

How Does El Niño Southern Oscillation Change Under Global Warming - A First Look at CMIP6

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Abstract

The latest generation of coupled models, the sixth Coupled Models Intercomparison Project (CMIP6), is used to study the changes in the El Niño Southern Oscillation (ENSO) in a warming climate. For the four future scenarios studied, the sea surface temperature variability increases in most CMIP6 models, but to varying degrees. This increase is linked to a weakening of the east-west temperature gradient in the tropical Pacific Ocean, which is evident across all models. Just as in previous generations of climate models, we find that many characteristics of future ENSO remain uncertain. This includes changes in dominant timescale, extra-tropical teleconnection patterns and amplitude of El Niño and La Niña events. For models with the strongest increase in future variability, the majority of the increase happens in the Eastern Pacific, where the strongest El Niño events usually occur.

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Key Points:

- Changes in El Niño Southern Oscillations are detected for future projections in the latest generation of climate models.
- Models agree on future decrease of the equatorial zonal temperature gradient, which facilitates conditions for stronger El Niño events.
- El Niño and La Niña global teleconnection patterns shift in the future, but there is a large uncertainty on the magnitude of the change.

Abstract

The latest generation of coupled models, the sixth Coupled Models Intercomparison Project (CMIP6), is used to study the changes in the El Niño Southern Oscillation (ENSO) in a warming climate. For the four future scenarios studied, the sea surface temperature variability increases in most CMIP6 models, but to varying degrees. This increase is linked to a weakening of the east-west temperature gradient in the tropical Pacific Ocean, which is evident across all models. Just as in previous generations of climate models, we find that many characteristics of future ENSO remain uncertain. This includes changes in dominant timescale, extra-tropical teleconnection patterns and amplitude of El Niño and La Niña events. For models with the strongest increase in future variability, the majority of the increase happens in the Eastern Pacific, where the strongest El Niño events usually occur.

Plain Language Summary

The El Niño Southern Oscillation (ENSO) is a naturally occurring irregular oscillation in the tropical Pacific Ocean alternating between warm (El Niño) and cold (La Niña) phases every 2-7 years. The sea surface temperature anomalies associated with ENSO are linked to variability in key climate quantities, such as temperature, winds, and precipitation over many parts of the globe. Hence it is of great scientific and societal interest to determine how ENSO may change in a warming climate. We find that the latest generation of climate models shows changes in ENSO in a warmer world. The future variability is increasing, especially in the eastern equatorial Pacific, where the extreme warm events usually occur. This increase appears to be related to a reduced temperature difference between the eastern and western equatorial Pacific. The global weather patterns influenced by both the warm and cold events will also change, but models disagree on how large these changes will be.

1 Introduction

ENSO is characterized by irregular fluctuations between cold (La Niña) and warm (El Niño) conditions in the eastern and central equatorial Pacific on a timescale of 2-7 years. The warm phase is associated with a weakening of the trade winds and eastward shift of convection, which brings the warm waters of the west Pacific eastward. This decrease of the east-west gradient in SST is concomitant with a deepening (shoaling) of the thermocline in the eastern (western) equatorial Pacific. Due to its global teleconnections, ENSO is not only the dominant mode of tropical interannual variability but also the leading source of forecast skill on seasonal to interannual timescales in many other parts of the world (Jin et al., 2008; Barnston, 2016). It has important impacts on fisheries, agriculture, hurricanes, droughts, floods, and other severe weather events.

A rich body of work has studied the response of ENSO to global warming in previous generations of climate models, but there has been no clear consensus on how ENSO will change under global warming (e.g., Collins et al. 2010, Yeh et al. 2012, Guilyardi et al. 2012, Stevenson 2012, Taschetto et al. 2014, Cai et al. 2015a, Berner et al. 2020). The CMIP6 archive provides a new opportunity to study the ENSO response to prescribed radiative forcing (Eyring et al., 2016) across a number of state-of-the-art climate models. Here, we will focus on the question: “To

83 **which degree do CMIP6 models agree on ENSO changes in different global warming**
84 **scenarios?”.**

85
86 Assessments of ENSO future changes must account for the diversity of ENSO spatial patterns
87 (Ashok et al., 2007; Capotondi et al., 2015). ENSO events display a broad spectrum of anomaly
88 centers ranging from the dateline (CP events) to the far eastern equatorial Pacific (EP events,
89 Capotondi et al., 2015; Capotondi et al., 2020), and the exact location of the warming centers
90 may be model dependent (Cai et al., 2018). This diversity can have very important consequences
91 for atmospheric teleconnections and worldwide impacts (Ashok et al., 2007; Larkin and
92 Harrison, 2005; Patricola et al., 2018), and needs to be considered when examining ENSO
93 response to global warming.

94
95 Several studies have shown that ENSO characteristics, such as period and growth rate are highly
96 dependent on the tropical Pacific mean state (Battisti and Hirst, 1989; Fedorov and Philander,
97 2001). In particular, the mean temperature in the eastern equatorial Pacific, which controls the
98 temperature gradient between the West Pacific warm pool and Eastern Pacific cold tongue, as
99 well as the zonal slope of the equatorial thermocline, are important factors controlling ENSO's
100 stability characteristics and ENSO diversity (Fedorov and Philander, 2000, 2001; Capotondi and
101 Sardeshmukh, 2015). Specifically, a deeper thermocline in the eastern equatorial Pacific,
102 accompanied by reduced easterly winds and weaker zonal SST gradient, favors longer periods
103 and larger SST anomalies in the eastern equatorial Pacific, as observed, for instance, in the 1980s
104 and 1990s (Fedorov and Philander, 2001, Capotondi and Sardeshmukh, 2017) relative to
105 previous decades. Another controlling factor is cross-equatorial winds, which can significantly
106 influence ENSO properties but with larger uncertainties in future scenarios (Hu and Fedorov,
107 2018). The ENSO mean state relationship is further complicated by the presence of ENSO
108 asymmetries, with warm events typically stronger than cold events in the eastern Pacific
109 (positive skewness), and cold anomalies somewhat larger than warm anomalies in the central
110 Pacific (negative skewness), an aspect of ENSO that may be indicative of system nonlinearities.
111 Such nonlinearities may, in turn, lead to a “rectification” of ENSO variations into the mean state,
112 resulting in a low-frequency modulation of equatorial SSTs that are El Niño-like. Indeed,
113 Karamperidou et al. (2017) find a significant relationship between ENSO amplitude changes and
114 the correlation between the patterns of ENSO and SST trends.

115
116 Analyses of previous generations of climate models reported a weakening of the zonal SST
117 gradient, and of the atmospheric Walker circulation across the majority of the models, a
118 consensus that did not translate, however, in a consistent change in ENSO amplitude, as
119 measured by commonly used ENSO indices (e.g., the Niño3.4 index) that are averages of SST
120 anomalies at a fixed location. Given the differences in ENSO spatial patterns across models, a
121 better model agreement was found, albeit for a selected group of models, when indices that
122 accounted for the ENSO patterns unique to each model were used (Cai et al., 2018 Carréric et al.,
123 2019). The selection criterion was based on a metric of model nonlinearity, as encapsulated by
124 the coefficient α of the nonlinear relationship between the two leading Principal Components
125 (PCs) of SST in the equatorial Pacific (Karamperidou et al., 2017). Models in the CMIP5 archive
126 with a parameter α in the pre-industrial control simulations close to the observed value (-0.29)
127 appeared to have a balance of (linear) ENSO feedbacks in better agreement with observations
128 and exhibited a warming trend in the eastern equatorial Pacific (Karamperidou et al., 2017). The

parameter α also appeared to be associated with values of SST skewness in the eastern and central equatorial Pacific similar to the observed values, as well as a “realistic” separation of EP and CP ENSO events (Cai et al., 2018). An increase in ENSO amplitude was found by Cai et al. (2018) in those models with values of α relatively close to the observed in the historical model simulations. This increase in amplitude was attributed to both the enhanced mean warming and increased vertical stratification in the eastern equatorial Pacific. In this study, we revisit the relationship between changes in ENSO amplitude and mean state changes in the latest generation of climate models with a primary focus on the connection between changes in ENSO amplitude and changes in the mean zonal SST gradient.

A rather robust response detected in previous generations of climate models is the projected poleward shift of the jet stream (Yin 2005), which changes the atmospheric meridional gradients, and thus affects tropical-extratropical teleconnection patterns (Stevenson 2012; Stevenson et al. 2012). Hence, extra-tropical teleconnection patterns may change under climate change scenarios, even if ENSO itself does not change significantly. This aspect is also examined in our analysis of the CMIP6 models.

To assess the degree of agreement among the CMIP6 models on the ENSO change under different warming scenarios, we use a number of established diagnostics. First, we investigate changes in power spectral densities, total variance, and zonal SST gradient. Then we examine variance changes in the context of ENSO diversity, and at last, we investigate global sea-level pressure teleconnection patterns during future El Niño and La Niña events.

2 Data and methods

Our analysis focuses on the projected change under four different Shared Socioeconomic Pathways (SSP) (O'Neill et al. 2016). The four SSP scenarios are expected to have an approximate forcing of 2.6, 4.5, 7.0 and 8.5 W/m² in the year 2100, as denoted by the last two digits of the names of the scenarios. Results obtained for these four future scenarios (covering the 86-yr period 2015-2100) are compared to those from the control simulation (piControl). Since different models have a different number of ensemble members, for a fair comparison we use only one member for each future scenario.

However, due to a large level of internal variability, one ensemble member may be insufficient to robustly detect inter-scenario differences in variance. Hence we focus only on the significant changes in each scenario relative to the pre-industrial control. Establishing significant variance changes between scenarios, or between scenarios and the historical period requires several ensemble members, e.g. like the 33-member ensemble of CESM1 used by Berner et al. (2020).

The analyses are performed for eleven models having a control simulation with at least 499 years. For all piControl simulations longer than 500 years, we only study the first 500 years. Changes from the piControl are analyzed to focus on the models' response to anthropogenic forcing rather than evaluating model skill over the historical period. The confidence intervals of the piControl simulations used for analyses in Figures 1, 2, and 3 are computed by first splitting the 500 yr records into 86 yr segments with 56 yr overlap. For each segment, we compute the quantity of interest in the same way as we would for the future scenarios, and determine the

range of possible values across segments. Changes from the piControl are considered statistically significant if they are outside this range.

Details regarding the detrending method, spectral analysis, definition of ENSO diversity, and ENSO teleconnections diagnostics are provided in Supplementary Text S1.

3 Results

3.1 Power Spectral Density of Niño 3.4-index

The Niño 3.4-index, defined as the area average of monthly SST anomalies in the region 5°S-5°N, 170°W-120°W, is a commonly used index to describe variability associated with ENSO (see Supplementary Text S1 for details on method). The power spectra of the Niño 3.4-index obtained from detrended scenarios show a wide range of variability with spectral peaks in the 2-7 year range (Fig.1 and Supplementary Fig.1), demonstrating the CMIP6 models' ability to produce a quasi-oscillatory behavior that is reminiscent of ENSO in nature.

Figure 1 shows the seven models with the most marked changes in the spectra of future scenarios. The most significant increases in variability are for the models MIROC6 and MIROC-ES2L. MIROC-ES2L is the model with the most regular periodic variations, centered at periods of about 5 years (Supplementary Fig.1). CESM2-WACCM and CESM2 also show significant increases in power for most future scenarios with CESM2-WACCM showing the largest increase around 3 years and CESM2 showing an increase at 1.5-3 year periodicities. CanESM5 shows a small increase in power, mainly at the seasonal cycle and at periods of 3-4 years. The limited duration of the scenario simulations (86 years) makes it difficult to estimate subtleties in the future change of spectra. In particular, it is hard to assess whether the increase in power is proportional to the radiative forcing.

