

Increasing Total Solar Irradiance on Far Future Climate: General Atmospheric Circulation

R.H.O. Rangel^{1,*}, M. Cataldi², L. Sancho³, A. Belém⁴, L. Landau⁵

Abstract

The total solar irradiation at the top of the atmosphere is the primary forcing mechanism for the Earth's Climate System. In this work, we used the addition of 10% in the radiation value (from 1360 Wm⁻² to 1496 Wm⁻²) to simulate the Earth's climate system in the habitable zone inner orbit. Two ten-year-long fully coupled simulations using the Community Earth System Model were performed; the CONTROL experiment was configured with the standard total solar irradiation value and the TSI10p experiment with a 10% increase. TSI10p experiment revealed latitudinal shifts in atmospheric pressure belts, and the energy input increased the mean surface air temperature by 7°C. This temperature increase led to an increase in the surface heat flux. Additional changes in the atmosphere were identified, such as moister summers and drier winters in mid-latitudes and changes in planetary runoff and ocean salinity.

Keywords: Total Solar Irradiance, Habitable zone, CESM, Climate change, Future climate.

INTRODUCTION

Computational models are indispensable tools for simulating phenomena in the atmosphere's present, past, or future state [1]. The primary forcing mechanism for the terrestrial climate system is the total solar radiation incident at the top of the atmosphere (total solar irradiance—TSI). Its intensity varies by a few percent with solar activity cycles [2, 3, 4, 5] on both short- and long-term scales. Additionally, the sun's TSI increases according to its natural evolution. The literature classifies the sun as a yellow dwarf star due to its current evolution stage [6]. The next evolutionary stage is the red giant type, where it will acquire other physical-chemical characteristics. However, doing so may take

a few billion years [6]. To estimate possible TSI values in the range of far future natural variability that could generate a catastrophic climate change scenario, we used the concept of a habitable zone (HZ). The HZ is the orbital interval around a star where planets with the presence of liquid water on the planet's surface may exist, which favors the existence of life [7, 8, 9, 10, 11, 12, 13]. Assuming something displaces the Earth from the current to an inner orbit (in the inner edge of the HZ), the effect would be similar to the TSI increase of 10% (+136 Wm²) from its current value (1360 Wm⁻²). This increase would cause a temperature increase, increasing the tropopause height [13].

Dangerous climate change thresholds have been discussed over the last four decades [14]. In addition to the consequences to natural systems, scientists are also interested in evaluating and quantifying other impacts, such as socioeconomic

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impacts [15]. A 2°C rise (above pre-industrial values) in average global temperature is commonly considered the threshold for dangerous climate change [16, 17, 18]. The European Union adopted this threshold in 1996, and the 2009 Copenhagen Accord endorsed it [18]. However, there is substantial uncertainty about the future effects of a 2°C temperature rise on society [19].

Public policymakers can use computational modeling to mitigate the impacts of the climate changes observed in the simulations. Since the first general circulation model of the atmosphere, derived from weather forecasting models in the 1950s [20], numerical and computational climate forecasts have been continuously developed, with the Community Earth System Model (CESM) being one of the state-of-the-art models [21, 22]. CESM has been widely used on past [23, 24, 25], present [26, 27], and future [28, 29] terrestrial climates. Some studies with partially coupled CESM (atmosphere and ocean) also changed the TSI to estimated values for a possible future solar minimum period. These studies analyzed surface air temperature [30], sea ice concentration, geopotential height, and surface air temperature for the Northern Hemisphere [31].

This work aims to evaluate a far future climatic response to a drastic increase (10%) in the TSI in the simulated fully coupled terrestrial system CESM (atmosphere + ocean + sea-ice + land-ice + land + river + coupler) when compared to a control simulation. We evaluated changes in the general atmospheric circulation to analyze the impacts of TSI changes on the planet's dynamic and thermodynamic balance. First, the control run was validated against two reanalysis model results, which assimilate the observations and are considered closer to the observed data. The reanalysis used here was the Interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ECMWF ERA-Interim; [32, 33]) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis-2 project [34, 35]. Once the control run was validated, it was used as a mean state to estimate possible changes on the increased TSI run.

DATA AND METHODS

The Community Earth System Model

The experiments analyzed in this study were performed with the CESM [36] version 1.2. CESM is composed of coupled global numerical models that simulate processes in the atmosphere (Community Atmosphere Model–CAM; [36]), ocean (Parallel Ocean Program–POP; [37]), sea ice (Community Ice Code–CICE; [38]), land ice (Community Ice Sheet Model–CISM; [39]), land (Community Land Model–CLM; [40, 41]) and river (River Transport Model–RTM; [36]). CPL7 coupler [42] (Figure 1) controlled the flow of data and its synchronization between the various model components. Both experiments were configured with a 10-year run and initial conditions from 2000 to simulate the current climate system, with activated CAM, CLM, POP, and CICE. The grid used was a T31_g37, which corresponds to a horizontal resolution of 3.75°(48 × 96 points in latitude and longitude, respectively) for CAM and CLM, a 1° resolution for POP and CICE (100 × 116 points in latitude and longitude, respectively), and a 0.5° resolution for RTM (360 × 720 points in latitude and longitude, respectively). The configured time steps were the model's default (CAM, CLM, and CICE, 1800 s; POP, 7200 s; CISM, 86400 s; RTM, 10800 s). Two experiments were performed to study the influence of increasing TSI on climate. The first one (CONTROL) with the TSI's standard value (1360 W·m⁻²), and the second one (TSI10p) with an increase of 10% (1496 Wm⁻²), which corresponds to the HZ inner edge [13]. Zonal means were calculated for mean sea level pressure, surface air temperature, total cloud cover, surface heat latent flux, precipitation, and zonal and meridional wind components at two different pressure levels. The results were grouped into two blocks, three months each (January/February/March–JFM; July/August/September–JAS), to observe seasonal patterns. Subsequently, 10-year means were calculated for each experiment for each group; in other words, each group is a 10-year average for those months.

Reanalysis Data

Reanalysis is valuable for climate studies since in situ meteorological observations are unevenly distributed and scattered over large areas [43, 44, 45, 46]. Reanalysis data sets provide global

coverage over long periods and are considered an acceptable estimate of historical atmospheric states. It combines historical atmospheric observations with data assimilated into atmospheric models [47, 48]. We acquired ERA-Interim [32, 33] and Reanalysis-2 [34, 35] monthly means data from January 1st, 2000, to December 31st, 2009, and averaged in their native grids (horizontal resolutions of 0.7° and 2.5°, respectively) to validate the control run.

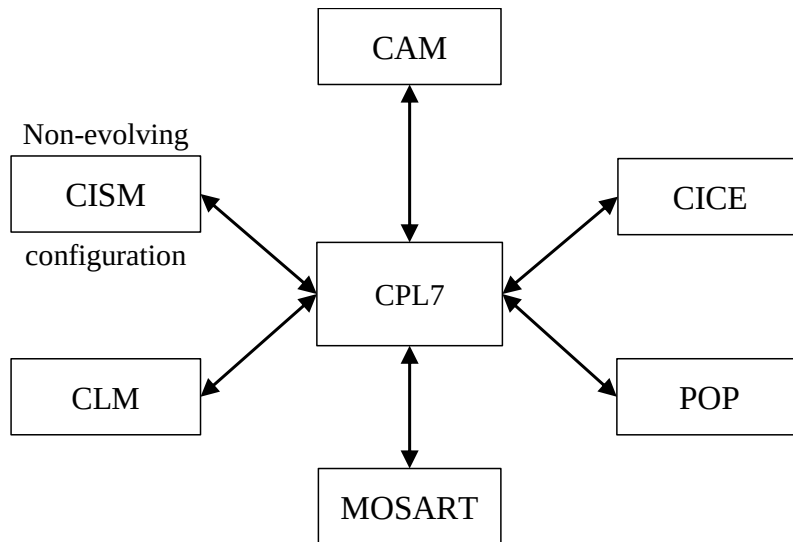
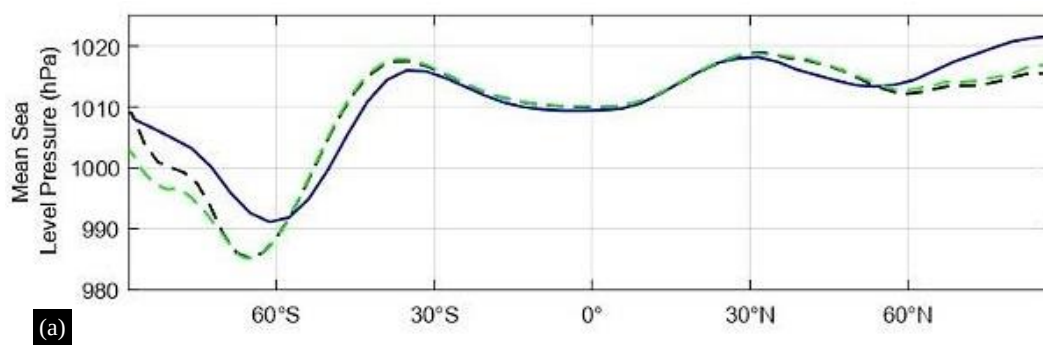


Figure 1. CESM components scheme with each numerical model. The CPL7 coupler performs the communication between each model. The coupler receives the prognostic value from the donor model, re-grids it, if necessary, and sends it to the recipient model. The CISM was used in a non-evolving configuration, assuming fixed ice sheets.

