESM2(WACCM6) of 2.0°C.

There are also a number of variations in how ECS is calculated, and one alternative uses the atmospheric models coupled to a nondynamic slab ocean, which yields ECS values for CESM2(CAM6) of 5.3°C and CESM2(WACCM6) of 5.1°C (Danabasoglu et al., 2020). A more detailed exploration of ECS methodologies and issues involved with them is given in Meehl et al. (2020). In any case, these CESM2 model versions have higher values of ECS than the previous generation of model, the CESM1, which has an ECS of 4.1°C calculated by the standard Gregory method, with a TCR of 2.3°C (Meehl et al., 2013). The higher values of ECS in the two CESM2 versions are mostly due to cloud feedbacks and aerosol-cloud interactions related to the details of stratiform cloud microphysics and associated ice nucleation, turbulence, rain formation and evaporation processes, and SO₂ lifetime (Gettelman, Hannay, et al., 2019). Specifically, changes made to increase high-latitude supercooled liquid water, and to adjust warm rain susceptibility to aerosols in shallow clouds, have increased cloud feedbacks in the CESM2. This would apply to

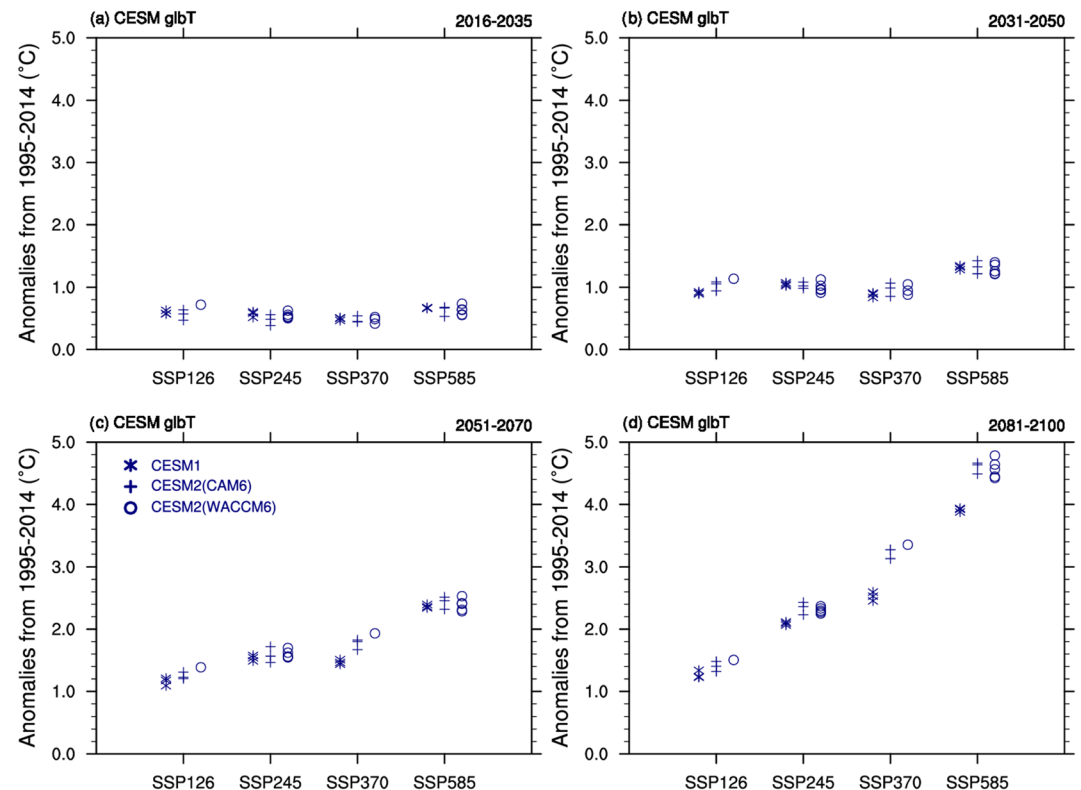


Figure 2. Globally averaged surface air temperature anomalies ($^{\circ}\text{C}$, computed relative to the 1995–2014 base period) for the four SSP scenarios in the CESM2 models, and comparable RCP scenarios for CESM1 as noted in Figure 1, denoted in legend in panel (c) with a value plotted for each ensemble member (see Table 2 for list of ensemble members), for (a) 2016–2035; (b) 2031–2050; (c) 2051–2070; and (d) 2081–2100.

anthropogenic and natural aerosols, and contribute to higher values of ECS compared to CESM1. The higher value of ECS for CESM2(CAM6) compared to CESM2(WACCM6) receives contributions from the ozone formulations in the two models. CESM2(WACCM6) interactively redistributes climatological ozone concentrations during the abrupt-4xCO₂ and scenario runs in order to retain the bulk of the ozone in the stratosphere as the tropopause height raises. Conversely, CESM2(CAM6) uses a fixed preindustrial ozone concentration climatology and thus, as the tropopause rises with warming, there is more ozone that remains in the upper troposphere and this contributes to larger magnitude ECS (Hardiman et al., 2019). Indications are that interactive stratospheric ozone accounts for ~40% of the difference in ECS between the CESM2(CAM6) and CESM2(WACCM6) (M. Mills, personal communication, June 2020).

The latest ECS values from both CESM2 versions are in the upper end of the CMIP6 ECS range of 1.9–5.6 $^{\circ}\text{C}$, while the TCR values are more in the middle of the CMIP6 range of 1.6–3.0 $^{\circ}\text{C}$ (Table 2 and Meehl et al., 2020). Possible reasons for the relationship between ECS and TCR values are reviewed by Meehl et al. (2020) and described by references therein.

3. Globally Averaged Temperature Response

Though the RCP and SSP emission scenarios have somewhat different forcings, the experimental design of ScenarioMIP (O'Neill et al., 2016) deliberately chose concentration pathways that could provide continuity with CMIP5 and therefore allow comparison of outcomes between generation of models (SSP1-2.6, SSP2-4.5, and SSP5-8.5 in ScenarioMIP Tier 1 should be comparable to RCP2.6, RCP4.5, and RCP8.5, aiming at achieving the same radiative forcings by 2100). Further, Forster et al. (2019) indicate that the temperature responses are comparable in the two sets of scenarios, while Nicholls et al. (2020) suggest that there could be different responses between comparable scenarios in CMIP5 and CMIP6. There is currently an