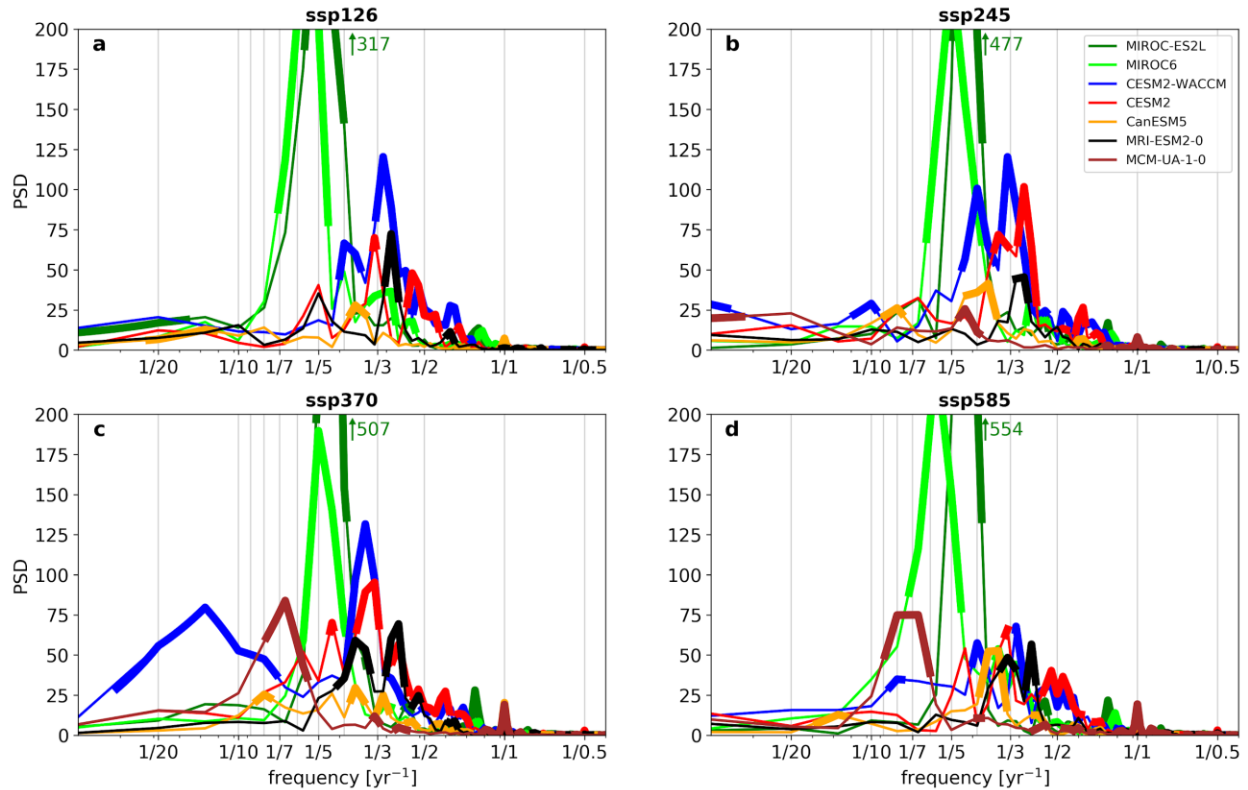


Figure 1: Power spectral density (PSD) of the detrended monthly Niño 3.4-indices for scenarios a) ssp126, b) ssp245, c) ssp370, d) ssp585 for CMIP6 models. PSDs that are statistically significantly different from pre-industrial internal variability (shown only in Supplementary Fig. S1) are shown with a thick line. The green numbers denote the maximum power for the model MIROC-ES2L.

3.2 Changes in Variance of Niño 3.4-index and zonal temperature gradient

Another important metric to assess ENSO changes is the variance of the Niño 3.4-index. All but one model show a significant increase in variance for most scenarios (Fig. 2a), but we observe no correlation between the magnitude of forcing and variance change. As the change in mean SST in the Niño3.4-region is proportional to the forcing (Supplementary Fig. S2), we conclude that there is no obvious relation between changes in variance and mean SST either.

The strength of ENSO variability has been linked to the east-west SST gradient in the Tropical Pacific. As this gradient weakens, westerly wind anomalies can more readily extend eastward and initiate strong warm events (Xie et al., 2018). Strikingly, all models agree that the east-west SST gradient weakens in future scenarios. Furthermore, in most models this weakening is proportional to the magnitude of the radiative forcing. This suggests an anti-correlation between the change in gradient and change in SST variance. Ten out of the eleven CMIP6 models show a decrease in SST gradient concurrent with an increase in SST variance (Fig. 2c) with a statistically significant ($p\text{-value} = 1.52 \cdot 10^{-4}$) correlation of -0.55. We expect that some of the scatter in Fig. 2c is due to the large internal ENSO variability (Berner et al., 2020) and the

uncertainty in the functional relationship displayed in Fig. 2c might be reduced if models with several ensemble members were analyzed.

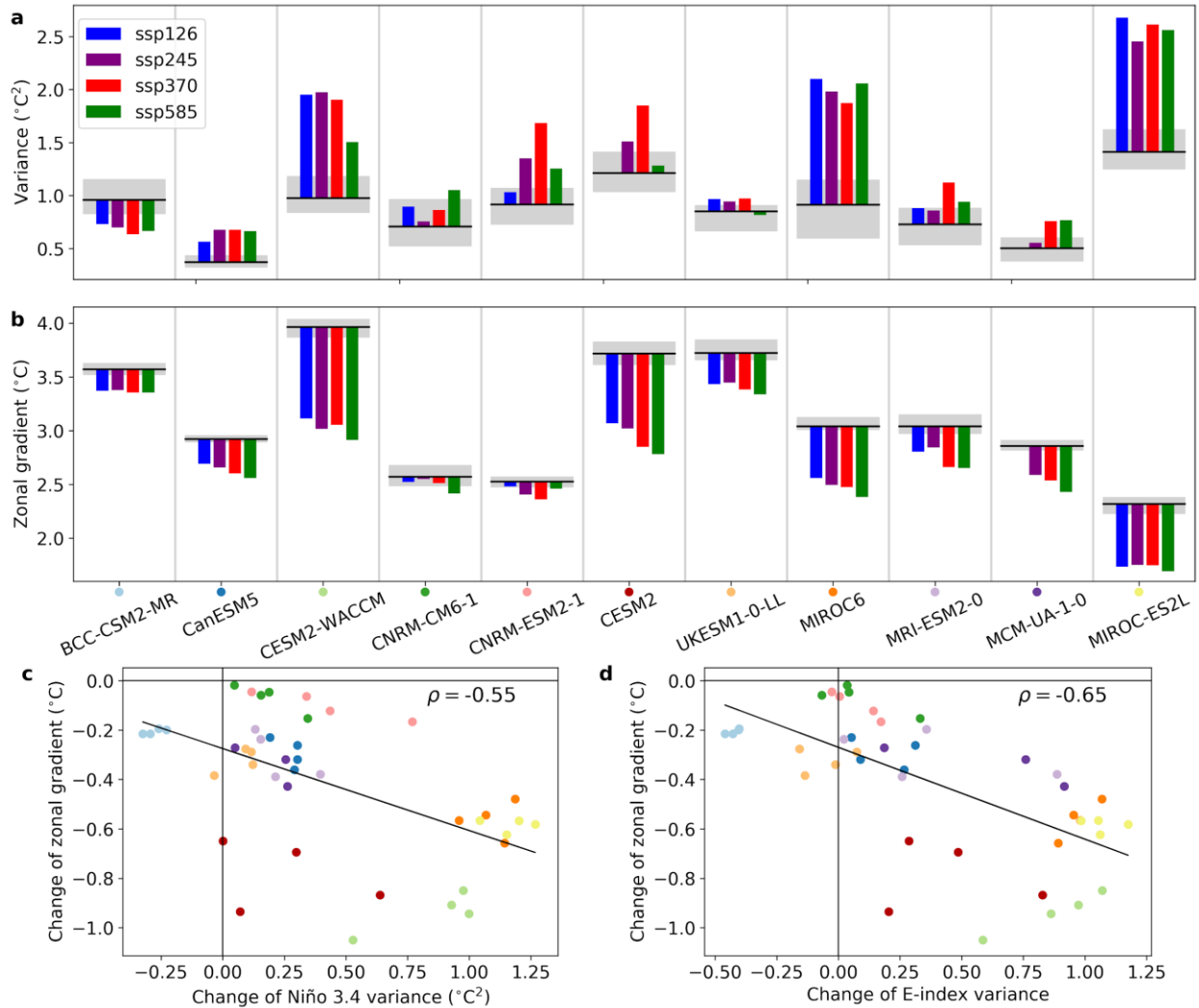


Figure 2: a) Variance of temperature anomalies in the Niño 3.4 region [$5^{\circ}\text{S} - 5^{\circ}\text{N}$, $170^{\circ}\text{W} - 120^{\circ}\text{W}$] for each model and scenario after detrending and removing the seasonal cycle (see Supplementary Text S1), shown as differences from the piControl estimate using the first 500 years (black line). b) The black lines show the piControl mean of the east-west temperature gradient, and the colored bars the mean change from piControl over the 86-year period 2015-2100 in the future scenarios. Temperatures in the west are averaged over the region $5^{\circ}\text{S} - 5^{\circ}\text{N}$, $120^{\circ}\text{E} - 170^{\circ}\text{E}$, and in the east over the Niño3 region [$5^{\circ}\text{S} - 5^{\circ}\text{N}$, $150^{\circ}\text{W} - 90^{\circ}\text{W}$]. Positive values mean the west is warmer than the east. In both panels, the light gray shading denotes the spread of these quantities in 86-year overlapping segments from the first 500 years of piControl, ranging from the minimum to the maximum estimates. c) Scatterplot and correlation coefficient of data in a) and b). d) As in c), but with E-index variance from the next section along x-axis.

3.3 ENSO diversity

A single index, like the Niño 3.4-index, is insufficient to capture the full range of ENSO expressions and the temporal evolution of ENSO events. In particular, more than one index is needed to describe differences in ENSO spatial patterns. Several indices have been proposed to describe this diversity in El Niño spatial patterns (Capotondi et al., 2020). Here we use the approach introduced by Takahashi et al. (2011) to construct the E- and C-indices, which describe events with enhanced variability in the eastern and central Pacific, respectively (see Supplementary Text S1, and Supplementary Fig. S3 for examples of their associated patterns). These indices are computed as linear combinations of the two leading Principal Components (PCs) of SST anomalies in the equatorial Pacific, and thus describe the patterns of variability typical of each model.

Fig. 3a shows the standard deviation of the E-index in the four climate change scenario simulations relative to the control simulation, whose standard deviation was normalized to one. Instead of arbitrarily selecting the models by their α value in the control simulation, we include all the models, and order them by increasing magnitude of α , to highlight the impact of this parameter on the changes in ENSO variance. While the only model showing a significant decrease in ENSO variance is the model with the smallest absolute value of α , no clear relationship can be seen in Fig. 3a between the variance changes and the magnitude of α . In addition, the parameter α may change in the scenario simulations relative to the control simulations (see Supplementary Figure S5, where the nonlinear fit of PC1 and PC2 is shown for all models and simulations), and is not an intrinsic property of each model, as implied in the studies of Karamperidou et al. (2017) and Cai et al. (2018).

When the change of the variance in the E-index is plotted against the change of the east-west SST gradient, we see an even stronger relationship between the two quantities, as quantified by a correlation coefficient of -0.65 with p-value $= 1.97 \cdot 10^{-6}$ (Fig 2d): generally, a weakening of the SST gradient will lead to an increase in the variance of Eastern Pacific (EP) events.