RESULTS AND DISCUSSION

CONTROL Experiment Validation

Figures 2(a) and 2(b) show the CONTROL, Reanalysis 2, and Era-Interim Longitude Mean Sea Level Pressure for JFM and JAS. For JFM (Figure 2(a)), in low and mid-latitudes, the CONTROL sea level pressure had the same pattern and similar pressure values as the reanalysis products. Outside of these regions, all results departed from each other, given the proximity to the poles. The southern high-pressure belt shifted slightly northward, placed at approximately 30°S. The austral summer is characterized by a southward Intertropical Convergence Zone (ITCZ) shift, shifting the high-pressure belt southward [1]. For JAS (Figure 2(b)), the CONTROL experiment was in good agreement with the reanalysis products in both pattern and intensity, similar to Figure 2(a). The high- (low-) pressure belt location was identified at approximately 30°S (60°S) in the Southern Hemisphere and approximately 40°N (60°N) in the Northern Hemisphere.



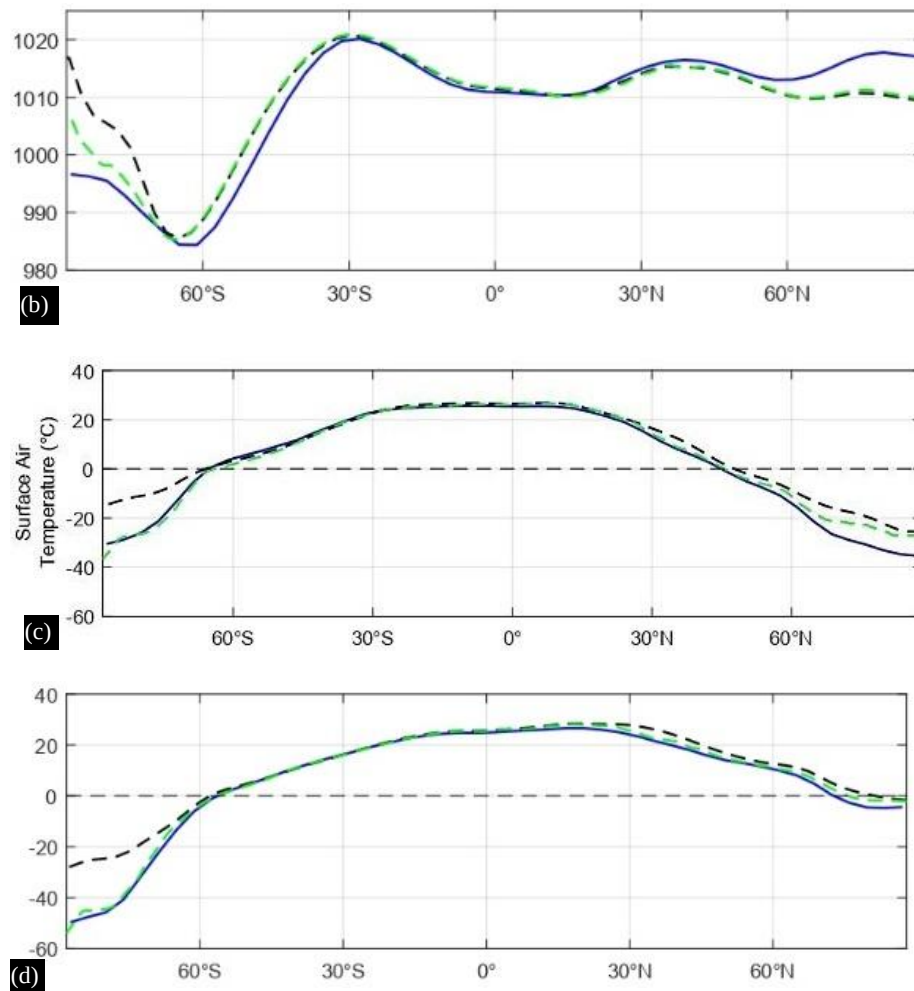


Figure 2. Mean zonal distributions for JFM (a) and (c) and JAS (b) and (d) from January 1st, 2000, to December 31st, 2009. Mean sea level pressure (a) and (b), and surface air temperature (c) and (d). The CONTROL experiment is shown in blue. The Reanalysis 2 and ERA-Interim data are shown with black and green dashed lines, respectively.

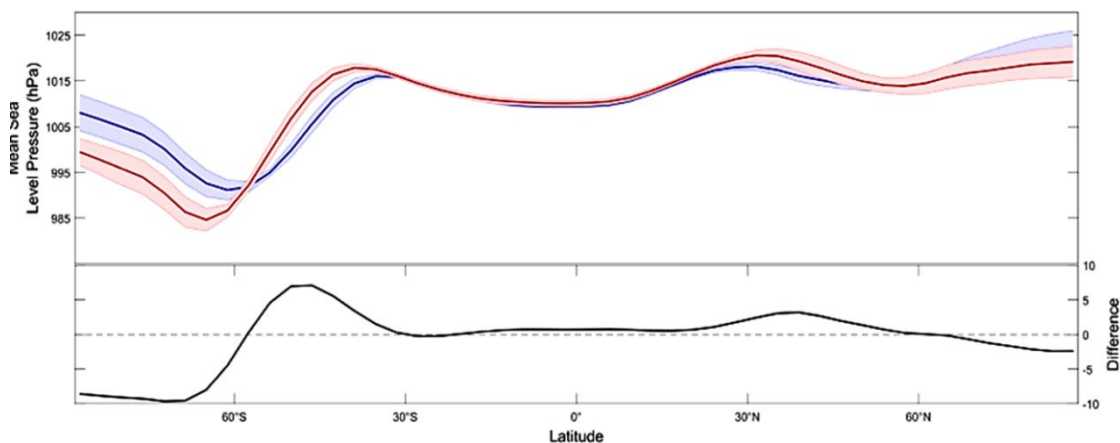
Figures 2(c) and 2(d) show the mean zonal surface air temperature. For both JFM (Figure 2(c)) and JAS (Figure 2(d)), there was a good agreement between CONTROL and reanalysis products in both pattern and value at low and mid-latitudes. They exhibit an expected average profile, with higher temperatures in the equatorial region that decrease toward the poles. Outside these regions, the results depart from each other, given their proximity to the poles. Even so, the CONTROL experiment and the Era-Interim products were in good agreement at high latitudes. Another interesting feature in these high latitude regions was the higher temperature difference between summer and winter in the Northern Hemisphere than in the Southern Hemisphere. This difference is closely linked with the continent-ocean ratio, which is more significant in the Northern Hemisphere (4:1) than in the southern one (1.5:1) [1].

Observed Changes with the TSI10p Experiment

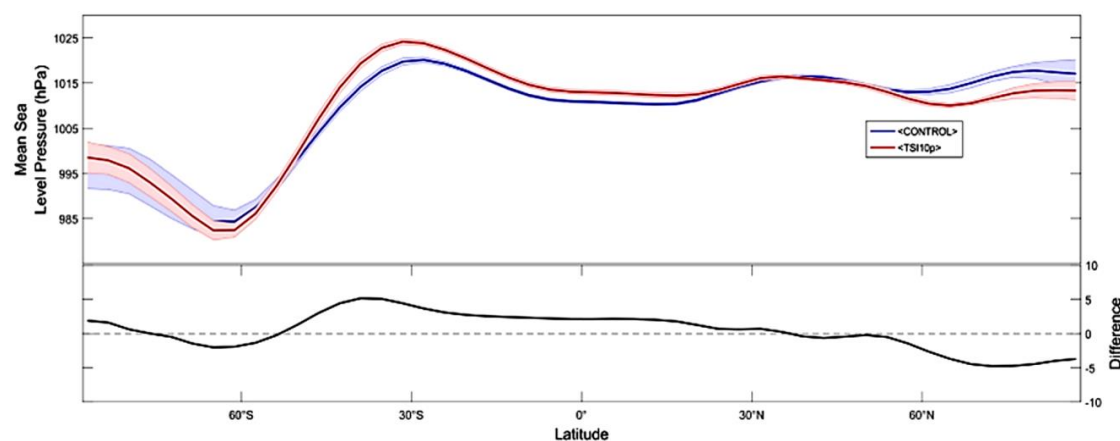
In this section, comparisons between CONTROL and TSI10p experiments are shown. The shaded lines represent the standard deviation of each simulation period. The mean sea level pressure for JFM (Figure 3(a)) represents, for both simulations, low-pressure belt features at approximately 60°N and 60°S. High pressures are shown in mid-latitudes, which is compatible with the expected behavior of the mean zonal pressure distribution. In the TSI10p experiment, the entire system shifts southward in the Southern Hemisphere and northward in the Northern Hemisphere, changing the circulation pattern.