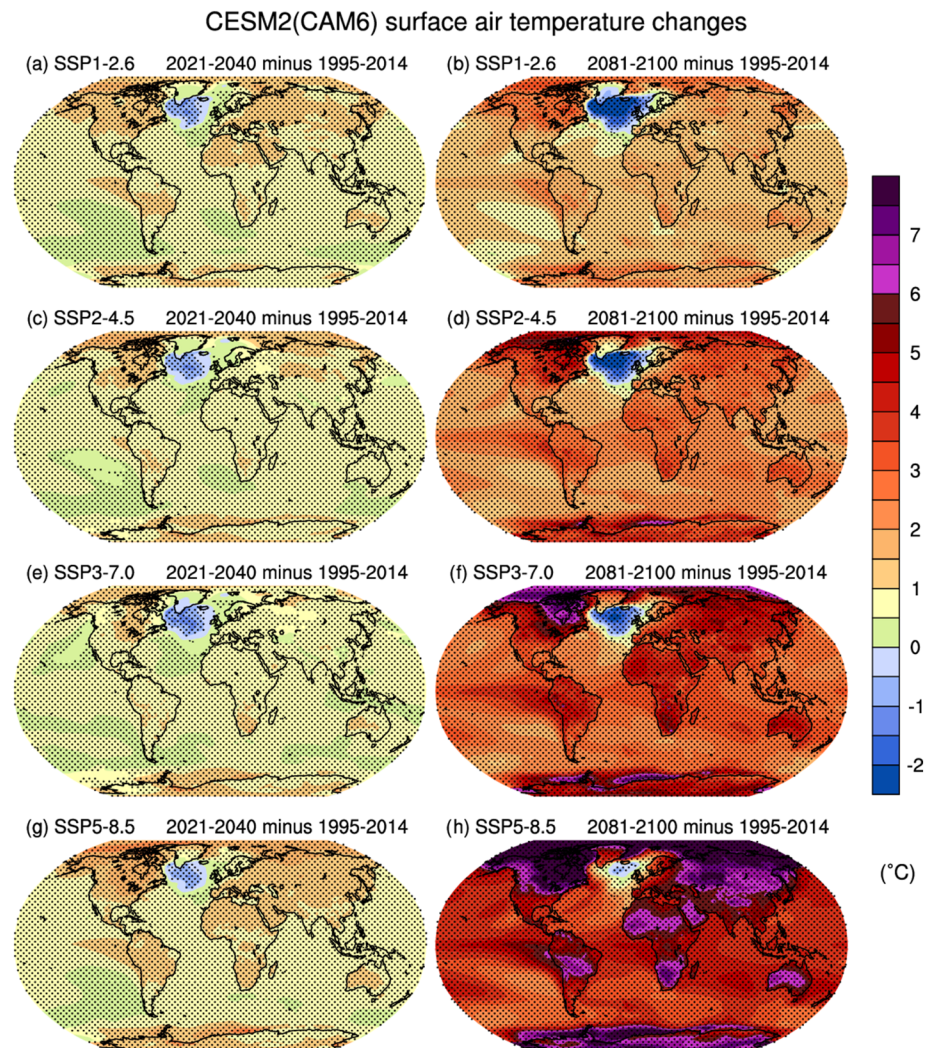


Figure 3. Surface air temperature anomalies (°C) for CESM2(CAM6) for near-term (2021–2040 minus 1995–2014) (a, c, e, and g), and longer term climate (2081–2100 minus 1995–2014) (b, d, f, and h), for the four SSP scenarios. Stippling indicates statistical significance at the 5% level.

experiment underway with CESM2 to perform an RCP8.5 simulation to compare to the existing CESM2 SSP5-8.5 experiment and address scenario forcing differences in this model.

The higher climate sensitivity in the CESM2 versions is reflected in higher values of global surface temperature increase by 2100 between comparable emission scenarios only for the higher forcing scenario (Figure 1a). The CESM2 versions have about 1°C greater warming for SSP5-8.5, but nearly the same warming at 2100 for the two lower forcing scenarios, SSP2-4.5 and SSP1-2.6. Before about the mid-21st century, the warming in all model versions and scenarios is nearly indistinguishable. This is consistent with previous results that have demonstrated that the response to different emission scenarios does not diverge until about midcentury (O'Neill et al., 2016). It also appears that model versions with higher ECS over the next several decades do not produce appreciably greater warming. This raises the issue of our understanding of the time scales at which TCR and ECS are relevant. There is evidence that TCR could be more representative of the response over the next 50 years or so (Figure 1b shows nearly the same temperature response in the 1% CO₂ increase runs until around the time of CO₂ doubling near Year 70), and ECS for higher forcing at longer time scales (note divergence of response in the 1% CO₂ increase runs in Figure 1b as the models approach 150 years where CO₂ is nearly quadrupled). However, there is also evidence to the contrary (see Meehl et al., 2020, and references therein). A different response to non-CO₂ forcings (e.g., vertical distributions

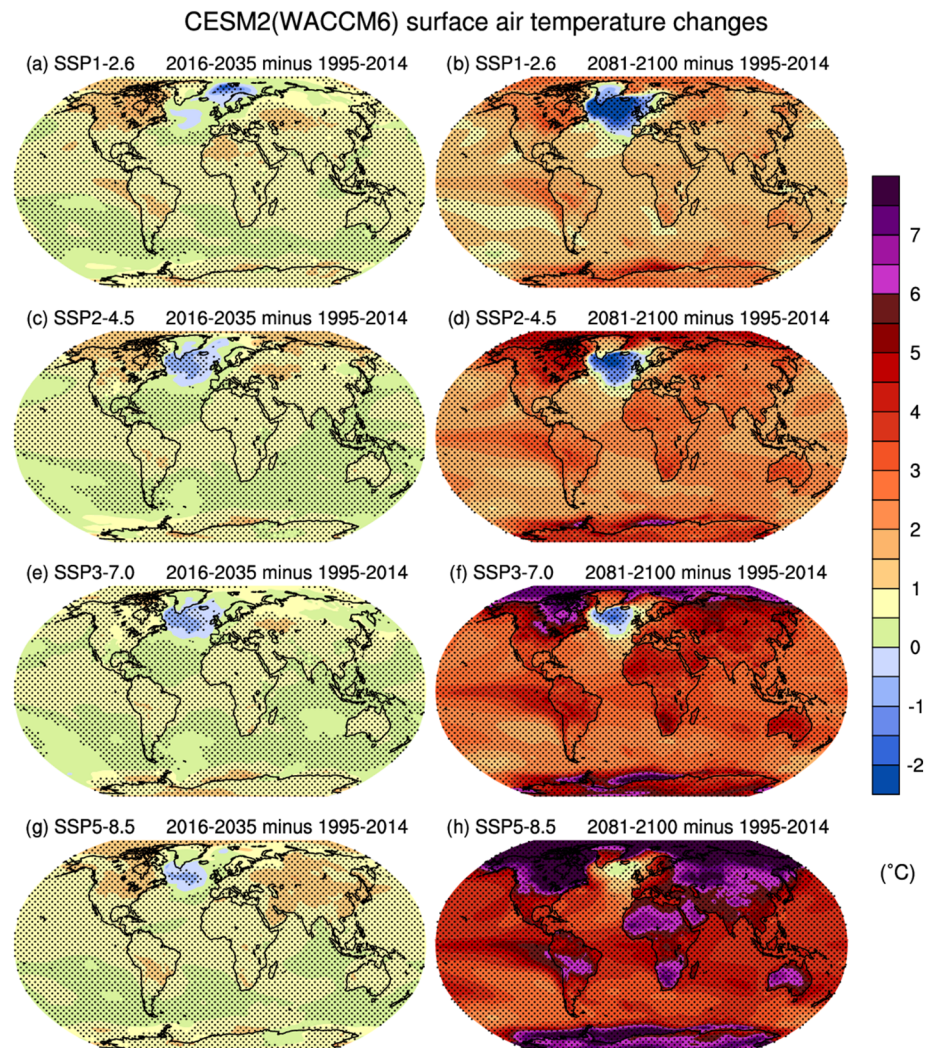


Figure 4. Same as Figure 3 except for CESM2(WACCM6).

of ozone as discussed above) between the CESM1 and CESM2 versions could also potentially contribute to the divergence between them in the latter decades of the 21st century.