Previous studies (Stevenson et al., 2012; Bellenger et al., 2014; Cai et al. 2015b; Capotondi 2015) have also suggested an increase in the frequency of extreme La Niña events with global warming due to a strengthened zonal temperature gradient between the Maritime Continent and the central Pacific, where La Niña events typically peak. This should be reflected in the standard deviation of the C-index (Fig. 3b). Robust increases in the C-index standard deviation are seen in some models, but in some cases the standard deviations show a significant decrease (BCC-CSM2-MR, CESM2, MCM-US-1-0) or insignificant changes (CanESM5, CESM2-WACCM, UKESM1-0-LL), indicating a larger degree of uncertainty in the projected changes of La Niña's (as well as CP El Niño) amplitude relative to the EP El Niño events.

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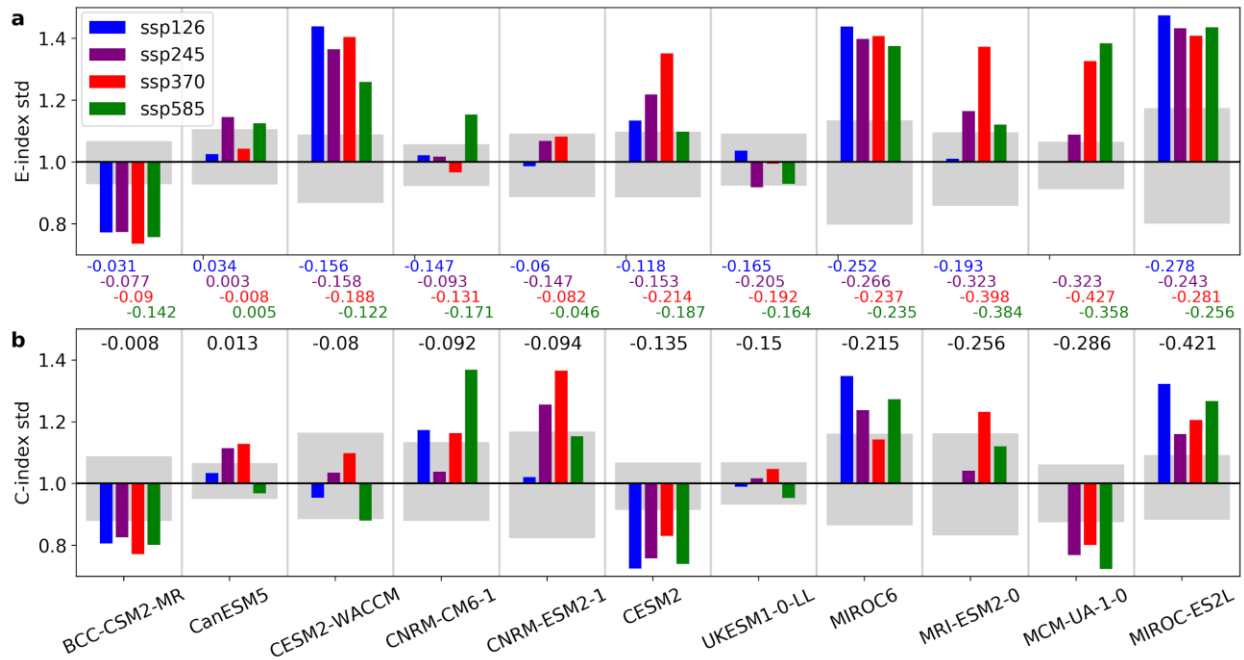


Figure 3: The standard deviations of the E-index (a) and C-index (b), shown as deviations from the piControl value. piControl standard deviation is by definition 1, due to normalization. The shaded gray areas show the spread of standard deviations in piControl segments of equal lengths as the future scenarios, ranging from the minimum to the maximum value. The black numbers are piControl α 's, whose magnitude is increasing from left to right. The colored numbers are the α values for future scenarios.

3.4 ENSO teleconnections

ENSO, primarily a tropical ocean-atmosphere coupled process, has an influence globally via atmospheric and oceanic teleconnections (Alexander et al., 2002; Deser et al., 2012; Yeh et al., 2018). The teleconnection diagnostics used in this study follows that of Stevenson et al. (2012). El Niño and La Niña composites for the ensemble mean of CMIP6 are computed for sea-level pressure (SLP) anomalies. The mean SLP anomalies of the ensemble mean show the canonical features of the Aleutian low deepening during warm events and anomalous higher pressures during cold events with pressures of opposite sign in the Southern Hemisphere at the same longitude. Teleconnection changes are then evaluated by comparing the ssp585 and piControl. The changes in the future climate across the CMIP6 ensemble are shown in the black contours in Fig. 4. Marked changes in the Aleutian island region and the southern ocean region are observed. The atmospheric teleconnections show a weakening signal in the ssp585 scenario compared to the piControl. This has been studied in previous versions of similar climate models and partly been attributed to the increase in atmospheric static stability in warmer climates (Ma et al., 2012; Stevenson et al., 2012)

The spatial patterns of the teleconnection of warm events in the future scenario shifts poleward and eastward in the CMIP6 ensemble mean over the Aleutian island regions and the Southern Ocean regions. The eastward shift can be seen as a weakening of the pressure anomalies in the

west, and a strengthening in the east in Figure 4a. This has also been seen in the model versions from CMIP5 and CMIP3 (Meehl and Teng 2007; Stevenson et al., 2012). The teleconnection patterns for La Niña events show a zonal elongation over the Aleutian region instead of a spatial shift, and a general weakening of the Southern Ocean anomalies as seen in Figure 4b. The standard deviation across the ensemble members is shown in Figure 4 c,d, where the largest variance is observed over the Aleutian region, which is also the region of the strongest teleconnection from the Tropical Pacific. This ensemble spread indicates the uncertainty in the observed changes to the ENSO teleconnections due to internal variability and differences in model physics.

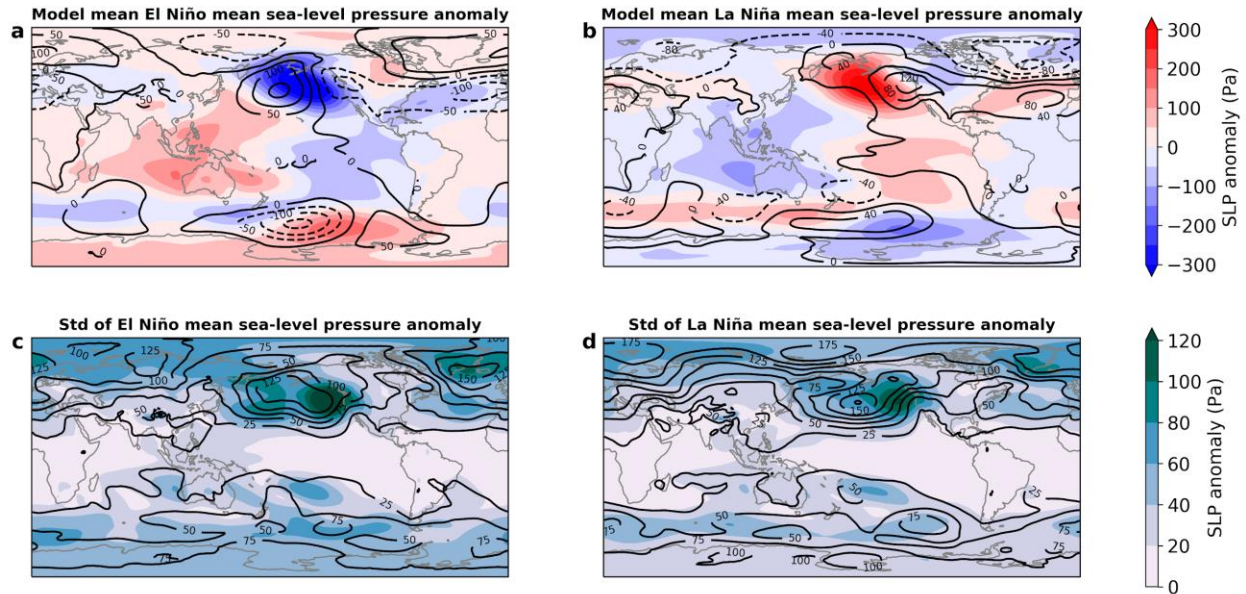


Figure 4: DJF ENSO teleconnection pattern shown as mean SLP anomalies across models for piControl (colors) for a) El Niño and b) La Niña, and the corresponding changes of mean SLP anomalies for future scenario ssp585 (black contours). c) El Niño and d) La Niña model spread of the piControl SLP anomalies (colors) and change for future scenario ssp585 (black contours), measured by the standard deviation.

4 Summary and Conclusion

In this study, we have provided a first look at the projected change of ENSO in four CMIP6 future scenarios. Our analysis focused on understanding to which degree the various models agree about projected changes. As reported for the previous intercomparison projects CMIP3 and CMIP5, ENSO is characterized by a high degree of variability and diversity (e.g., Collins et al. 2010, Yeh et al. 2012, Guilyardi et al. 2012, Taschetto et al. 2014) across models and long data records are needed to establish statistically significant changes in its characteristics. While there continues to be no across-model consensus on the change in variance and spectra of ENSO, we see agreement on some emerging signals:

- 1) In all eleven models the east-west gradient of SST decreases in the future, with larger decreases in the scenarios with higher radiative forcing. A weaker gradient has been

associated with increased likelihood of strong East Pacific warm events, which have large socio-economic impacts.

- 2) Out of the eleven models ten show a significant increase in variance of SST in the Niño 3.4 region for at least one SSP and four models for all future scenarios. This increase in variance is likely linked to the decrease in the zonal temperature gradient and increase of strong warm events.
- 3) While all CMIP6 models are able to produce quasi-oscillatory behavior reminiscent of ENSO, there is a wide range of variability with spectral peaks in the 2-7 year range. Seven out of the eleven CMIP6 models show a significant increase in power spectral density in the ENSO band with periods ranging from 3-7 years.
- 4) In eight out of the eleven models we see a significant increase in the standard deviation of the E-index for at least one SSP. Previous studies (Cai et al. 2015a, 2018) have linked the change in variability of the E-index to model's nonlinearities, a relationship that does not seem to be as robust for the models studied here.
- 5) In nine of the eleven models, the centers of the extra-tropical teleconnection pattern shift eastward and poleward for warm events. However, since the centers of the teleconnections coincide with the regions of largest internal variability, it is hard to establish significance for this shift.

The eleven CMIP6 models analyzed here appear to be in better agreement than the models contributing to the previous intercomparison projects CMIP3 and CMIP5. However, their projections still differ in many key aspects of ENSO, such as the spectra, the representation of ENSO diversity and the change in extra-tropical teleconnection patterns.

No attempt has been made here to evaluate the models' skill in representing observed ENSO variability. A careful assessment of the models' fidelity in representing ENSO during the historical period together with in-depth process-level analysis might enable to further constrain the projected change in ENSO in current and future CMIP simulations.

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Author contributions

All authors contributed to designing the study, interpreting results, and writing the paper. H.-B.F. performed all the analyses.

Data availability

The CMIP6 data are available through <https://esgf-node.llnl.gov/search/cmip6/>.

Code availability

Code used for this paper will be available in Github: https://github.com/Hegebf/enso_paper

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Figure 1.