Furthermore, TSI10p shows the intensification of both low (60°S–984 hPa) and high (40°S–1017 hPa) pressures related to CONTROL, in addition to the displacement of their respective positions towards greater latitudes. Both simulations retained similar patterns in the equatorial belt region at the ITCZ location. There was a more considerable difference between them at approximately 50°S and 40°N due to the latitudinal shift of high-pressure belts. Similar behavior occurs with the low-pressure belt in the Southern Hemisphere. Both experiments exhibited the same pattern without significant shifts in JAS (Figure 3(b)). Low-pressure belts were lower in both hemispheres for TSI10p and were located approximately at 60°S (982 hPa) and 60°N (1010 hPa). The high-pressure belt in the Southern Hemisphere was located at approximately 30°S and was higher in the TSI10p model (1024 hPa). The high-pressure belt in the Northern Hemisphere was located at approximately 40°N and did not show significant changes.

Surface air temperature (Figures 3(c) and 3(d)) presented the expected average profile, with higher temperatures in the equatorial region that decreased towards the poles. In the TSI10p experiment, the temperature increased globally, leading to a global warming scenario. For JFM Figure 3(c)), the increase in average temperature was 7.5°C, and for JAS, it was 6.6°C. The Northern Hemisphere showed a more significant difference between JFM and JAS, emphasized at high latitudes. This behavior is linked to a greater water heat capacity. Once the Southern Hemisphere has a smaller continent-ocean ratio, it will preserve heat more efficiently than the Northern Hemisphere. The surface temperature did not increase equally globally. The Southern Hemisphere Hadley Cell was heated more on its descending branch (30°S) than on its ascending branch (60°S (Figure 3(c)). This heating difference led to a southward shift of the Southern Hemisphere's high-pressure belt, leading to a southward shift of its low-pressure belt (Figure 3(a)).



(a)



(b)

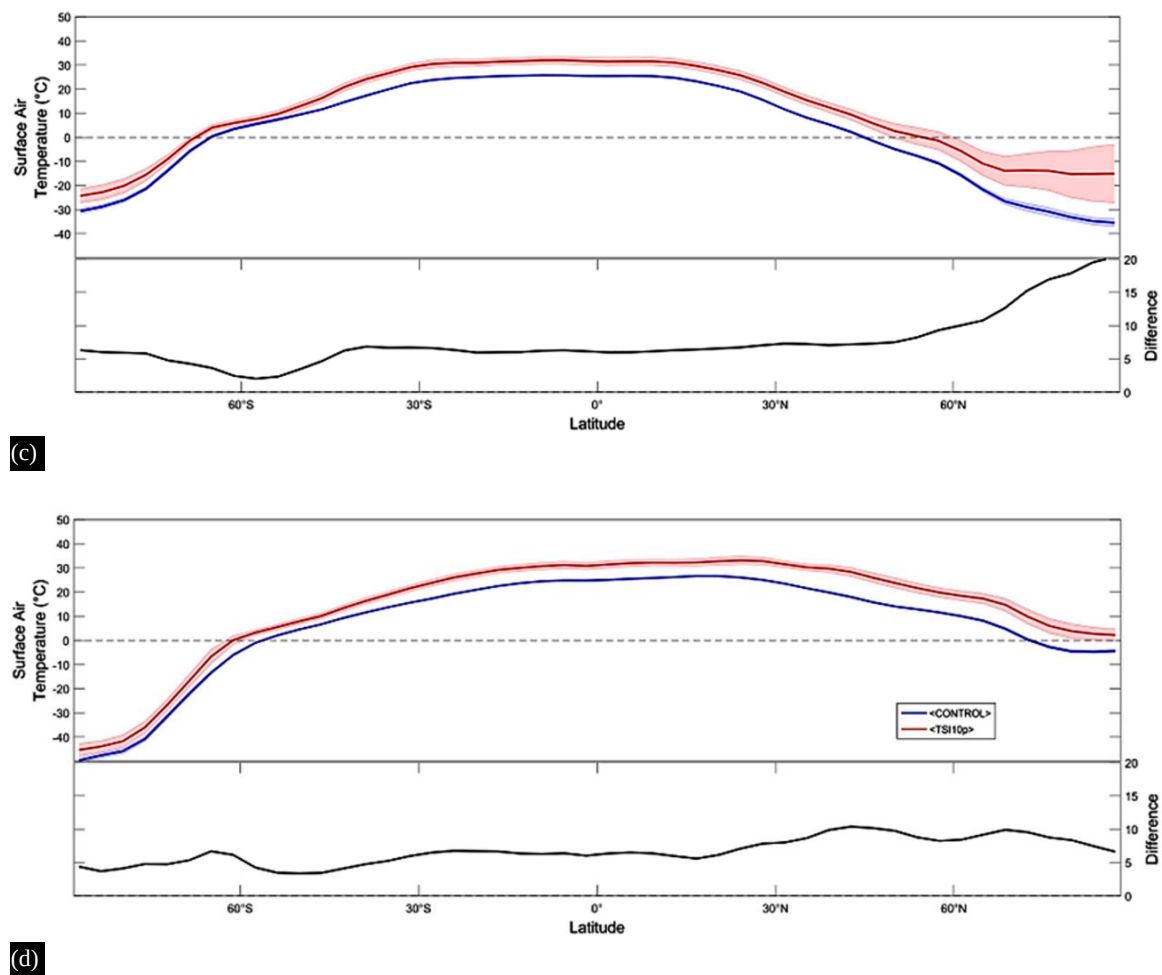
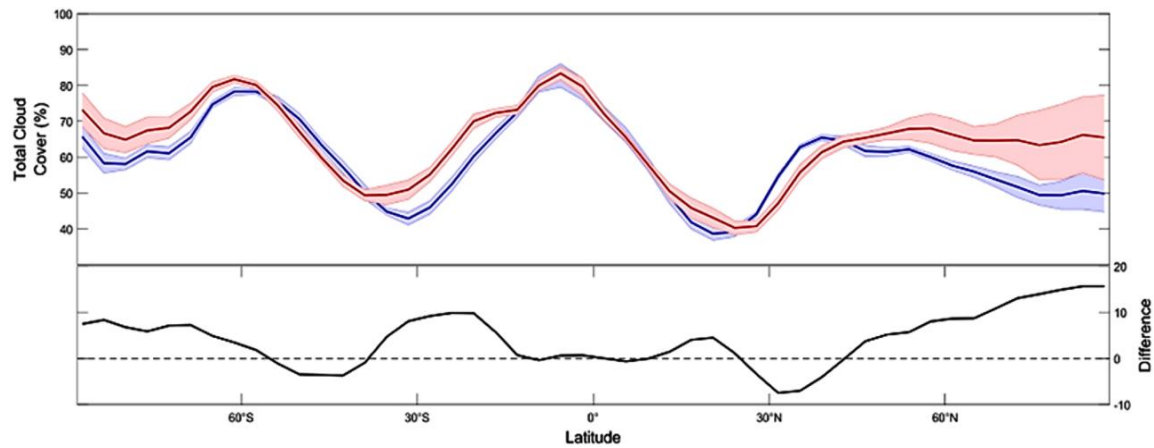


Figure 3. Mean zonal distributions for JFM (a) and (c) and JAS (b) and (d). The 10-year simulation mean values for each atmospheric variable are blue (CONTROL) and red (TSI10p). (a) and (b) represent mean sea level pressure, and (c) and (d) represent surface air temperature.

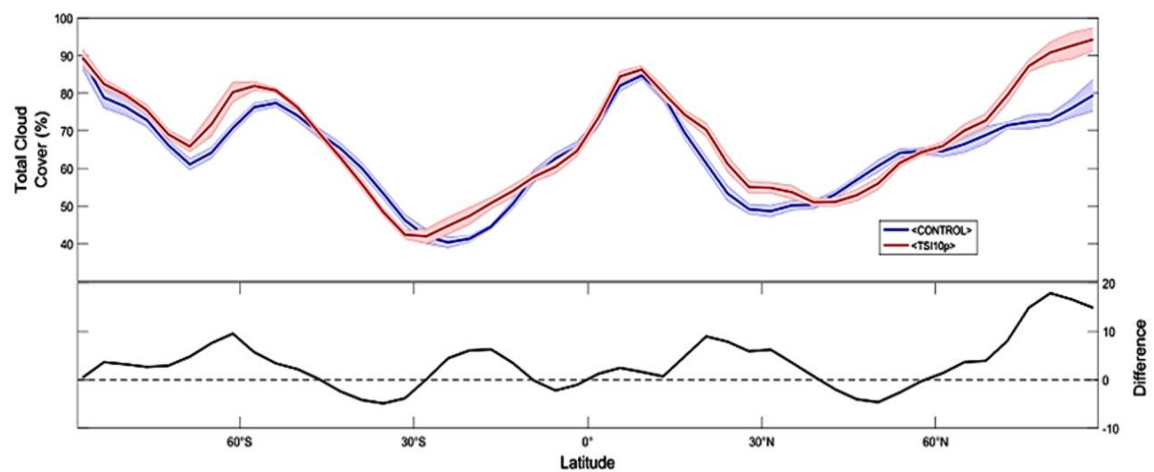
The total cloud cover variable (Figures 4(a) and 4(b)) presented the expected observed pattern, with higher values in equatorial regions and around 60°S and 60°N. On the other hand, around 30°S and 30°N showed lower values, coherent with ascending and descending circulation cells [1]. It is important to notice that for JAS, the cloud distribution for both experiments shifted northward due to Northern Hemisphere winter and the greater amount of continental mass relative to the Southern Hemisphere. Comparing both experiments for JFM, it was noted that between 20°S and 40°S, there was a significant difference in cloud cover, with a southward shift of the minimum. At approximately 60°S, there was an increase in maximum cloud cover and a southward shift. This behavior is possibly related to a Southern Hemisphere low-pressure belt intensification (Figure 3(a)), which enables an increase in cloud cover. Between 15°S and 15°N, there was no significant cloud cover change, possibly due to an unchanged behavior in the mean sea level pressure (Figure 3(a)) for the same region. On the other hand, between 20°N and 40°N, a decrease in cloud cover was observed with a northward shift. This behavior seems to relate to the high-pressure belt increase and shift over this region.