To illustrate the spread among ensemble members and relative values of warming for different time periods, Figure 2 shows globally averaged temperature differences for the different scenarios, models, and time periods taken from Figure 1. For the near-term averaged from 2015–2035 (Figure 2a), as noted above all models and scenarios are virtually indistinguishable, all with warming values around $+0.6^\circ \pm 0.1^\circ\text{C}$ (uncertainty is the range of responses). Approaching midcentury for the time period 2031–2050 (Figure 2b), all models with the high forcing scenario SSP5-8.5, with warming values of about $+1.4^\circ \pm 0.1^\circ\text{C}$, are different from the other scenarios which cluster around $+1.0^\circ \pm 0.2^\circ\text{C}$. After midcentury for the time period 2051–2070 (Figure 2c), there is greater spread across the models and scenarios. For the low forcing scenarios (SSP1-2.6), CESM1 is about $0.1\text{--}0.2^\circ\text{C}$ lower than the two CESM2 versions, with warming values for the latter of about 1.4°C . For SSP2–4.5 for the 2051–2070 period (Figure 2c) the different model versions are more comparable. But for SSP3-7.0 there is greater spread between the CESM2 versions and CESM1, likely due to the different radiative forcing in RCP6.0 (in CESM1) compared to SSP3-7.0 (in CESM2). Both CESM2 model versions show warming around about $+1.8^\circ\text{C}$, while CESM1 is lower with a value of about 1.5°C which is roughly 0.1°C lower than its value for the lower SSP2-4.5. It would seem that for the higher forcing scenario (plotted as SSP3-7.0 but for CESM1 is actually RCP6.0 as noted earlier) compared to SSP2-4.5, CESM1 should have

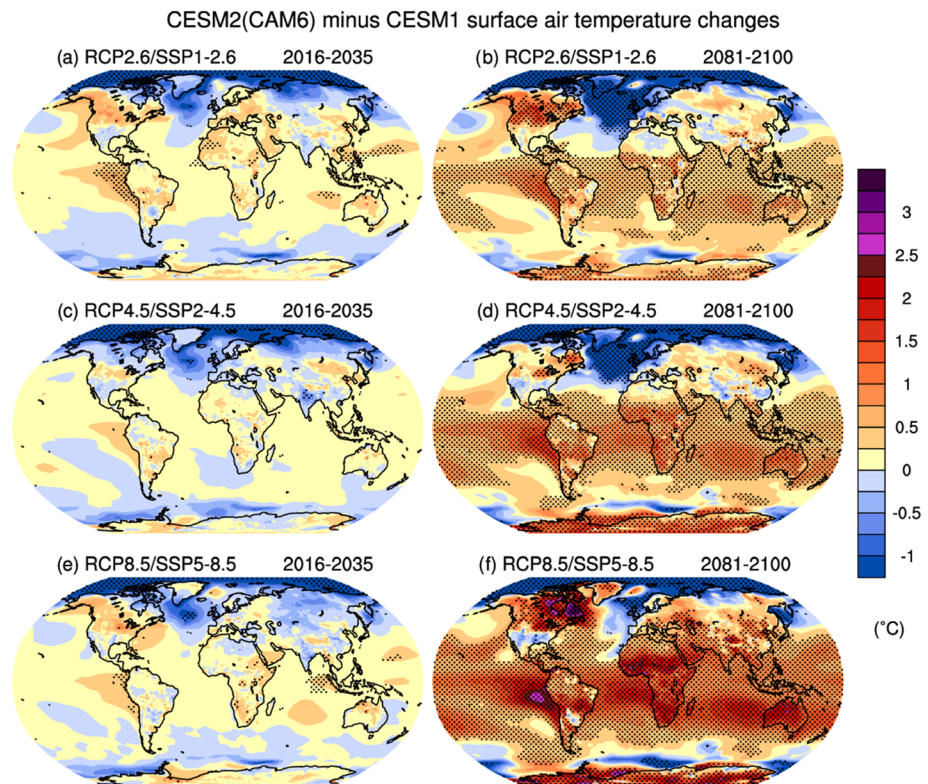


Figure 5. Same as Figure 3 except for the differences compared to the 1986–2005 base period, CESM2(CAM6) minus CESM1 (SSP3-7.0 and RCP6.0 are not plotted due to the differences in their forcings).

more warming for the former. However, the time evolution of the forcings between RCP4.5 and RCP6.0 produce lower warming for RCP6.0 in CESM1 compared to RCP4.5 from about 2030 to 2060 (Meehl et al., 2013, Figure 1) and this is shown here in Figures 2b and 2c. Meanwhile, for the high forcing scenario SSP5-8.5, all models cluster near +2.4°C.

For the late century period 2081–2100, there is a clear differentiation between the models and scenarios. It is only for this late-century period that CESM1 with the lower ECS has consistently lower warming values compared to the two CESM2 versions, with the difference in response being larger for the high-amplitude forcing scenario. Though CESM2(WACCM6) has a somewhat lower ECS, there is no appreciable differentiation in the response for this time period compared to CESM2(CAM6), with warming values for the four scenarios of about +1.4°C, +2.4°C, +3.4°C, and +4.8°C, respectively. CESM1 has values lower than those just listed of −0.1°C, −0.2°C, −0.9°C (again likely due to the lower radiative forcing in RCP6.0 compared to SSP3-7.0), and −0.9°C, respectively.

The model simulations of the time evolution of the twentieth century global temperatures qualitatively follow the low-frequency variability of the observations (Figure 1a), though both CESM2 versions are somewhat cooler than observations and CESM1 for parts of the historical period. This is particularly evident from about 1940 to about 2000. Reasons for these differences, some related to aerosols, are discussed in Danabasoglu et al. (2020). To look in more detail at the contributions from various forcings to the twentieth century simulation of global temperature in CESM2(CAM6), Figure 1c shows the time evolution of global temperatures from the various natural and anthropogenic forcing experiments of DAMIP (Gillett et al., 2016), along with the all-forcings simulation (also shown in Figure 1a) compared to observations. As noted in previous model versions (e.g., Meehl et al., 2004), temperature anomalies from the natural forcings fluctuate around zero for most of the record, with low-frequency variability in the first half of the twentieth century related to solar forcing, and periodic cooling for several years after large volcanic eruptions. The GHG forcing lies above the all-forcing simulation as expected and is countered by the aerosol forcing that by itself would produce about −0.5°C cooling by 2014 (Figure 1c). The rise of temperatures in the GHG-only