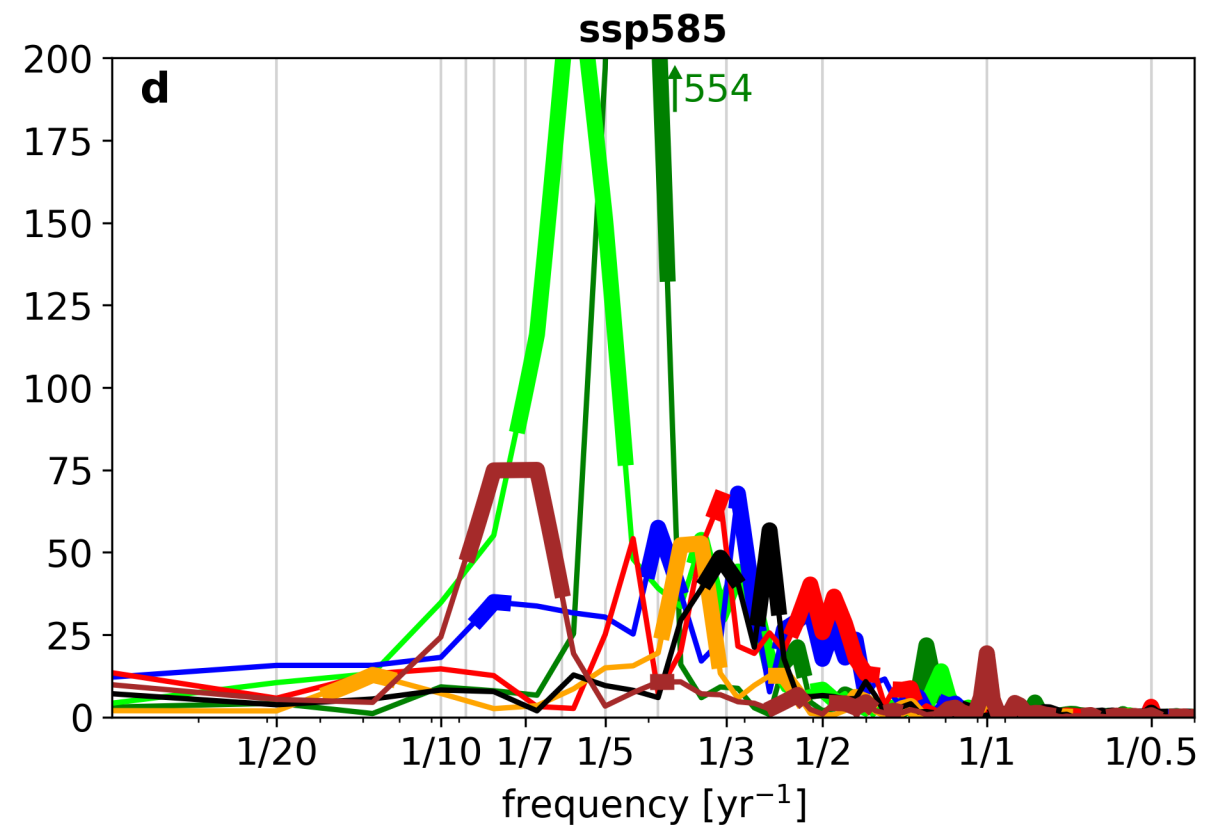
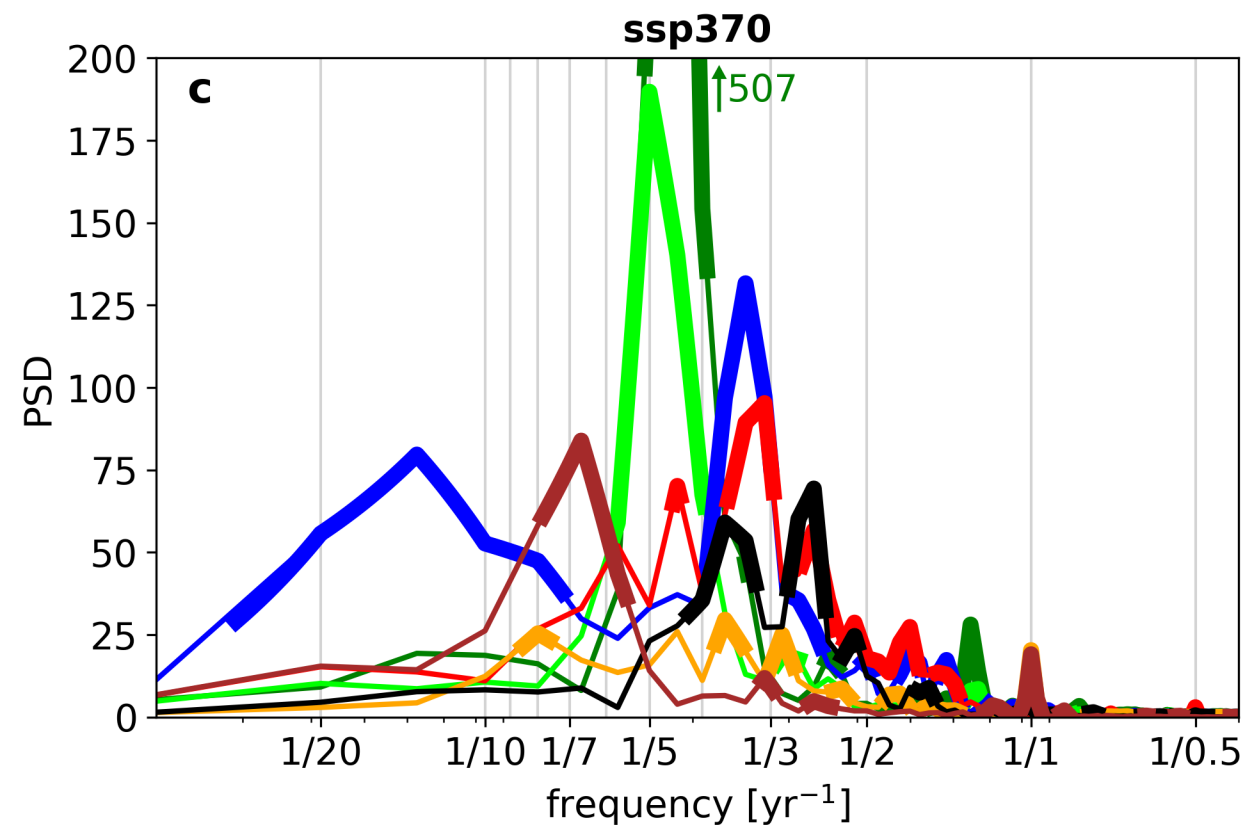
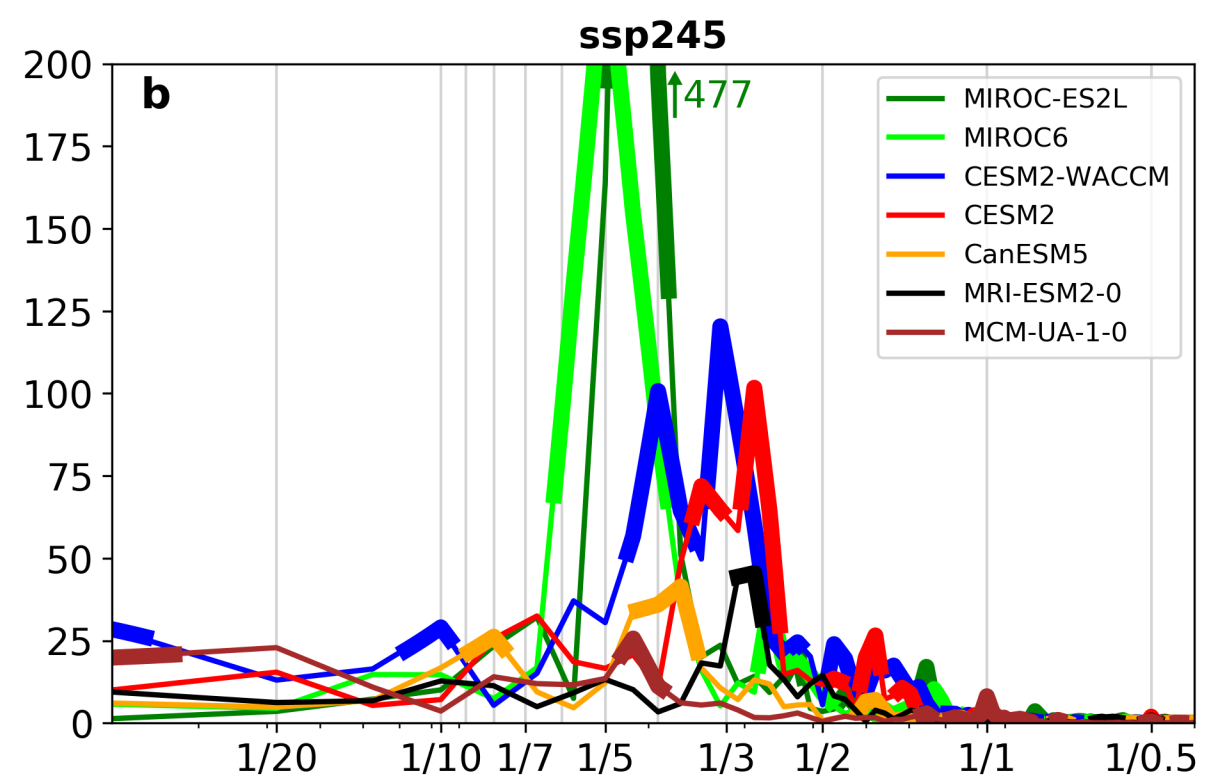
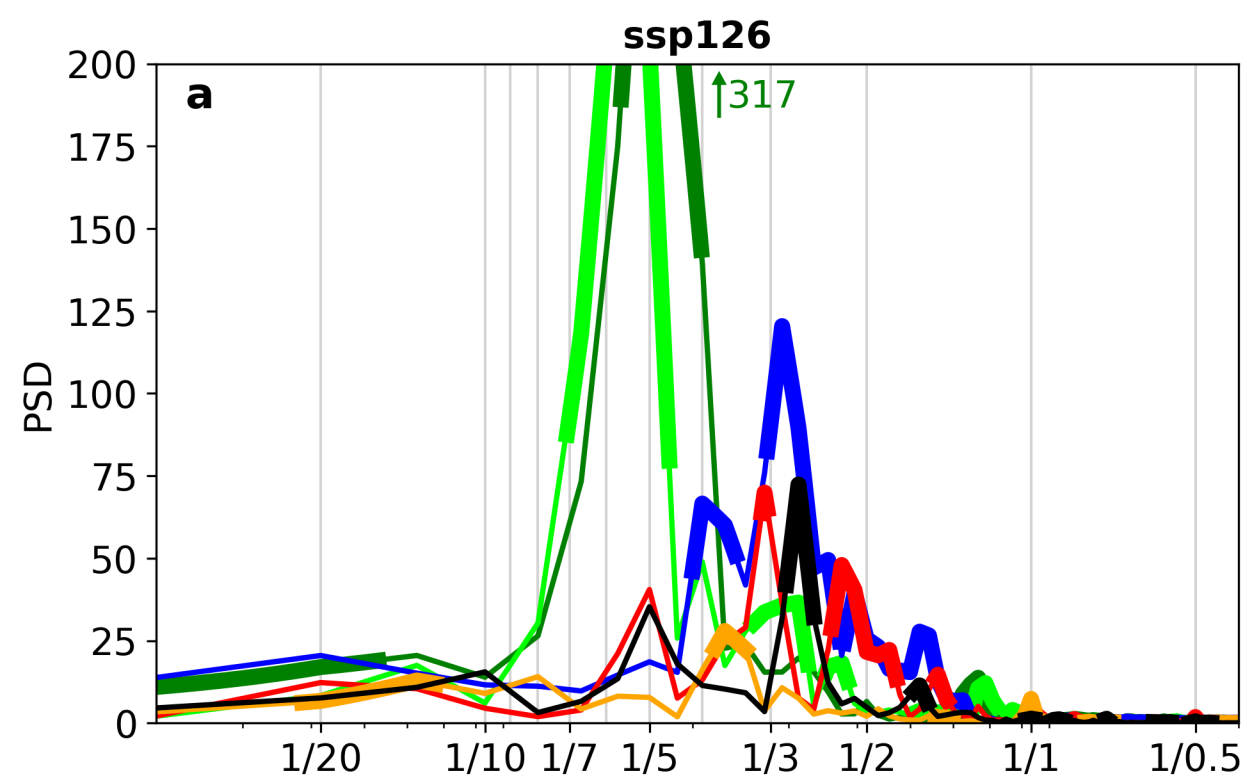


Figure 2.