The distribution of surface latent heat flux (Figures 4(c) and 4(d)) showed more intense flows with peaks at 20°S and 10°N that gradually fell towards the poles due to a decrease in solar radiation incidence in these regions. At the equator, the flow was less intense due to the presence of constant nebulosity in the region (Figures 4(a) and 4(b)), which the ITCZ influenced. For the JAS period, the

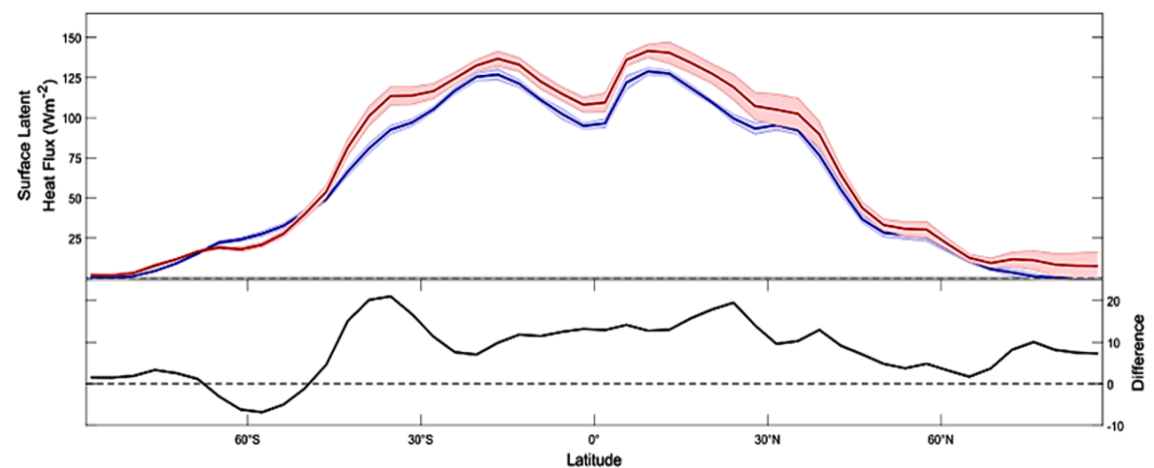
latent heat flux was also larger; however, a more pronounced peak occurred at 20°S due to larger water bodies in the Southern Hemisphere and lower cloud cover values than JFM. In TSI10p, the fluxes were more intense mainly due to the temperature increase observed in this experiment (even in the equatorial region), thus increasing evaporation over the sea and evapotranspiration over forests or dense vegetation.



(a)



(b)



(c)

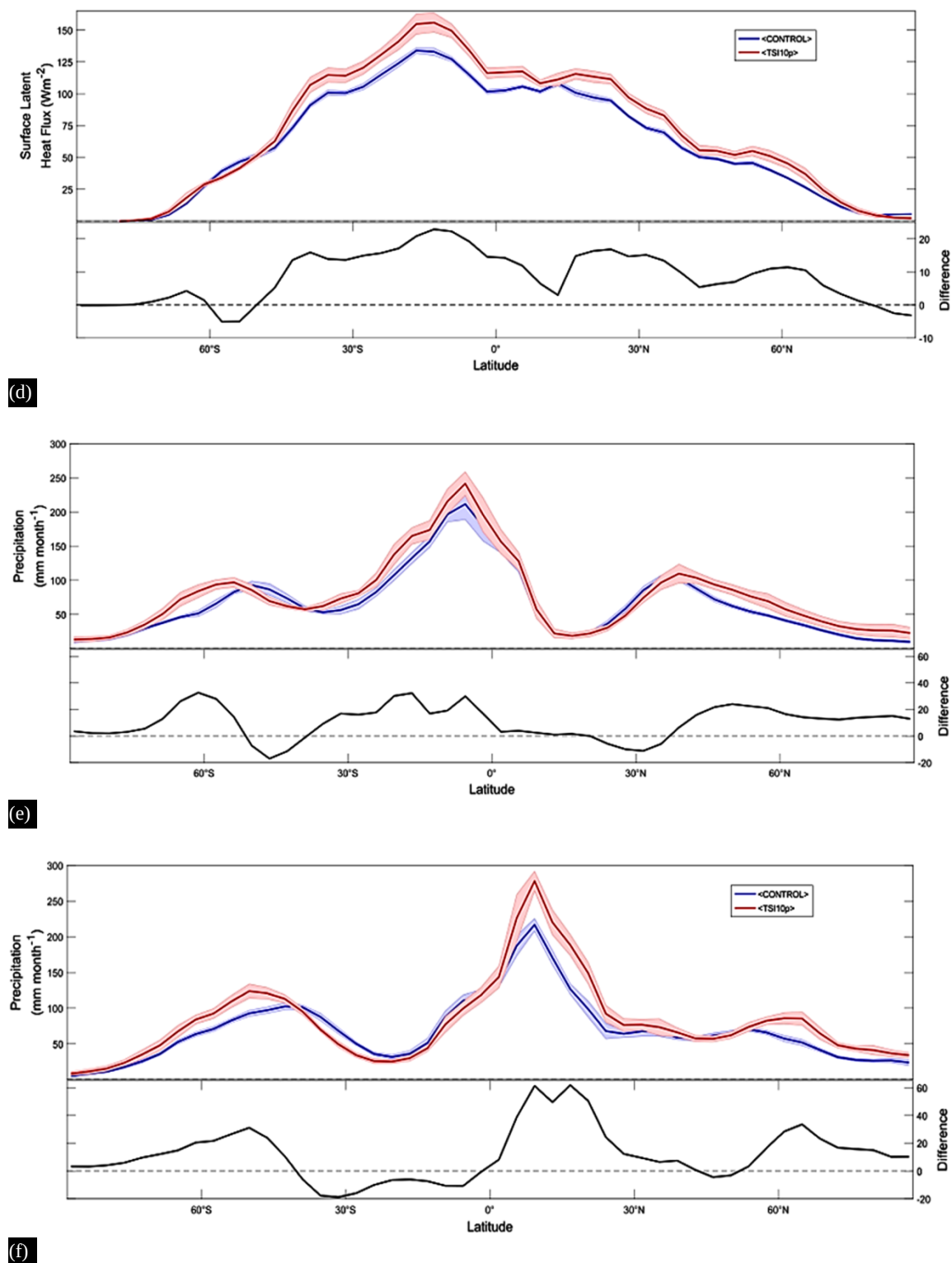
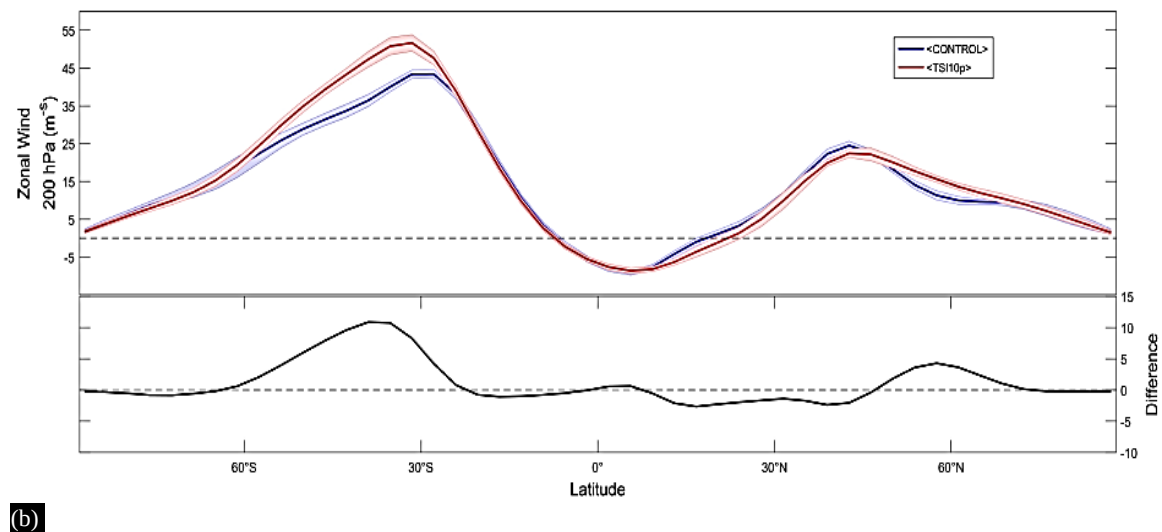
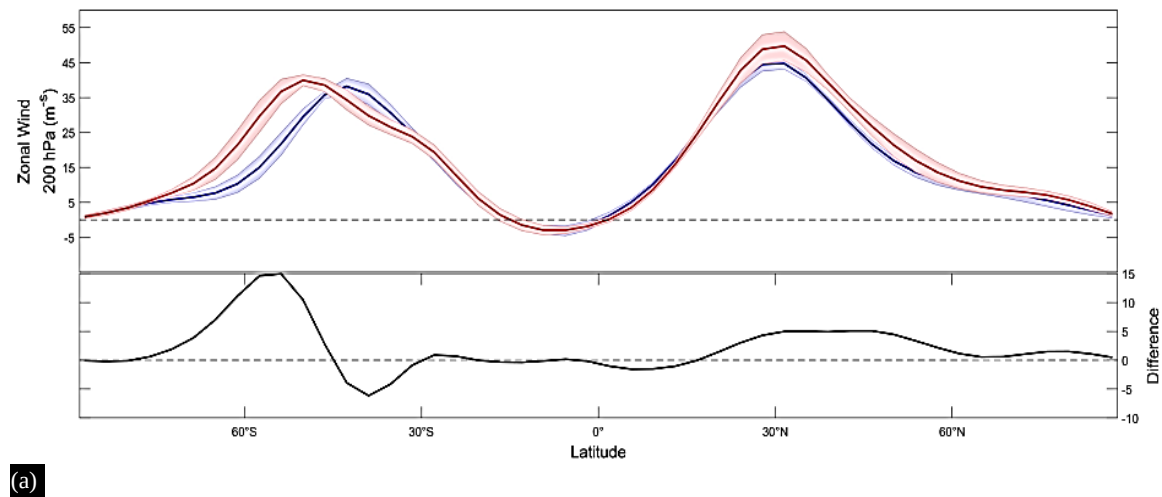