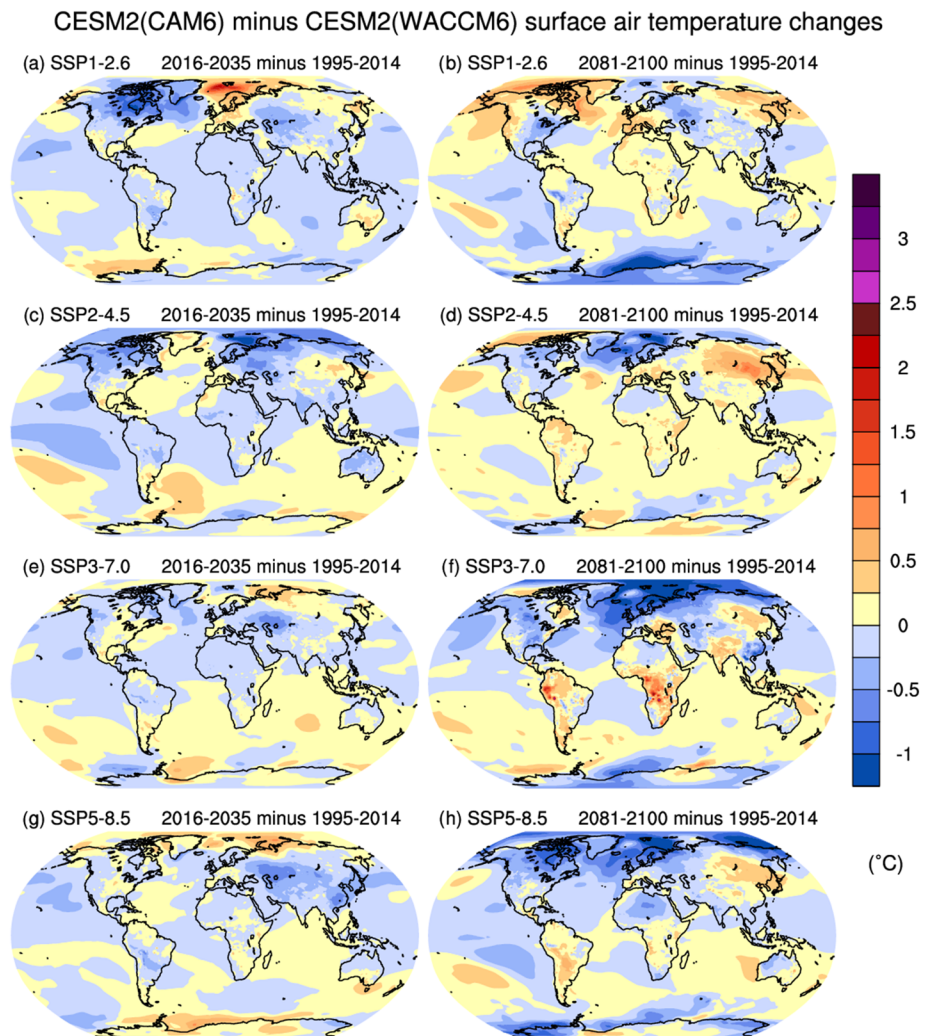


Figure 6. Same as Figure 5 except for CESM2(CAM6) minus CESM2(WACCM6) with the addition of SSP3-7.0. No significance is indicated due to the availability of only a single member of CESM2(WACCM6) for some of the scenarios and time periods shown (see Table 1).

simulations from about 1920–1940 is also seen in a multimodel ensemble of GHG-only forcing (not shown) and thus is likely a product of the CMIP6 GHG forcings.

4. Geographical Patterns of Response

4.1. Surface Air Temperature

Surface air temperature anomalies for the four scenarios and two time periods, one near-term and the other end of century, for CESM2(CAM6) and CESM2(WACCM6) are shown in Figures 3 and 4, respectively. As seen before in previous versions of CESM (e.g., Meehl et al., 2013) and in the CMIP5 models (e.g., Collins et al., 2013), there is significant warming almost everywhere in all scenarios in both models and both time periods except for an area of significant cooling in the North Atlantic in association to the weakening of the Atlantic Meridional Overturning Circulation in response to the increased greenhouse gas forcing (e.g., Hu et al., 2013). Warming is generally greater over land areas than ocean, and at high northern latitudes. Somewhat greater warming compared to other ocean areas begins to emerge in the eastern tropical Pacific becoming especially notable in late century in SSP5-8.5 (Figures 3h and 4h).

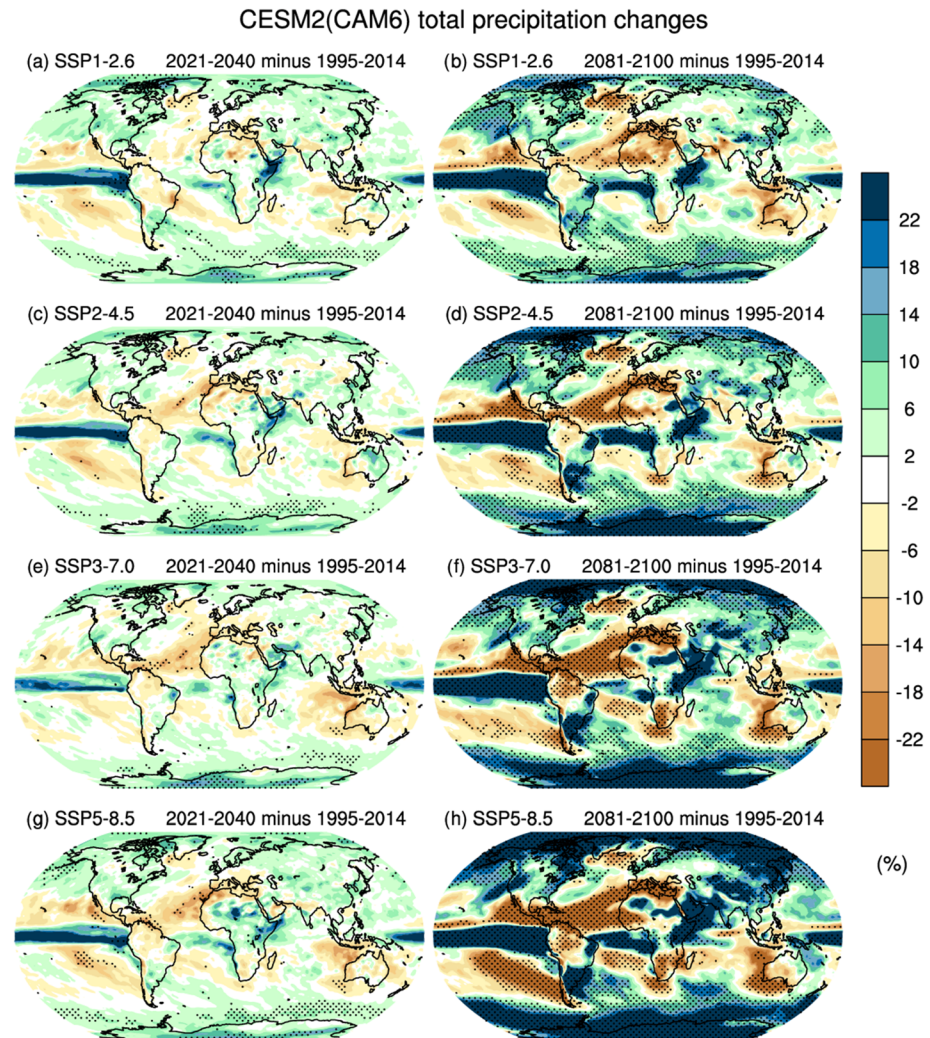


Figure 7. Same as Figure 3 except for precipitation (%).

Comparing the patterns of CESM2(CAM6) surface temperature response to CESM1 as differences in the anomalies (Figure 5), the tropics in general are notably warmer (e.g., positive anomalies of over $+1^{\circ}\text{C}$ in the higher scenarios and late century) while the Arctic appears colder in CESM2(CAM6) (negative differences). These are differences in anomalies as noted above, and CESM2(CAM6) actually starts with a warmer baseline compared to CESM1 (DeRepentigny et al., 2020). The warmer tropics in CESM2 compared to CESM1 were noted to have been present in the twentieth century historical simulations as discussed by Danabasoglu et al. (2020). There are some indications that sea ice retreat in CESM2(CAM6) is faster than CESM1 (discussed later in Figure 12) associated with the warmer baseline Arctic temperatures documented by DeRepentigny et al. (2020) even though there are negative differences in the response of Arctic temperatures in Figure 6. This indicates in relative terms that CESM2(CAM6) warms less at high latitudes. This is consistent with the TCR being similar in the two model versions, and with the mechanism for higher ECS that involves better representation of high-latitude cloudiness in CESM2(CAM6) as noted earlier. This comes with removal of a negative cloud phase feedback (Gettelman, Hannay, et al., 2019), but this is not realized if the high-latitude oceans do not warm (Figure 5). Note that CESM2(CAM6) and especially CESM2(WACCM6) have improved Arctic surface fluxes due to increased supercooled liquid water and a better distribution of aerosols (Gettelman, Hannay, et al., 2019).