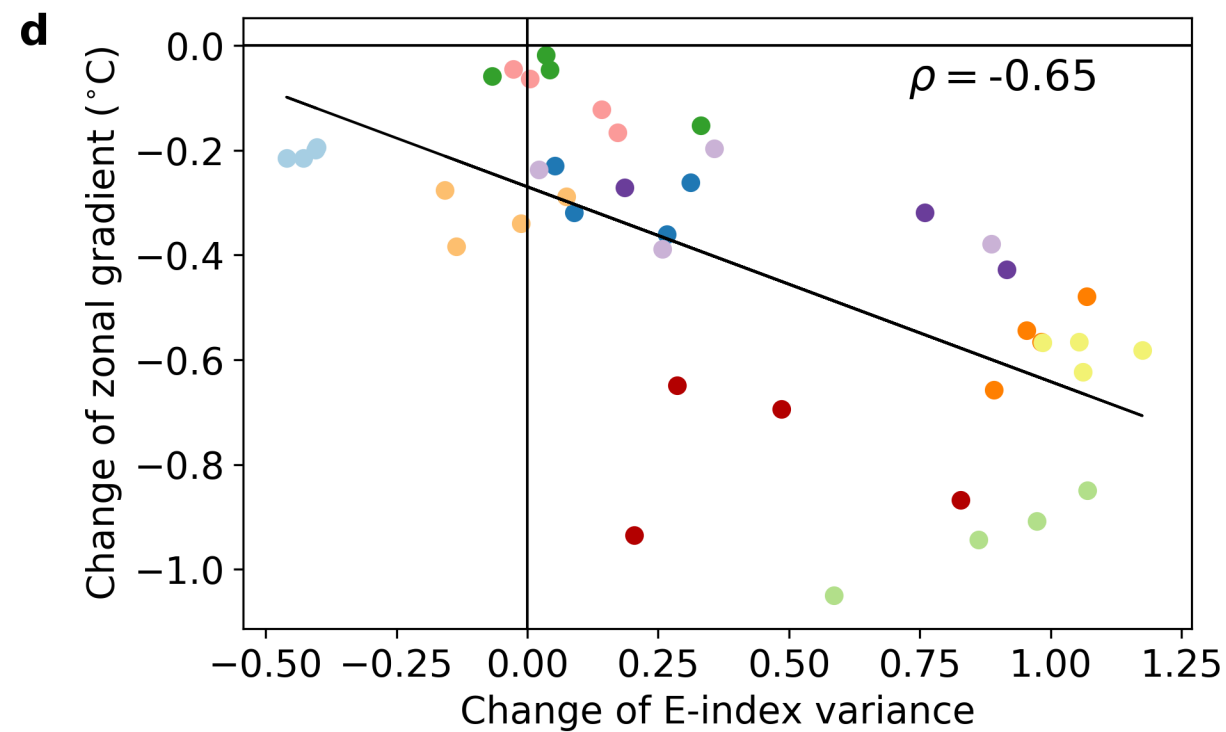
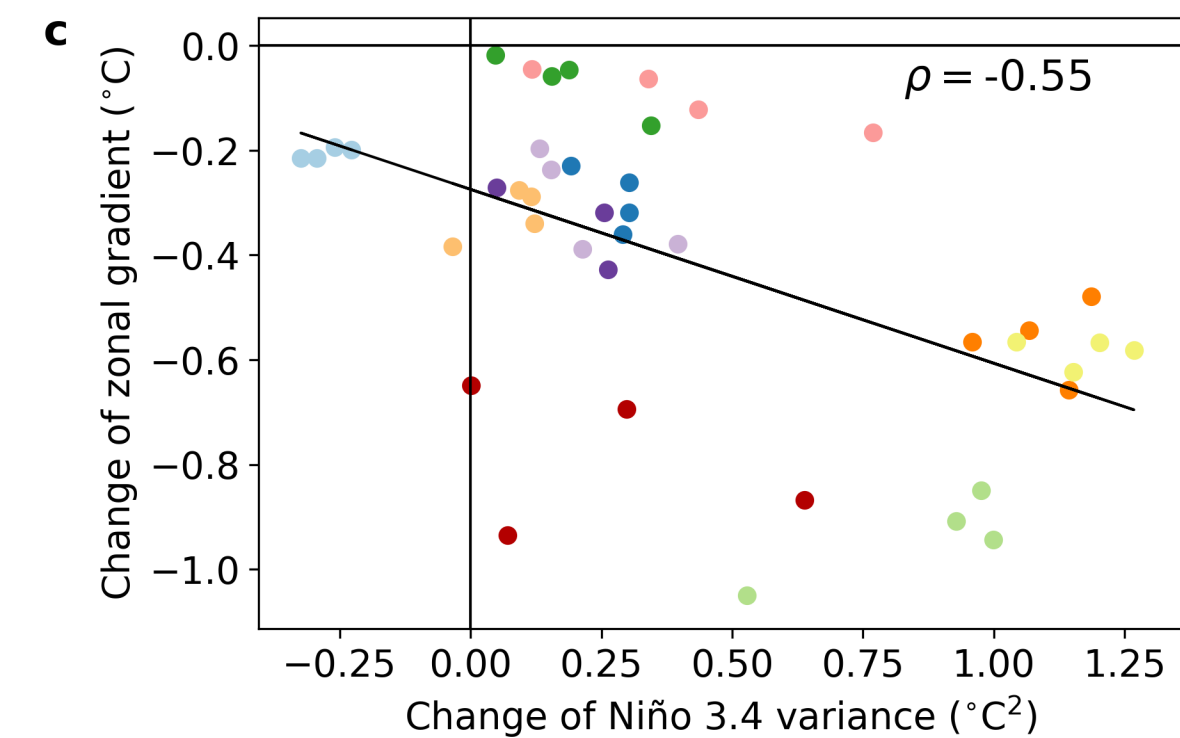
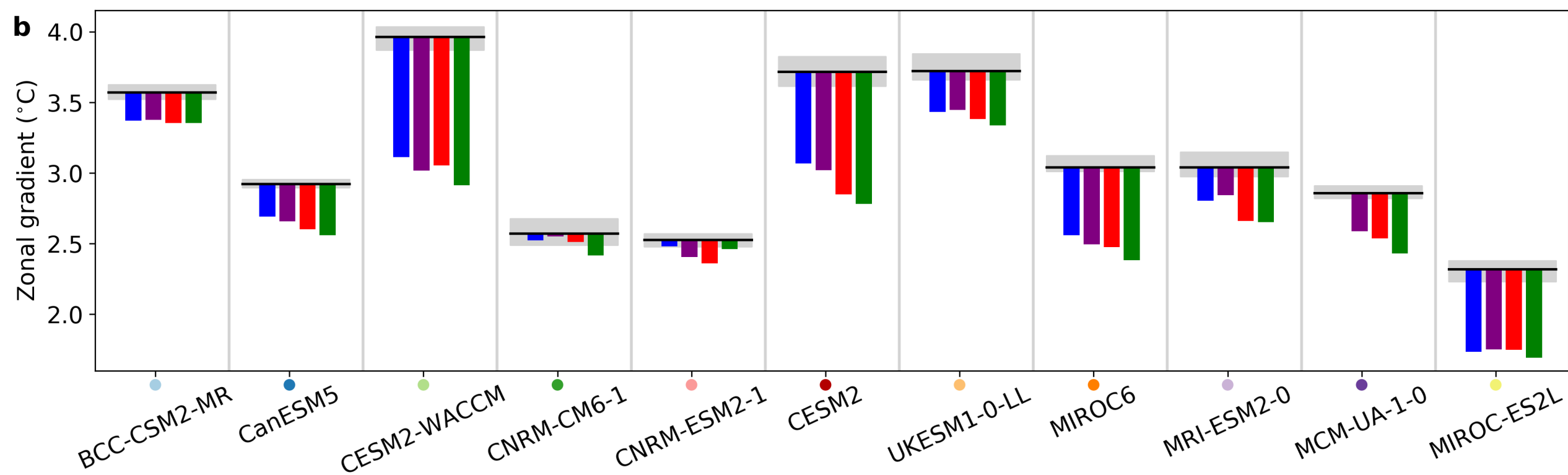
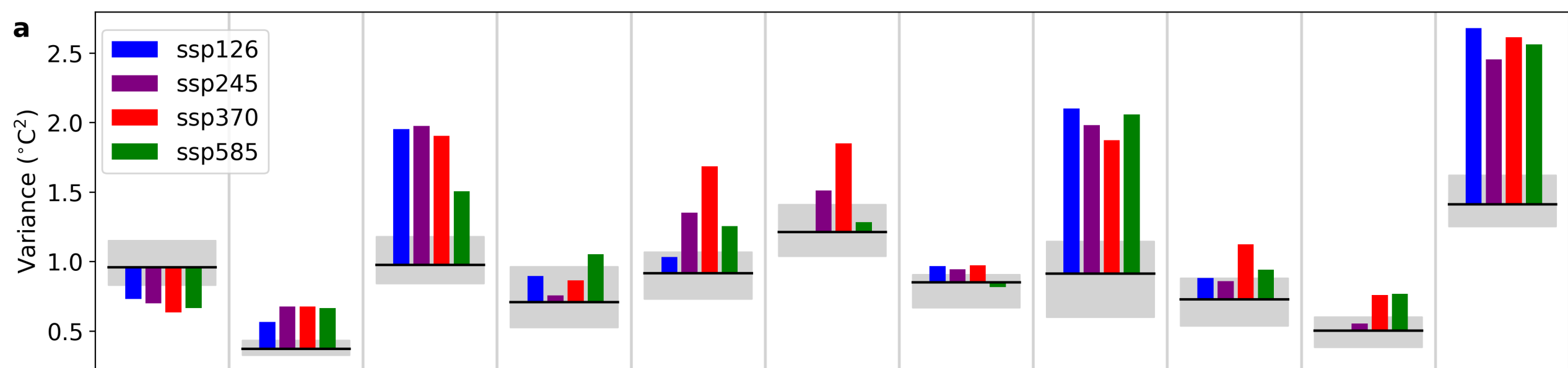


Figure 3.