Figure 4. Mean zonal distributions for JFM (a, c and e) and JAS (b, d and f). The 10-year simulation mean values for each atmospheric variable are blue (CONTROL) and red (TSI10p). (a) and (b) represent total cloud cover, (c) and (d) represent surface latent heat flux, and (e) and (f) represent precipitation.

Precipitation (Figures 4(e) and 4(f)) presents a pattern of higher values along the equatorial region, decreasing towards high-pressure belts and increasing towards low-pressure regions. The maximum

precipitation region follows climatology, located southward for JFM and northward for JAS due to ITCZ dynamics. The TSI10p in the Southern Hemisphere exhibited moister summers and drier winters. Moreover, an ITCZ intensification in JFM and JAS was observed with a precipitation increase. This intensification was more pronounced for JAS than for JFM. Between 40°S and 60°S, and 40°N and 60°N, there was a shift towards greater latitudes for both periods. This shift may be related to shifts found in the same regions for the mean sea level pressure (Figures 3(a) and 3(b)).

The average distribution of zonal winds at 200 hPa, shown in Figure 5(a) and Figure 5(b), shows a coherent representation of the dominant weak easterly winds in the equatorial region, with an inversion and intensification at mid-latitudes and a composition of the general atmospheric circulation model, with winds out of the east with lower intensities in Polar Regions. In general, the zonal component's intensification justifies by the pressure gradient increase caused by the greater amount of energy available in the TSI10p. The lower branch (850 hPa-Figure 5(c) and (d)) of the circulation cells completes the general circulation model. For JFM and JAS, weak trade winds converged on the equatorial region. Outside this region, the winds progressively turned into stronger westerlies and weak easterlies again at higher latitudes. For JFM (Figure 5(c)), the TSI10p exhibited a poleward shift with wind intensification in the Southern Hemisphere. This behavior follows the changing pressure pattern (Figure 5(a)). On the other hand, for JAS (Figure 5(d)), the TSI10p showed a poleward shift only in the Northern Hemisphere, with an intensification in the Southern Hemisphere.