Some interesting features of the responses in the two CESM2 versions emerge when the differences are computed for CESM2(CAM6) minus CESM2(WACCM6) in Figure 6. For SSP1-2.6 (Figures 6a and 6b),

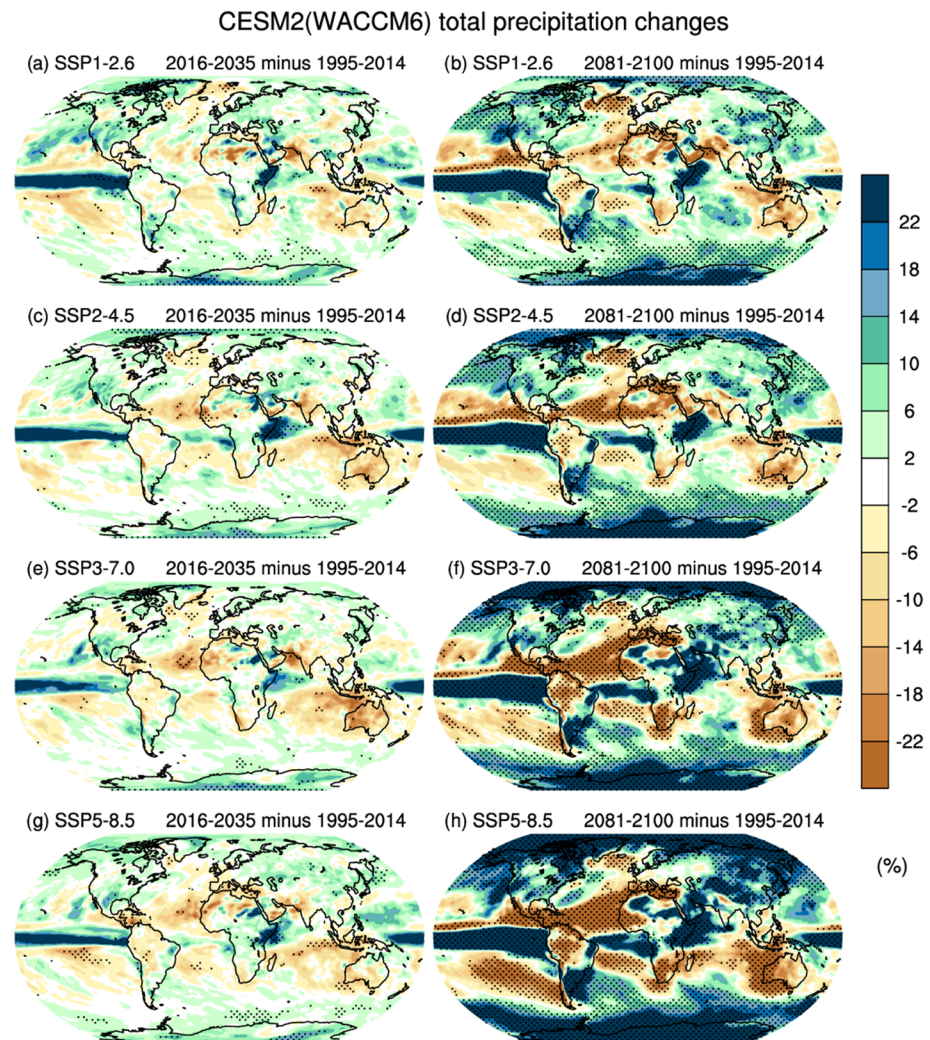


Figure 8. Same as Figure 4 except for precipitation (%).

CESM2(CAM6) has areas of less warming over northern North America and northwest Asia, as well as the Southern Ocean, the latter being particularly notable for late century (Figure 6b). Meanwhile, in the tropical Pacific, and to a lesser extent in the tropical Atlantic, negative differences indicate there is a tendency for less warming in CESM2(CAM6) compared to CESM2(WACCM6).

4.2. Precipitation

Previous CESM model versions (e.g., Meehl et al., 2013) and the CMIP5 models (e.g., Collins et al., 2013) have shown that a warmer climate generally produces greater tropical precipitation, reduced precipitation in the subtropics, and increases at middle and high latitudes where warmer air has an increased capacity for moisture. This pattern is seen for all scenarios and both time periods in both the CESM2(CAM6) and CESM2(WACCM6) (Figures 7 and 8).

For the comparison between CESM1 and CESM2(CAM6) (Figure 9), as could be expected from the discussion above, the CESM2(CAM6) with the warmer tropics produces greater tropical precipitation (positive anomalies) compared to CESM1 in all scenarios and time periods. The expanded Hadley Circulation noted in previous studies (e.g., Kang et al., 2013), associated with those positive tropical precipitation anomalies, is associated with mainly reductions in subtropical precipitation in CESM2(CAM6) compared to CESM1 (negative anomalies in Figure 9 in those regions) for all scenarios and time periods.

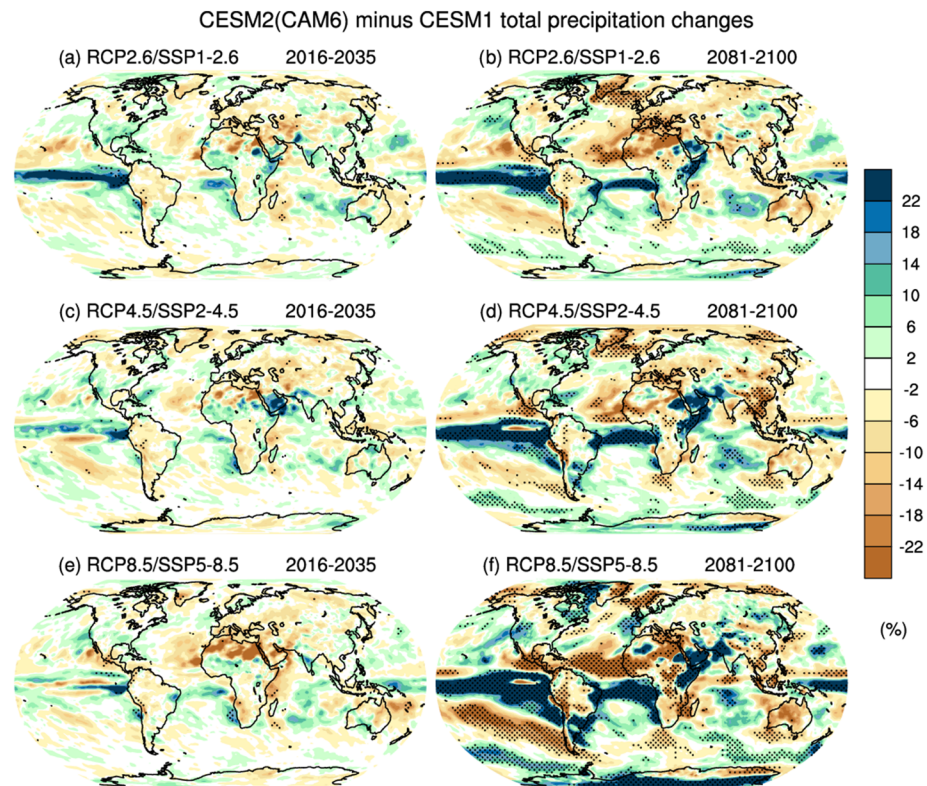


Figure 9. Same as Figure 5 except for precipitation (%).