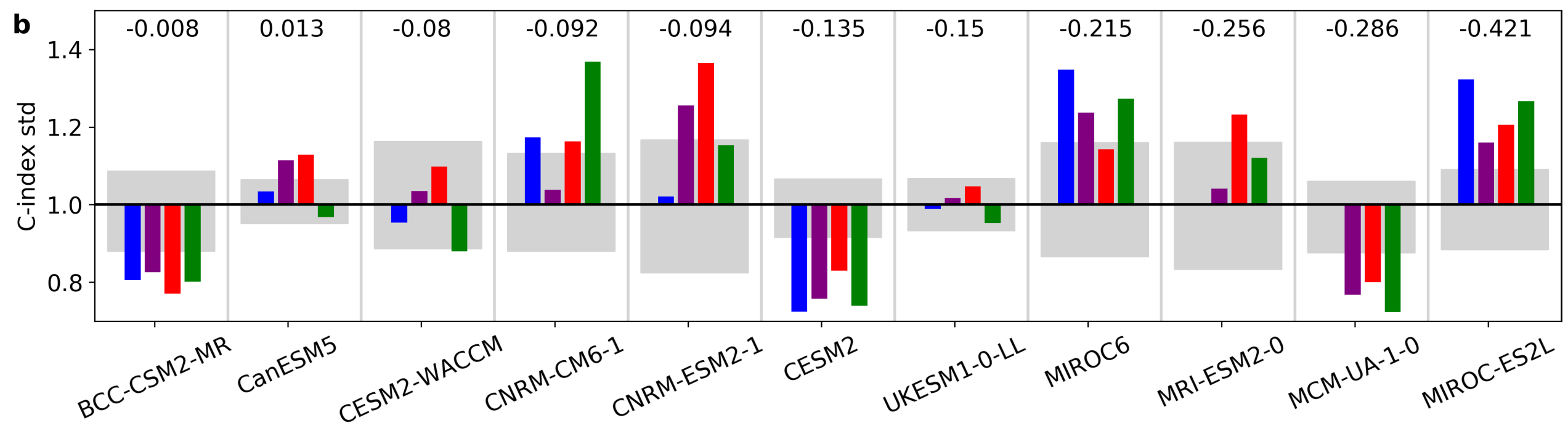
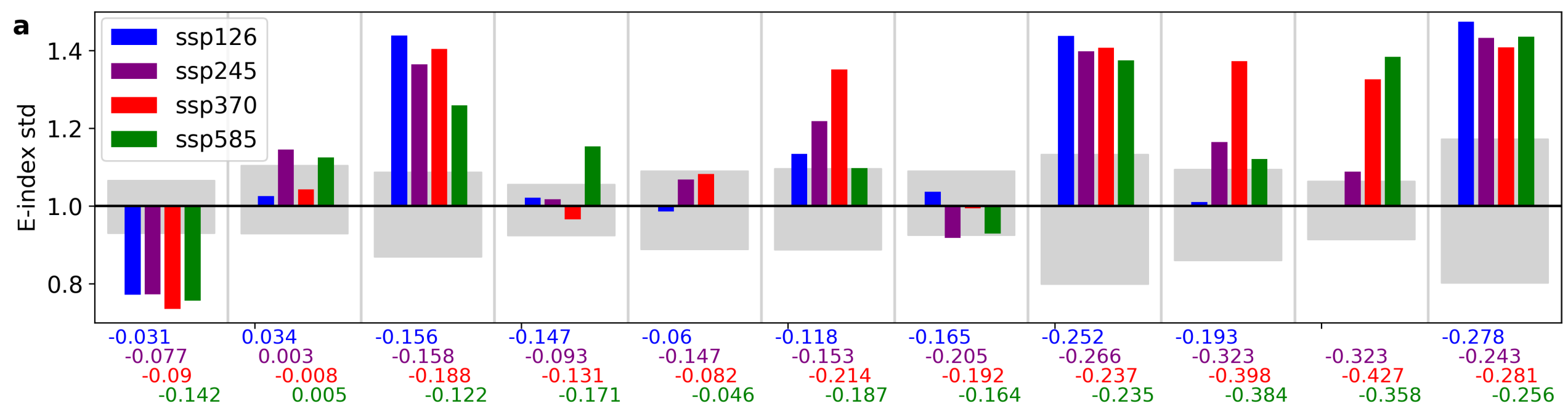
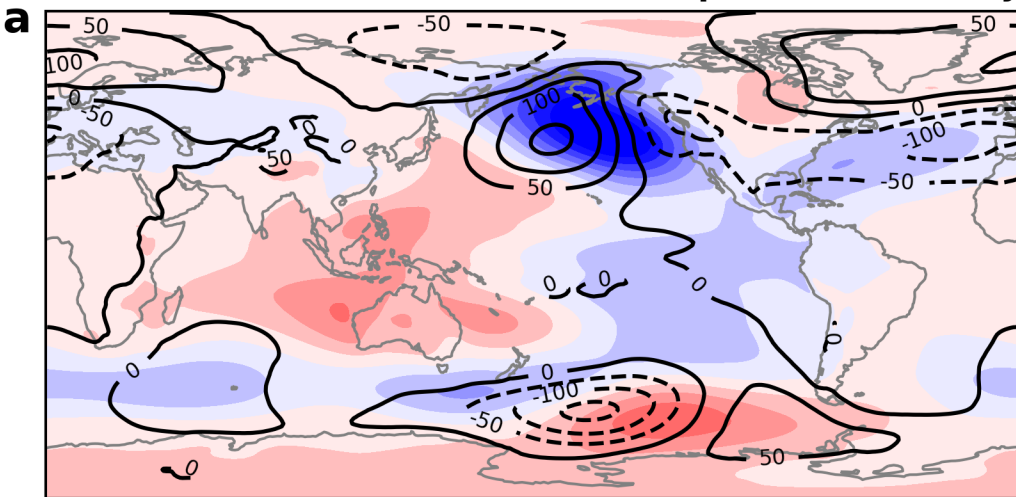
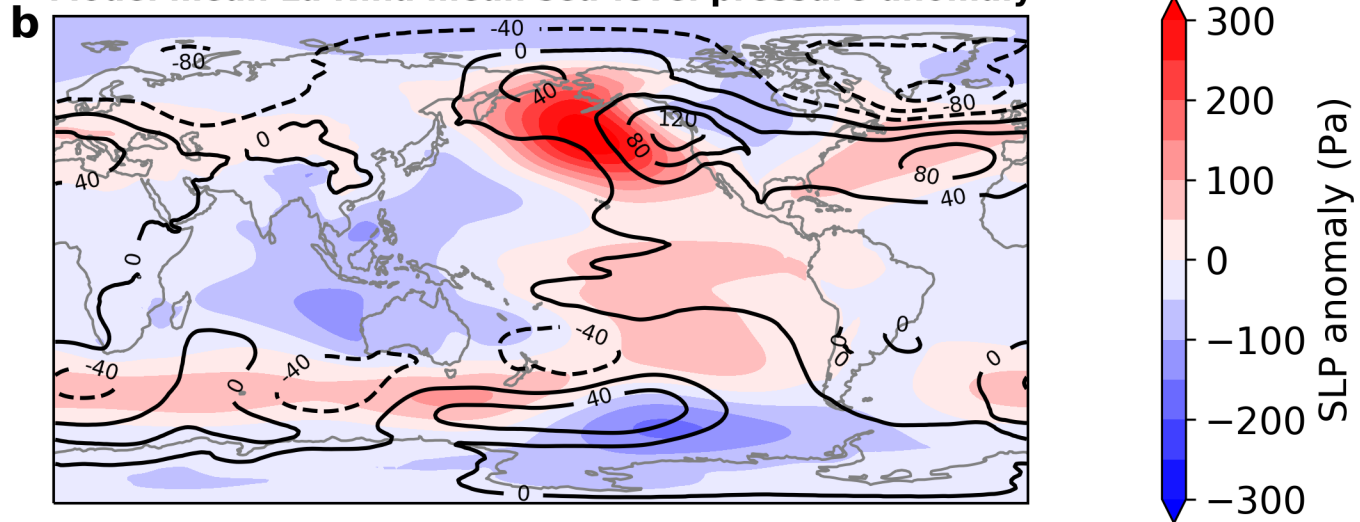


Figure 4.

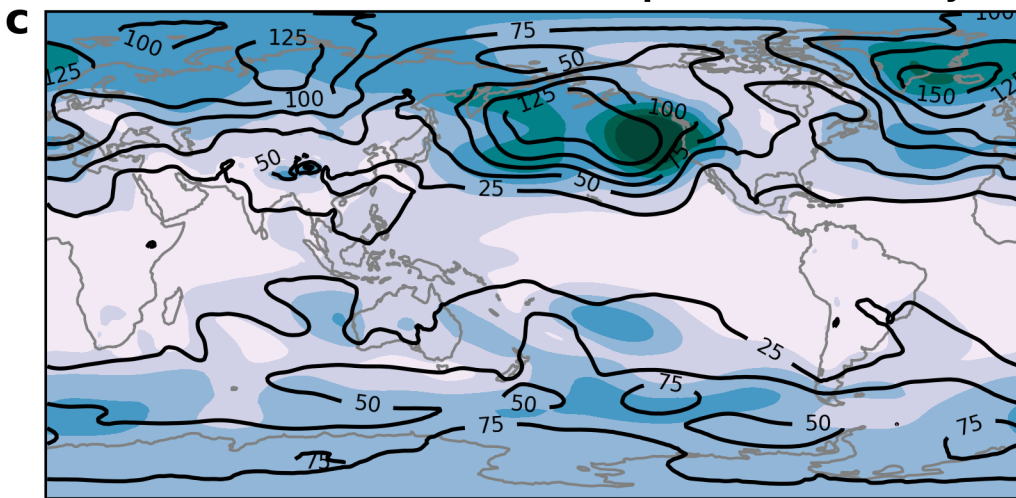
Model mean El Niño mean sea-level pressure anomaly



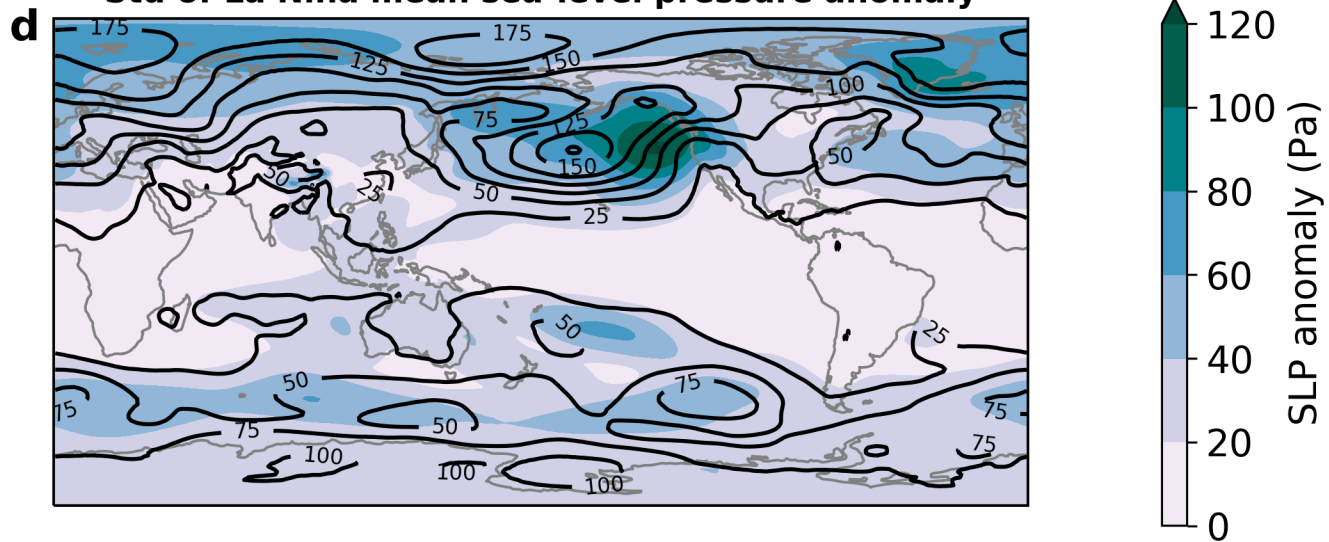
Model mean La Niña mean sea-level pressure anomaly



Std of El Niño mean sea-level pressure anomaly



Std of La Niña mean sea-level pressure anomaly



How does El Niño Southern Oscillation Change Under Global Warming – A First Look at CMIP6

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Figures S1 to S7

Introduction

This supporting information provides further details on the methods and analyses done in the main paper. Text S1 contains an extended description of the data and methods, Text S2 gives a brief discussion of the results of Figure S1, and Text S3 describes some background information for Figures S3 - S6.