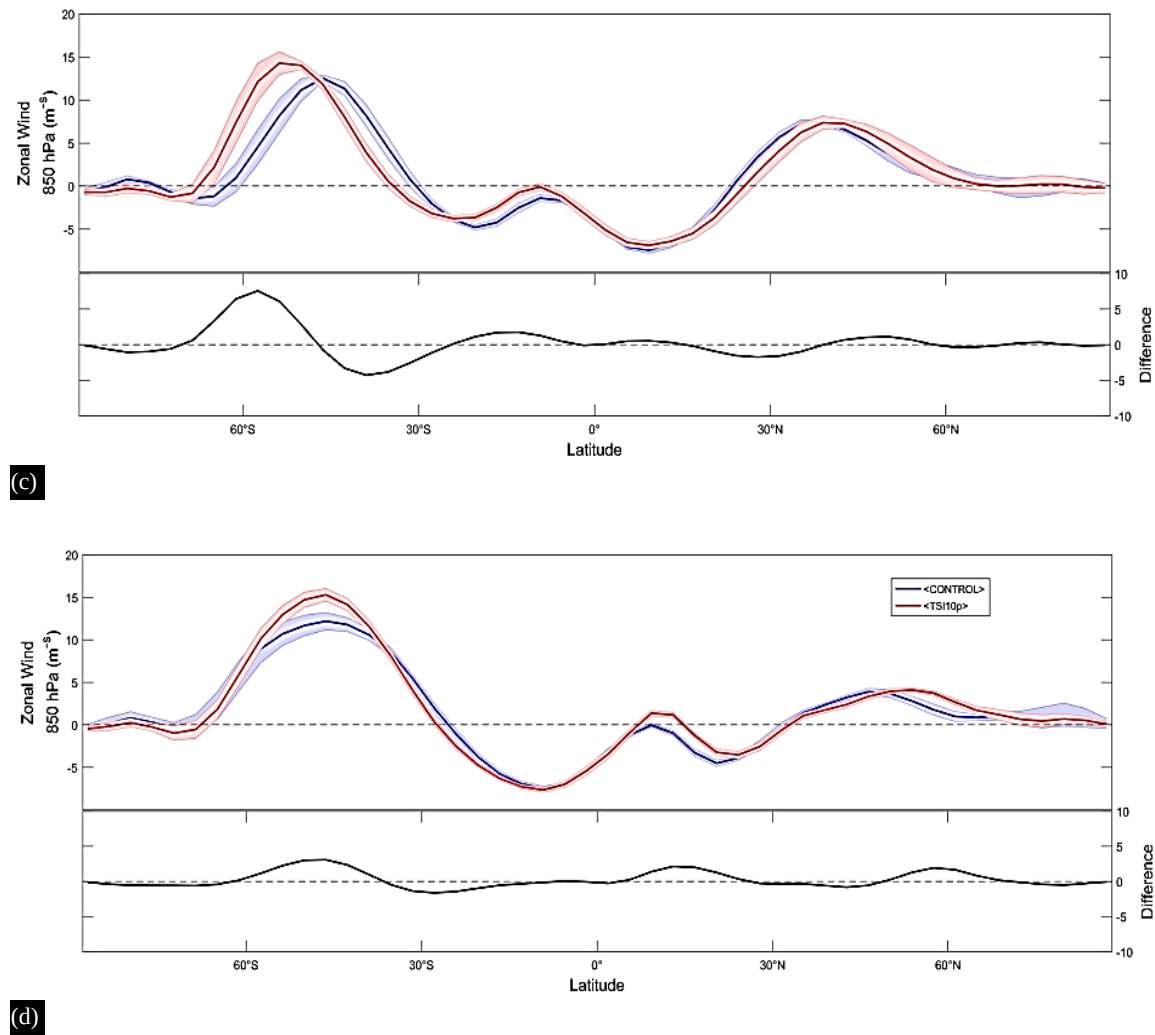


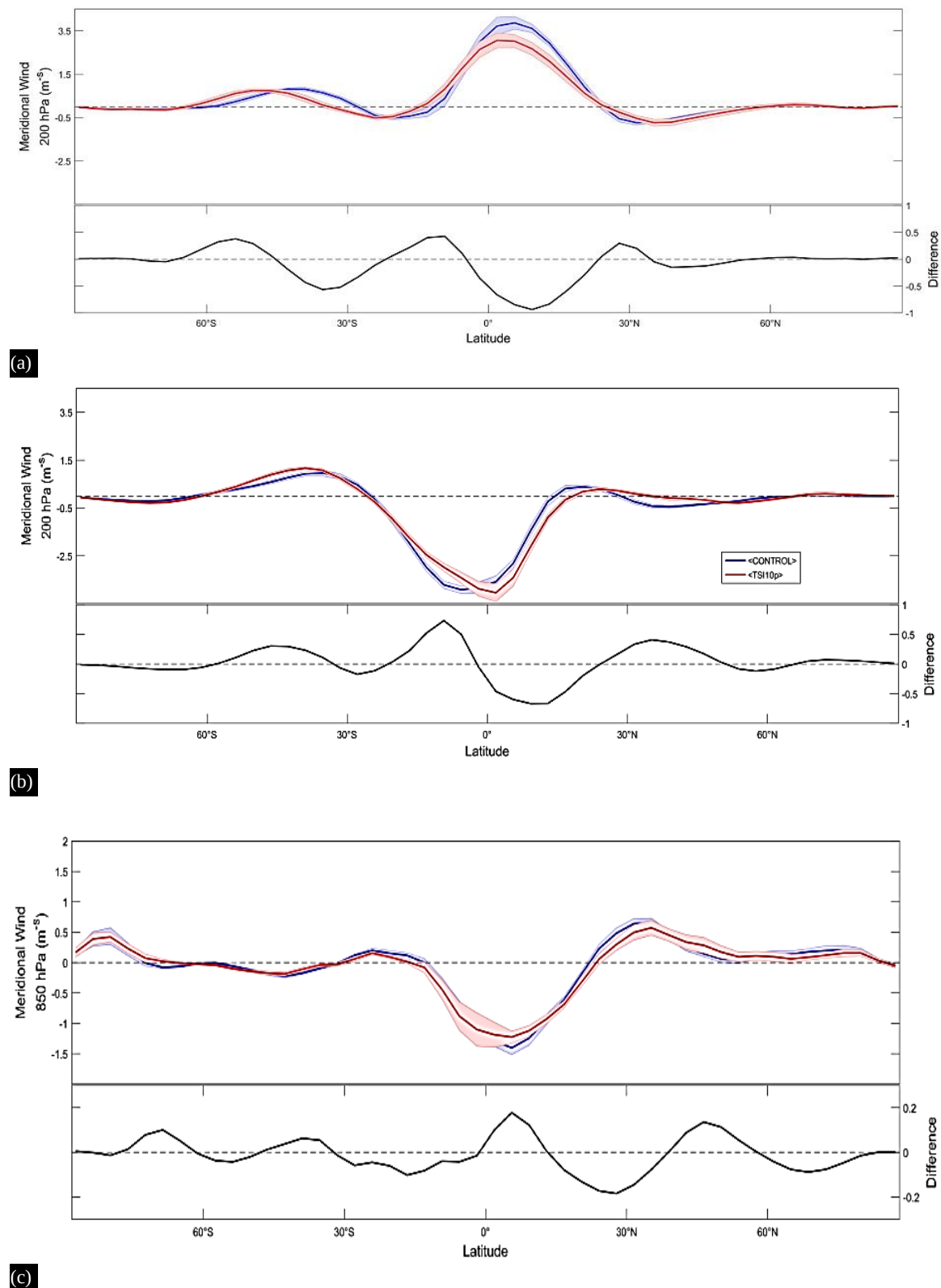
Figure 5. Mean zonal distributions for JFM (a and c) and JAS (b and d). The 10-year mean value simulations for each atmospheric variable in blue (CONTROL) and red (TSI10p) lines. The shaded lines are the standard deviations for each simulation. (a) and (b) represent zonal winds at 200 hPa, and (c) and (d) represent zonal winds at 850 hPa.

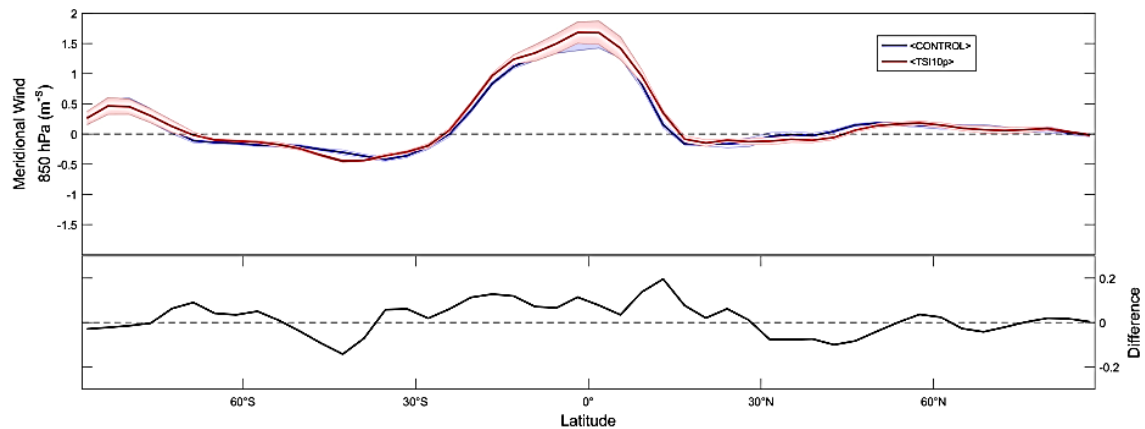
Distributions of the meridional wind component at 200 hPa are shown in Figures 6(a) and (b). For JFM (Figure 6(a)), both simulations showed convergence of the wind near mid-latitude and divergence in the equatorial region, consistent with the atmosphere's general circulation. The TSI10p showed a de-intensification of the wind compared to CONTROL in the equatorial region. For JAS (Figure 6(b)), the pattern is the opposite of JFM due to general circulation cell seasonal patterns, which showed negative values over the equatorial regions, displaced southward, and intensification over the northern equatorial region. The lower branch (850 hPa–Figure 6(c) and (d)) showed the exact opposite behavior from its higher branch; in other words, what was convergence at one level became divergence at the other. The TSI10p showed minor differences relative to the CONTROL experiment.

Spatial Analysis

In order to verify the spatial impacts of the TSI increase and check the coupling between CESM models, temperature (from CAM), ocean salinity (from POP), the ice-covered surface fraction (from CICE), and runoff (from RTM) were evaluated. The differences (EXPi_TSI10p–EXPi_CTRL) for June and December of the last year of the experiments were calculated for each field. The air temperature fields exhibit positive differences across the globe for both June (Figure 7(a)) and

December (Figure 7(b)), indicating higher temperatures in EXPi_TSI10p due to the more significant amount of energy ($+136 \text{ W} \cdot \text{m}^{-2}$) injected into the system. For December, the differences are more striking than in June, mainly in high latitudes of the northern hemisphere, reaching positive differences of up to 40°C in the EXPi_TSI10p experiment.





(d)

Figure 6. Mean zonal distributions for JFM (a and c) and JAS (b and d). The 10-year mean value simulations for each atmospheric variable in blue (CONTROL) and red (TSI10p) lines. The shaded lines are the standard deviations for each simulation. (a) and (b) represent meridional winds at 200 hPa, and (c) and (d) represent meridional winds at 850 hPa.