For the differences between the CESM2(CAM6) and CESM2(WACCM6), those generally relate to the surface temperature differences, with the CESM2(CAM6) and its cooler tropical Pacific producing reduced precipitation there. The other tropical oceans respond in part to locally warmer SSTs and to the likely effects of a weakened Walker circulation to produce positive precipitation anomalies as evident in all scenarios and both time periods (Figure 10). The response in the subtropics is sometimes connected to regional SSTs, with areas of increased SSTs and precipitation in CESM2(CAM6) (e.g., Australia and southeastern Indian Ocean in SSP5-8.5, Figures 10g and 10h), while other areas have likely more to do with other regional or remote forcing (e.g., subtropical Atlantic and South Asia in SSP2-4.5, Figures 10c and 10d). The role of changes in the Hadley Circulation related to these patterns of precipitation change will be the subject of a subsequent paper.

Figure 11 displays the surface temperature and precipitation changes in CESM2(CAM6) relative to the CESM1 and CESM2(WACCM6) per degree of global warming. These provide a generalized view of the different model responses across all scenarios, allowing for a greater sample size to test for significance. The main results are consistent with those above, that is, there is more warming in the tropics and less warming in the high latitudes in the CESM2 compared to CESM1, with corresponding increases in tropical precipitation. Although there is weaker high-latitude warming in the CESM2 per degree of global warming compared to CESM1, its warmer base state results in a larger precipitation response in the high latitudes as well. Differences between CESM2(CAM6) and CESM2(WACCM6) are smaller and also less consistent across time periods, indicating some difference in their response to near-term climate forcings.

5. Sea Ice

A detailed discussion of future sea ice response in CESM2(CAM6) and CESM2(WACCM6) is given in DeRepentigny et al. (2020), and we mention only a few aspects here for context. In general for Arctic (Figure 12) and Antarctic (Figure 13) sea ice, both CESM2(CAM6) and CESM2(WACCM6) simulate less sea ice extent than CESM1, with CESM2(WACCM6) being in better agreement with the observations

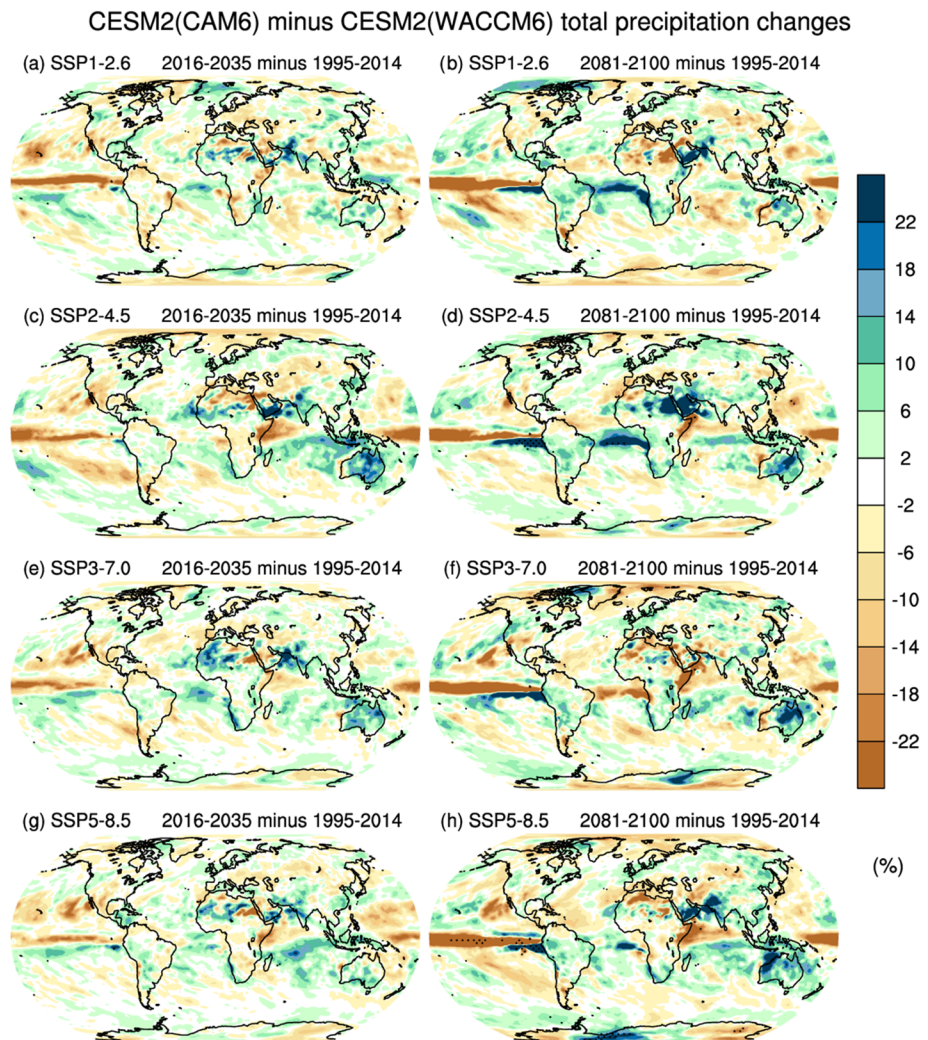


Figure 10. Same as Figure 6 except for precipitation (%). No significance is indicated due to the availability of only a single member of CESM2-WACCM for some of the scenarios and time periods shown (see Table 1).

(discussed in greater detail in DeRepentigny et al. (2020)). In fact, even in models with high ECS, in the Arctic the CESM2(WACCM6) does a remarkably good job in simulating the observations with regards to tendencies as well as the climatology and is not too far off in Antarctic summer.

The timing of the first instance of a simulated ice-free Arctic in September (defined as ice extent falling below $1 \times 10^6 \text{ km}^2$, indicated by the dashed line in Figure 12) occurs roughly 10 years earlier for all scenarios in CESM2(CAM6) compared to CESM2(WACCM6), though there is overlap with the CESM1 represented here by the CESM1 large ensemble (DeRepentigny et al., 2020; Kay et al., 2015). There is no scenario dependence on the timing of first instance of September ice-free conditions in the Arctic in CESM2(CAM6), but winter ice extent is still very sensitive to the choice of future forcing scenario (Figure 12 and DeRepentigny et al., 2020). In the Antarctic, the CESM2(CAM6) is more in line with observations during the austral summer (Figures 13a and 13b) whereas the CESM1 is in closer agreement with observations in the austral winter (Figures 13c and 13d). Note however that neither the CESM2(CAM6) nor the CESM1 is able to reproduce the trend in Antarctic ice extent over the satellite era.