Figure S1 shows spectra of the piControl Niño 3.4-index, Figure S2 shows the mean warming of in the Niño 3.4 region for future scenarios, Figures S3 and S4 show patterns associated with the E-index and C-index, Figure S5 shows the quadratic relationship of the two first principal components, Figure S6 the coefficient of the quadratic relationship plotted vs the skewness, and Figure S7 shows teleconnection patterns of sea level pressure for each model.

Text S1: Extended description of data and methods

Data

For the models BCC-CSM2-MR, CanESM5, MIROC6, MRI-ESM2-0, CESM2-WACCM we have used member r1i1p1f1 for all experiments. For models MIROC-ES2L, CNRM-CM6-1, MCM-UA-1-0, UKESM1-0-LL we have used member r1i1p1f2, except for MCM-UA-1-0 piControl, where r1i1p1f1 is used. For this model we note that historical r1i1p1f2 branches from piControl r1i1p1f1. For the model CNRM-ESM2-1 we have used member r1i1p1f2 for piControl, and its child member r2i1p1f2 for historical and future scenarios. For CESM2 we have used r1i1p1f1 for piControl and r4i1p1f1 for the other experiments.

For all piControl simulations, a linear trend is subtracted, to reduce a possible tiny influence of drift. For all future scenarios, a cubic spline detrending is used. When computing the trend, each of the future scenarios are first concatenated with the historical experiment. Then a cubic spline with two internal knots is fitted to the record from 1850 to 2100. The internal knots are chosen to be at the mid year (1932) and end year (2014) of the historical simulation. The only purpose of the historical data in this study is to improve the trend estimates of the future scenarios.

To ensure that the exact same region [5° S - 5° N, 170° W - 120° W] is used for all the models when computing the Niño 3.4-index, models' output is regridded to 1° x 1° degree resolution prior to spatial averaging. The data have monthly resolution, are smoothed by a 3-month running mean, and piControl mean seasonal variations are subtracted. The variances in Figure 2a and spectral analyses in Figure 1 are computed from anomalies obtained by detrending the Niño 3.4-index.

Spectral analysis

Spectral estimates are computed using Welch overlapped segment averaging on the Niño 3.4 index with monthly resolution. With this method we split the 86-yr long future scenarios into segments of 40 years, with 20 years overlap. For each segment, a windowed periodogram is computed with the Hanning window, then the results of each segment are averaged.

ENSO diversity

Following Cai et al. (2018), EOF analysis is applied to the region 15° S to 15° N, 140° E - 80° W. Before this analysis, models are regridded to a 1° x 1° grid to ensure the exact same regions are used for all models, then the monthly data are detrended and deseasonalized in each grid point. The first two EOFs and corresponding principal components are computed for piControl, then the two first principal components for future scenarios are estimated by projecting the data onto the piControl EOFs. All principal components are normalized by the estimated standard deviation of the first 500 years of piControl. As Cai et al. (2018) and Takahashi et al. (2011), we compute the E-index as $(PC1 - PC2)/\sqrt{2}$ and C-index as $(PC1 + PC2)/\sqrt{2}$, where the signs of the principal components are defined such that positive PC1 corresponds to positive anomalies in large parts of the Equatorial Pacific, and positive PC2 corresponds to positive anomalies in the western and negative in the eastern part of the Equatorial Pacific. Examples of E and C mode patterns are shown in Supplementary Figure 3.

ENSO teleconnections

An El Niño/La Niña event is defined to occur when the DJF mean exceeds ± 1 standard deviation of the 3-month running mean piControl Niño 3.4-index from the same model. Preprocessing of the sea-level pressures are done as follows for each model: (i) DJF means are computed in all grid points, (ii) detrending in all grid points, (iii) find mean sea-level pressure for all DJF means classified as an El Niño or La Niña event, respectively. The model mean and standard deviations of these results are then computed in Figure 4, after regridding all models to a 1° x 1° grid.

Text S2: Power spectral density of piControl Niño 3.4-index

Supplementary Figure 1 shows that nine out of eleven models have a piControl spectral peak in the periodicity range 3-7 years. In the high-frequency end we find the model BCC-CSM2-MR, peaking at a period between 2 and 3 years, and in the low-frequency end we find MCM-UA-1-0, peaking at a period of 8 years.

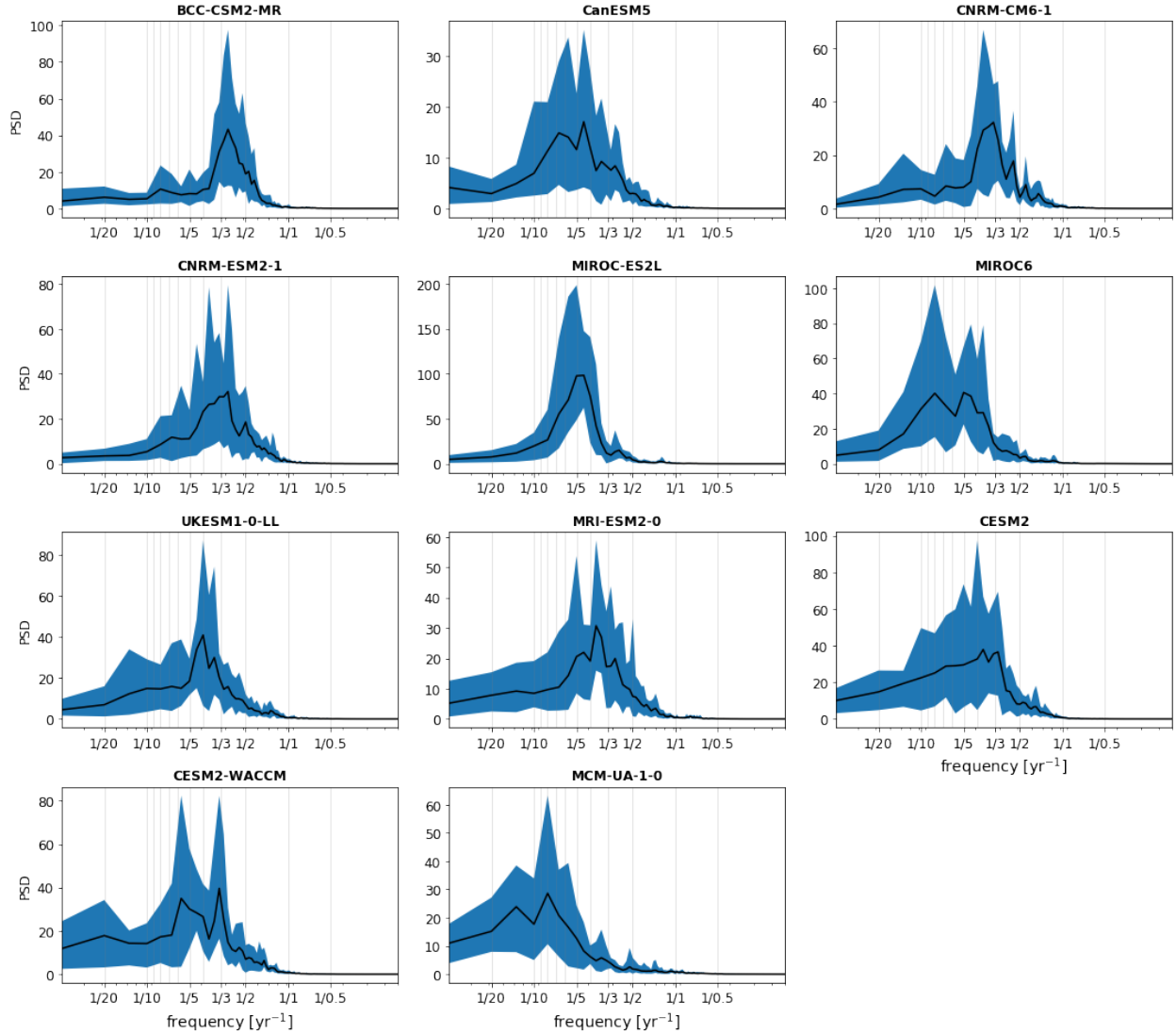


Figure S1. The black curves show the PSDs of the Niño 3.4-index computed using all of the first 500 years of piControl of each of the models. The shaded areas are the spread of the PSDs of 86-yr segments of the control runs, ranging from the minimum to the maximum values.

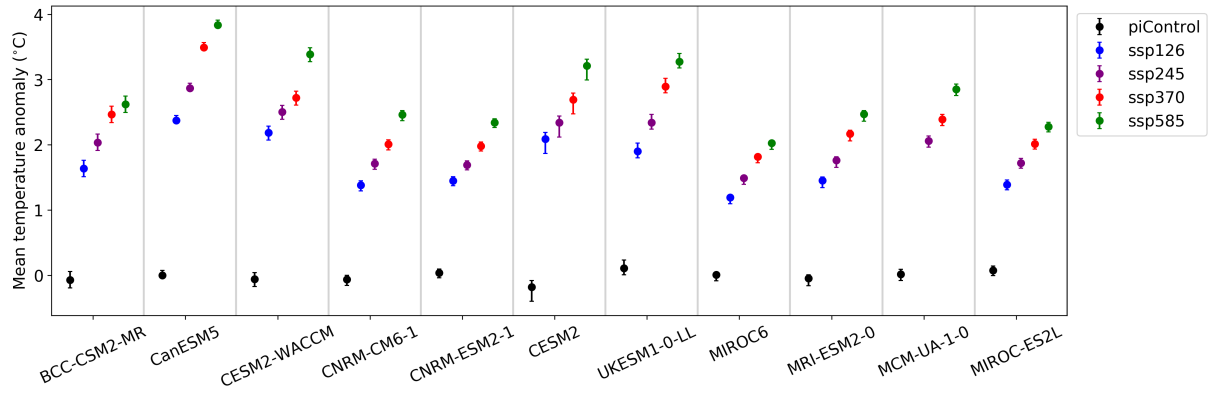


Figure S2: Mean temperature anomaly (°C) in the Niño 3.4 region [5° S - 5° N, 120° W - 170° W] for each of the CMIP6 models for piControl (black), and scenarios ssp126 (blue), ssp245 (purple), ssp370 (red) and ssp585 (green). The anomaly is computed as the difference between the time-averaged absolute temperatures from one member from each experiment and piControl, using monthly data with 3-month running mean. The error bars represent the spread of means in 86-year segments from piControl, ranging from the minimum to the maximum estimates.

Text S3: EP-ENSO and CP-ENSO patterns

The patterns associated with EP-ENSO and CP-ENSO are here calculated following the definition of Takahashi et al. (2011) as:

$$EP - ENSO \text{ pattern} = \frac{\sqrt{2}}{2}(EOF1 \cdot std(PC1) - EOF2 \cdot std(PC2)) \quad (1)$$

$$CP - ENSO \text{ pattern} = \frac{\sqrt{2}}{2}(EOF1 \cdot std(PC1) + EOF2 \cdot std(PC2)) \quad (2)$$

These expressions are derived such that:

$$\begin{aligned} PC1(t) \cdot EOF1 + PC2(t) \cdot EOF2 \\ = C - index(t) \cdot CP - ENSO \text{ pattern} + E - index(t) \cdot EP - ENSO \text{ pattern} \end{aligned}$$

The patterns obtained using this method are very similar to patterns obtained by performing a regression of the fields onto the C-index and E-index. The patterns for CESM2 are shown in Figure S3, and for the other models in Figure S4.