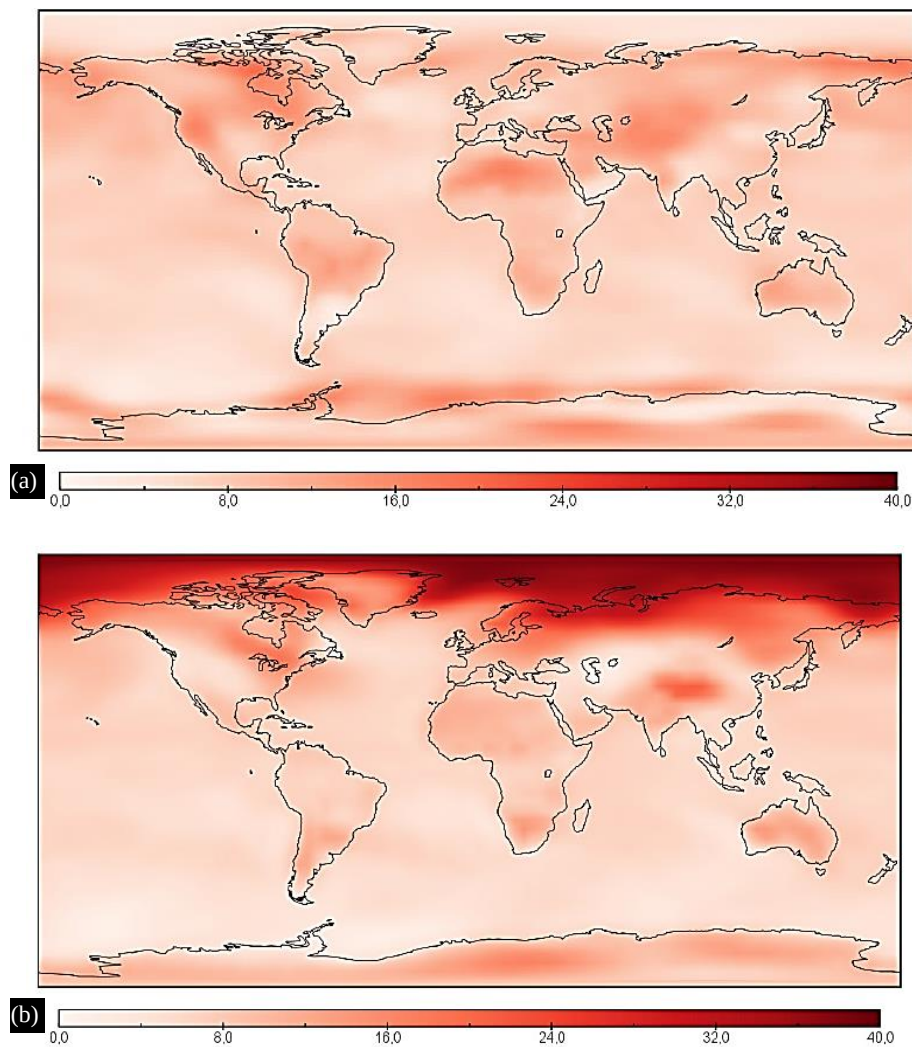


Figure 7. 2-m air temperature spatial distribution ($^{\circ}\text{C}$) differences (EXPi_TSI10p-EXPi_CTRL) for June (a) and December (b). Positive values indicate higher temperatures in the EXPi_TSI10p.

The salinity differences between EXPi_TSI10p e EXPi_CTRL from POP are shown in Figure 8. With greater intensity in December, we observe negative differences in the northern hemisphere's high latitudes, indicating lower values in this region in EXPi_TSI10p. The lower salinity in EXPi_TSI10p at high latitudes indicates ice melting. On the other hand, positive differences are observed in the regions of the subtropical gyres in all oceans, also for both months, indicating greater salinity in EXPi_TSI10p, probably associated with an increase in evaporation rates. Changes in ocean surface salinity alter the ocean surface buoyancy, which, in some cases, impact water formation and circulation, e.g., North Atlantic Deep Water formation and Atlantic Meridional Overturning Circulation [49].

The oceanic region close to the eastern portion of Greenland presents an intense positive difference in June and December. The North Brazil Current area also presents an intense positive difference in June and the region where the upwelling in west Africa occurs in December. On the other hand, the region close to the coastal Indian Ocean presents a negative salinity difference, mainly next to India and Indonesia, indicating a possible discharge of freshwater from EXPi_TSI10p due to ice melting.

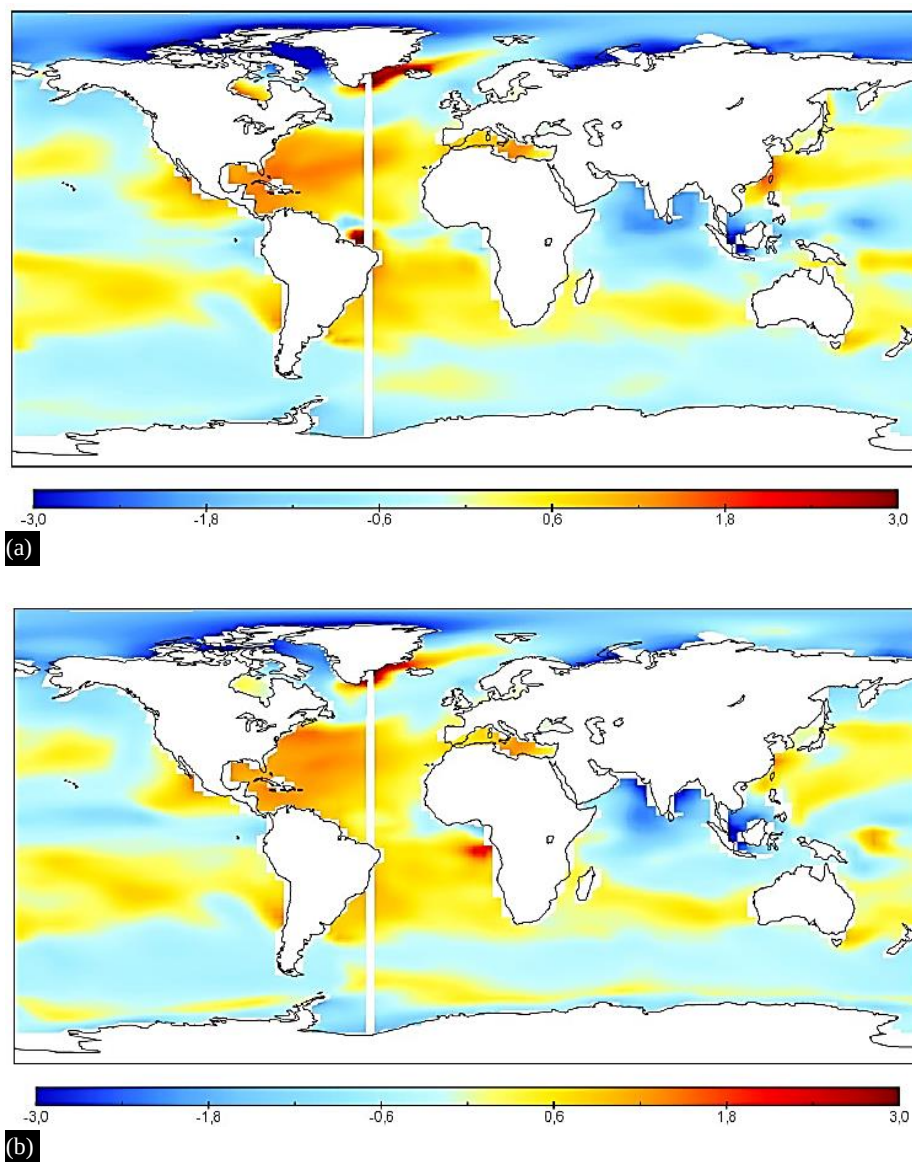


Figure 8. Salinity spatial distribution (g/kg) differences (EXPi_TSI10p–EXPi_CTRL) for June (a) and December (b). Positive (negative) values indicate higher (lower) salinity in the EXPi_TSI10p.

Differences in the sea ice-covered fraction from CICE are shown in Figure 9. In the northern hemisphere winter (December Figure 9(b)), a larger region with negative values of up to 100% indicates the absence of ice in EXPi_TSI10p. Thus, the negative difference indicates sea ice formation or greater defrost due to the large thermal energy injection into the climate system, which increases air temperature, as shown in Figure 7. Furthermore, it is possible to identify a relationship between sea ice differences in the northern hemisphere and ocean salinity in the northern hemisphere (Figure 8). We observe that the regions with the most negative sea ice difference coincide with the negative salinity difference. Thus, once there is a decrease in sea ice, the local salinity also decreases, causing negative ice cover anomalies.