The increase in sea ice extent in the first part of the 21st century is seen in all members and all scenarios of both CESM2(CAM6) and CESM2(WACCM6). This is discussed in DeRepentigny et al. (2020) but needs further investigation to fully understand what drives this behavior. Also, the v-shape in the time series

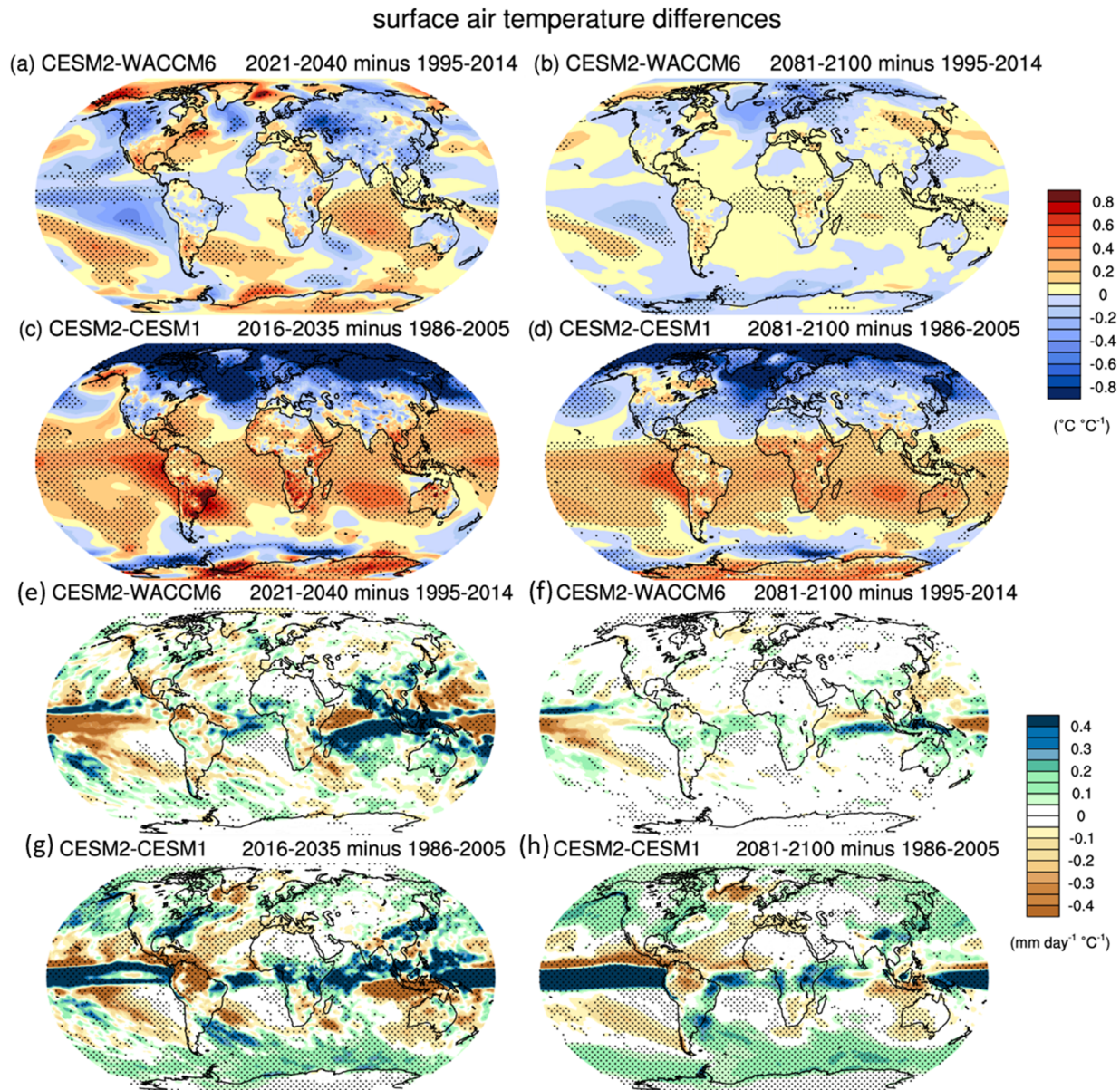


Figure 11. Surface warming and precipitation change per degree of global warming across all ensemble members and all scenarios, surface air temperature (°C °C⁻¹), CESM2(CAM6) minus CESM2(WACCM6), (a) 2021–2040 minus 1995–2014 and (b) 2081–2,100 minus 1995–2014; (c) and (d) same as (a) and (b) except for CESM2(CAM6) minus CESM1 using the 1986–2005 base period; (e) and (f) same as (a) and (b) except for precipitation change per degree warming (mm day⁻¹ °C⁻¹); (g) and (h) same as (c) and (d) except for precipitation change per degree warming.

around 2010 is a result of internal variability, as it does not occur exactly on the same year in all ensemble members.

An analysis of the preindustrial control and twentieth century historical simulations from the two new models (not shown) finds that there are fewer aerosols to form cloud condensation nuclei in CESM2(CAM6) compared to CESM2(WACCM6), which results in thinner liquid clouds. This results in more shortwave radiation early in the melt season, driving a stronger ice albedo feedback and leading to additional sea ice loss and significantly thinner ice year-round. There is the possibility that this stronger ice-albedo feedback in CESM2(CAM6) could contribute to its higher ECS compared to CESM2(WACCM6). These sea ice changes also likely contribute to warmer Arctic conditions in CESM2(CAM6) compared to CESM2(WACCM6) seen most clearly in the higher forcing scenarios (Figures 6e–6h).

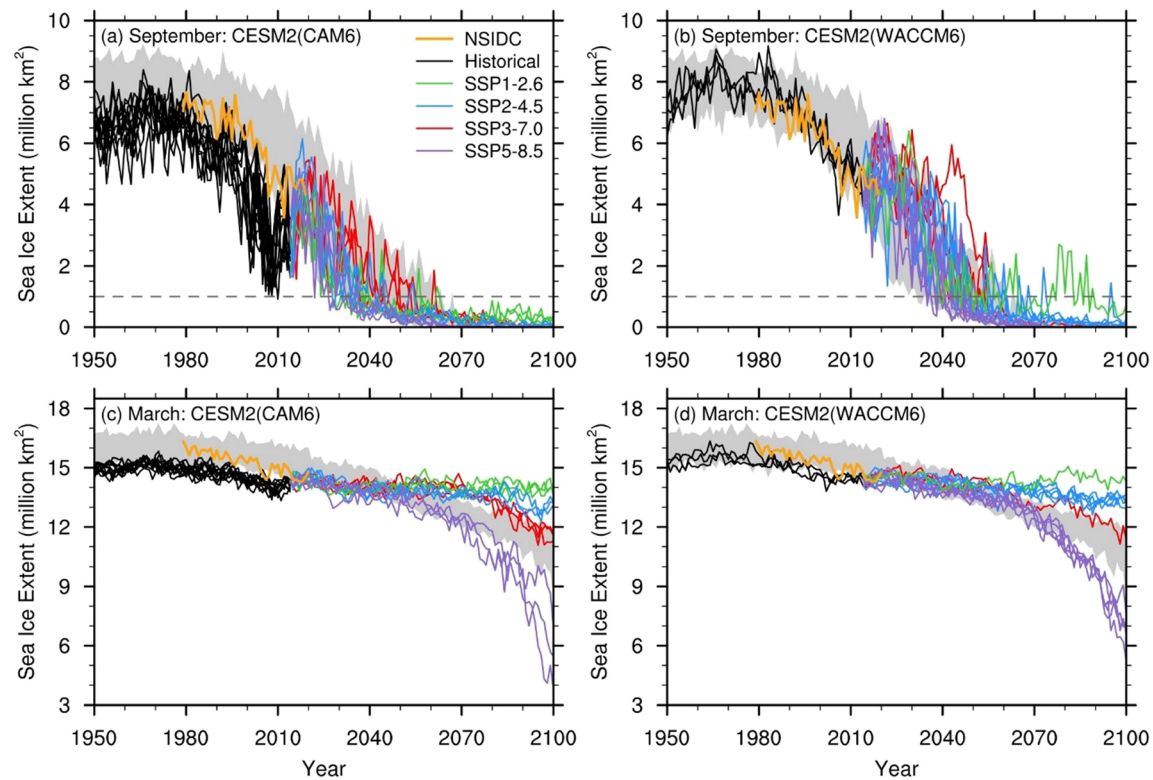


Figure 12. Time series of Arctic sea ice extent (million km²) over the historical period and for the four scenarios (legend in panel a) compared to the gray shading which represents the range in the CESM1 large ensemble, and observations from NSIDC (orange), for (a) CESM2(CAM6), September, (b) CESM2(WACCM6), September; (c) CESM2(CAM6) March; (d) CESM2(WACCM6) March. Dashed lines indicate the threshold for ice-free conditions of less than 1×10^6 km².