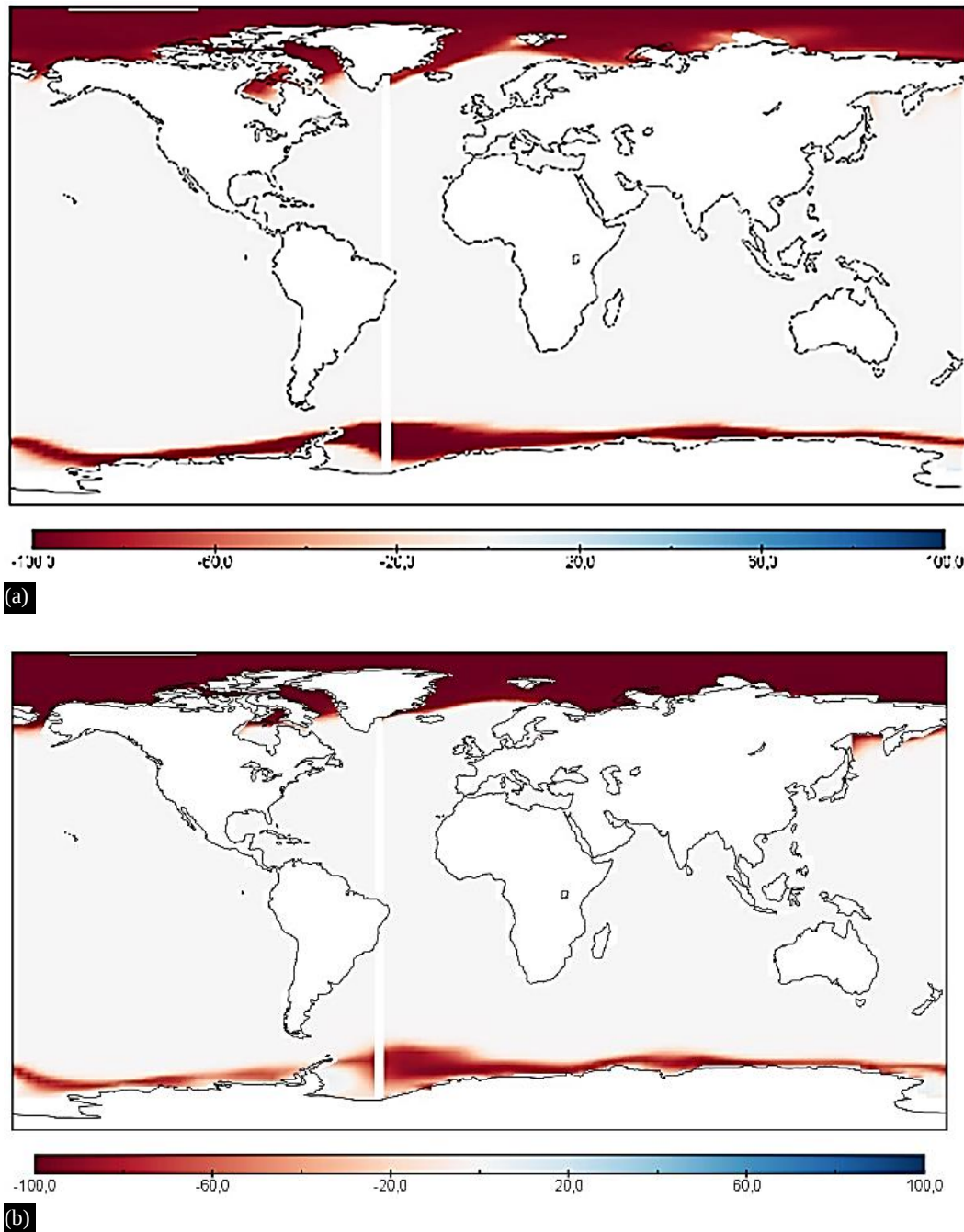
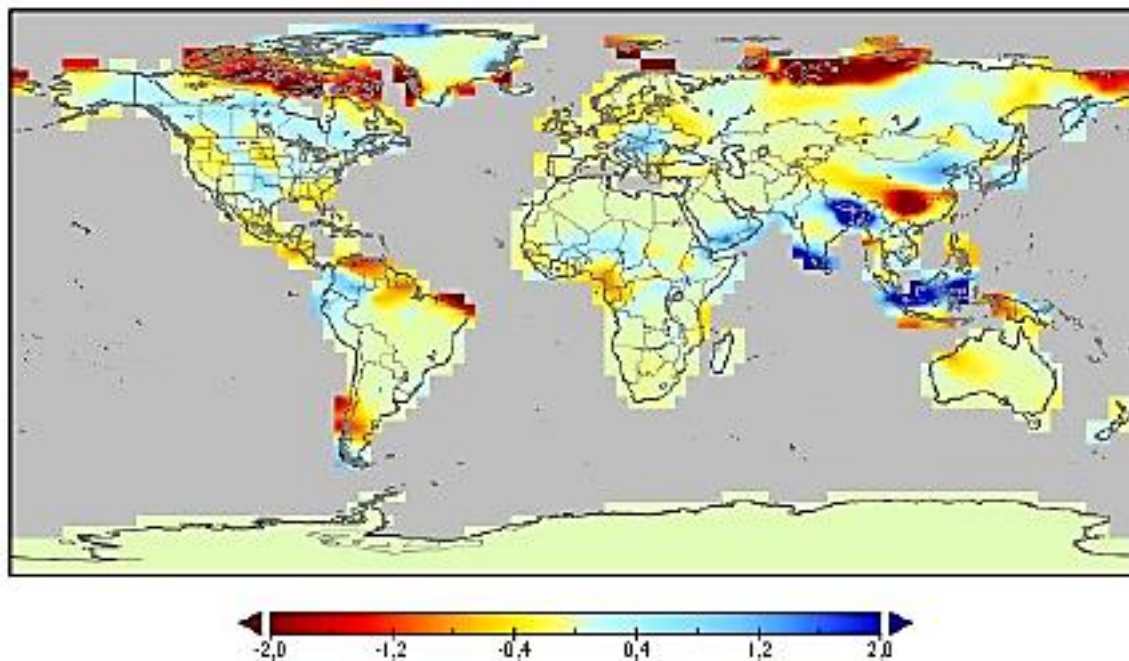
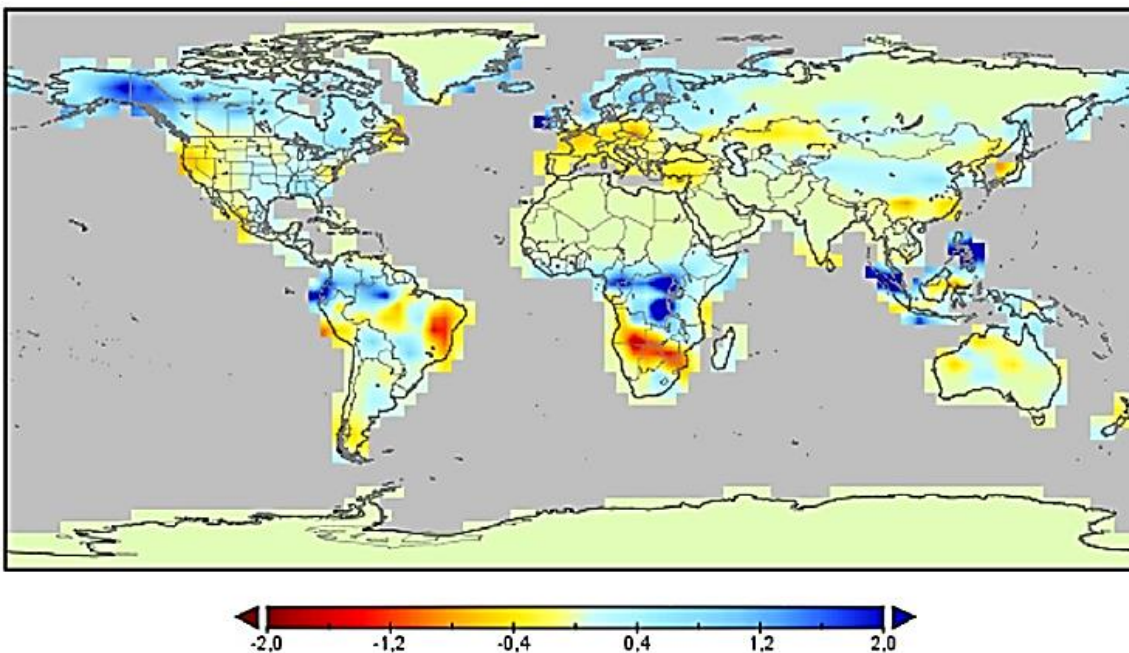


Figure 9. Ice-covered fraction spatial distribution (%) differences (EXPi_TSI10p–EXPi_CTRL) for June (a) and December (b). Positive (negative) values indicate a higher (lower) ice-covered area in the EXPi_TSI10p.

In the Brazilian north coastal region, there is a negative runoff difference (Figure 10(a)), which means less runoff on EXPi_TSI10p in June. The difference is smoothed in December (Figure 10(b)). However, there is also a negative difference in the region covering Brazil's northeast. In addition, changes in river runoff are observed in Iceland, England, Norway, northern Russia, and Canada. These changes alternate from positive in December Figure 10(b), i.e., more flow in EXPi_TSI10p to the ocean, to negative differences in July Figure 10(a), i.e., less freshwater discharge.



(a)



(b)

Figure 10. Runoff spatial distribution (10^5mm/s) differences (EXPi_TSI10p–EXPi_CTRL) for June (a) and December (b). Positive (negative) values indicate higher (lower) runoff in the EXPi_TSI10p.

CONCLUSIONS

Experiments using a fully coupled Earth System Model investigate the seasonal effects of a 10% increase in the total solar irradiance. Two ten-year-long CESM simulations differed by a 10% increase in the TSI. The analyzes performed were concentrated in the atmosphere, although other models' parameters were briefly evaluated. The latitudinal distributions were grouped into January-February-March and July-August-September averages, representing summer and winter, and the horizontal distributions were evaluated for June and December. The CONTROL was validated and considered fit to be compared with the TSI10p experiment through two atmospheric reanalysis products. The TSI10p experiment revealed several atmospheric changes, both in intensity and pattern. The distribution of sea-level pressure exhibited a poleward shift of the high and low-pressure belts and an intensification of the southern pressure belts. As expected, the energy input increased the global surface air temperature by around 7°C. The changes in cloud cover followed the ones in sea level pressure. They presented an increase (decrease) in the southern (northern) cloud cover, related to the southern (northern) low- (high-) pressure belt intensification and a general poleward shift of the surface covered by clouds. The surface heat flux in TSI10p increased due to increased temperature once the heating caused more evaporation over the ocean and evapotranspiration over vegetation. Changes in precipitation presented moister summers and drier winters in mid-latitudes and increased rainfall over the ITCZ region. A poleward shift was observed between 40° and 60° in both hemispheres and for both periods.

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