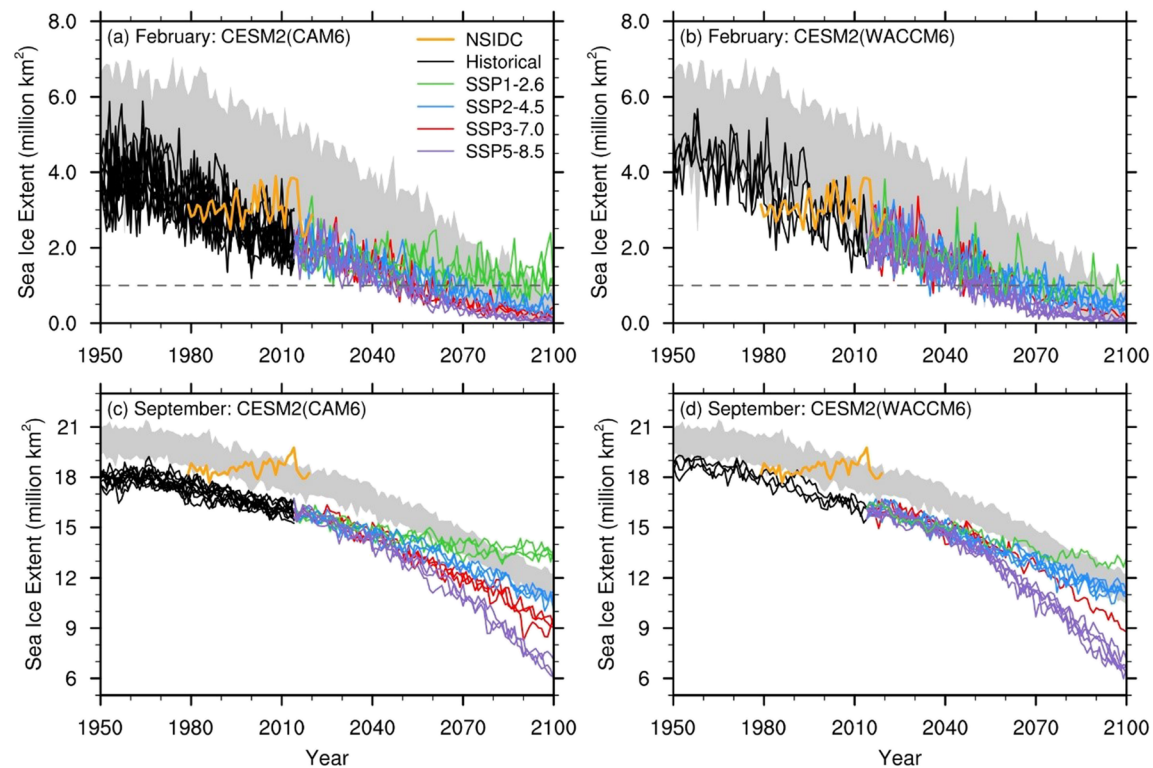


Figure 13. Same as Figure 12 except for Antarctic sea ice extent for February (a, b) and September (c, d).

6. Conclusions

The new versions of CESM2(CAM6) and CESM2(WACCM6) have higher equilibrium climate sensitivities than the previous model version, CESM1, but comparable values of transient climate response. While the higher ECS values in the newer versions contribute to greater warming by the end of the 21st century in CESM2(CAM6) and CESM2(WACCM6) compared to CESM1 for the high forcing scenario, prior to midcentury the warming is comparable among all model versions and scenarios. This is consistent with a mechanism for the higher ECS, which is partly related to high-latitude cloud feedbacks and does not take effect until the high-latitude oceans warm significantly. The higher climate sensitivity in CESM2(CAM6) and CESM2(WACCM6) compared to CESM1 is associated with greater tropical warming and precipitation increase in those regions. CESM2(CAM6) does not warm as much in the tropics as CESM2(WACCM6), though CESM2(CAM6) warms more at high latitudes than CESM2(WACCM6).

The relatively larger magnitude of ECS in CESM2(CAM6) compared to CESM2(WACCM6) relates to the fact that CESM2(WACCM6) interactively redistributes climatological ozone concentrations during the abrupt-4xCO₂ and scenario runs in order to retain the bulk of the ozone in the stratosphere as the tropopause height raises. Conversely, CESM2(CAM6) does not redistribute ozone and thus, as the tropopause rises with warming, there is more ozone that remains in the upper troposphere. This likely contributes to an increase in the ECS in CESM2(CAM6) compared to CESM2(WACCM6) as noted in another model (Hardiman et al., 2019).

CESM2(CAM6) shows the first instance of an ice-free Arctic in September for all scenarios and ensemble members about a decade earlier than CESM2(WACCM6) likely due to different representations of Arctic clouds driven by interactive aerosol chemistry. Thus, the 21st century scenarios are consistent broadly with TCR and ECS estimates, with a significant difference in global average surface temperature in 2100 in CESM2(CAM6) over CESM1 only for the highest forcing scenario. This goes along with the high-latitude ice and cloud feedback processes that contribute to ECS differences between CESM1, CESM2(CAM6) and CESM2(WACCM6).

Data Availability Statements

Previous and current CESM versions are freely available at this site (www.cesm.ucar.edu/models/cesm2/). The CESM solutions/data sets used in this study are also freely available from the Earth System Grid Federation (ESGF) at esgf-node.llnl.gov/search/cmip6 or from the NCAR Digital Asset Services Hub (DASH) at data.ucar.edu or from the links provided from the CESM web site (www.cesm.ucar.edu). The CESM solutions/data sets used in this study are freely available from <http://tinyurl.com/y9lbcjsj>. Arctic and Antarctic sea ice extent data are available from <http://nsidc.org/data/search/#keywords=Arctic+sea+ice+extent/sortKeys=score,desc/facetFilters=%257B%257D/pageNumber=1/itemsPerPage=25> and <http://nsidc.org/data/search/#keywords=Antarctic+sea+ice+extent/sortKeys=score,desc/facetFilters=%257B%257D/pageNumber=1/itemsPerPage=25>, respectively.

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Acknowledgments

The CESM project is supported primarily by the National Science Foundation (NSF). This material is based upon work supported by the National Center for Atmospheric Research (NCAR), which is a major facility sponsored by the NSF under Cooperative Agreement 1852977. Computing and data storage resources, including the Cheyenne supercomputer, were used for the CESM simulations (doi:10.5065/D6RX99HX). This research also used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract DE-AC02-05CH11231. Portions of this study were supported by the Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program of the U.S. Department of Energy's Office of Biological & Environmental Research (BER) via National Science Foundation IA 1947282.

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