Following Karamperidou et al. (2017) and Cai et al. (2018), we estimate parameters in a quadratic relationship between PC1 and PC2:

$$PC2 = \alpha PC1^2 + \beta PC1 + \gamma$$

The scatterplots of PC1-PC2, as well as the estimated values of α are shown in Figure S5, while the relationships between α and the skewness of the E and C indices (Cai et al., 2018) are displayed in Figure S6.

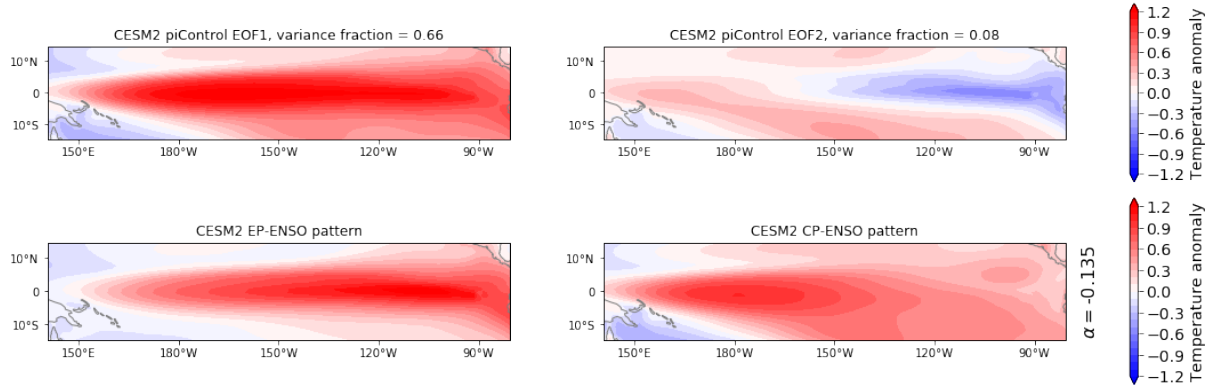


Figure S3: EOF1 and EOF2 for CESM2 (top row), and patterns associated with CP-ENSO and EP-ENSO (bottom row), calculated using Eqs. (1), (2). The patterns are scaled such that their corresponding principal component or index have standard deviation 1.

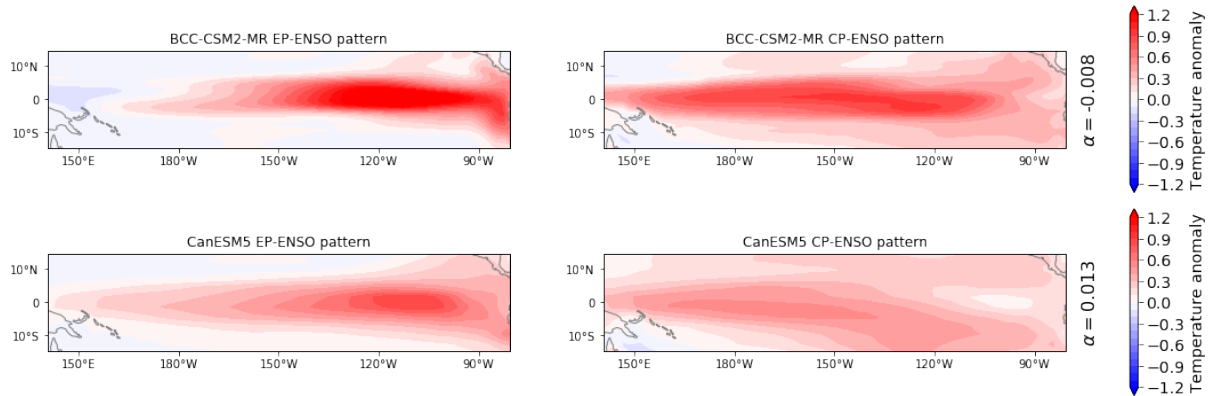


Figure S4: Patterns associated with CP-ENSO and EP-ENSO calculated using Eqs. (1), (2). The patterns are scaled such that their corresponding index have standard deviation 1.

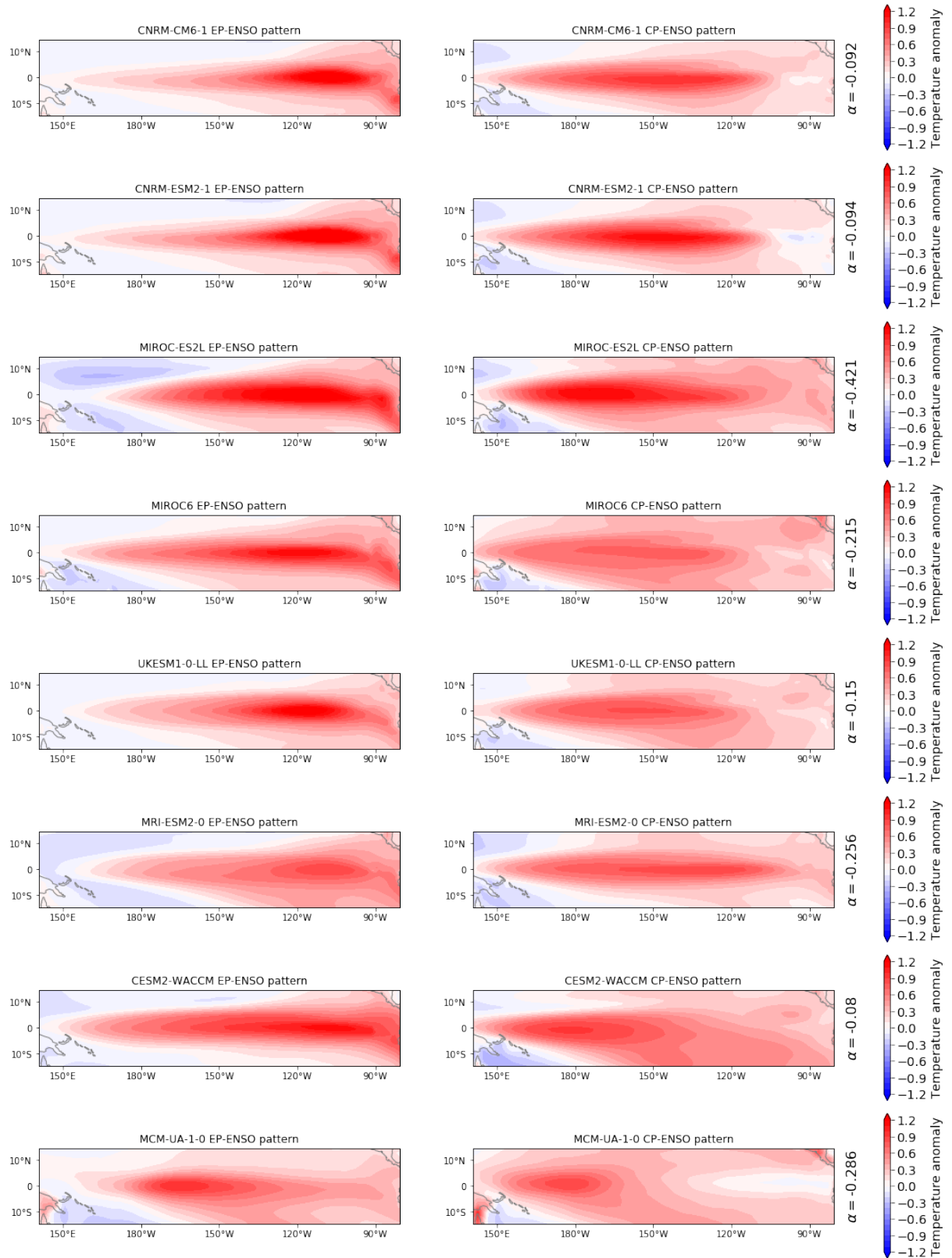


Figure S4 continued.

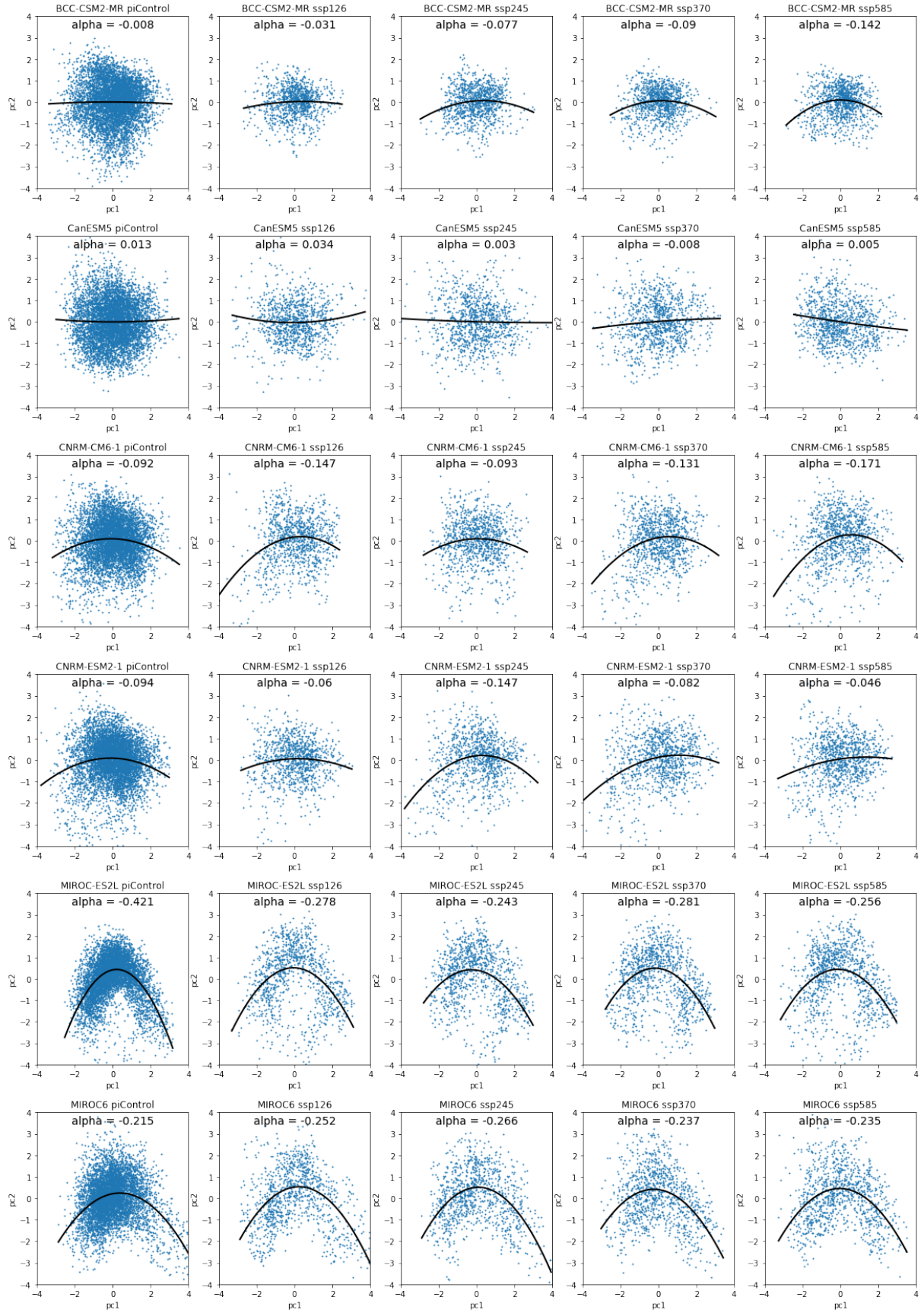


Figure S5: Scatterplots of PC1 vs PC2 for all models and scenarios in this study, and quadratic fits (black curves).

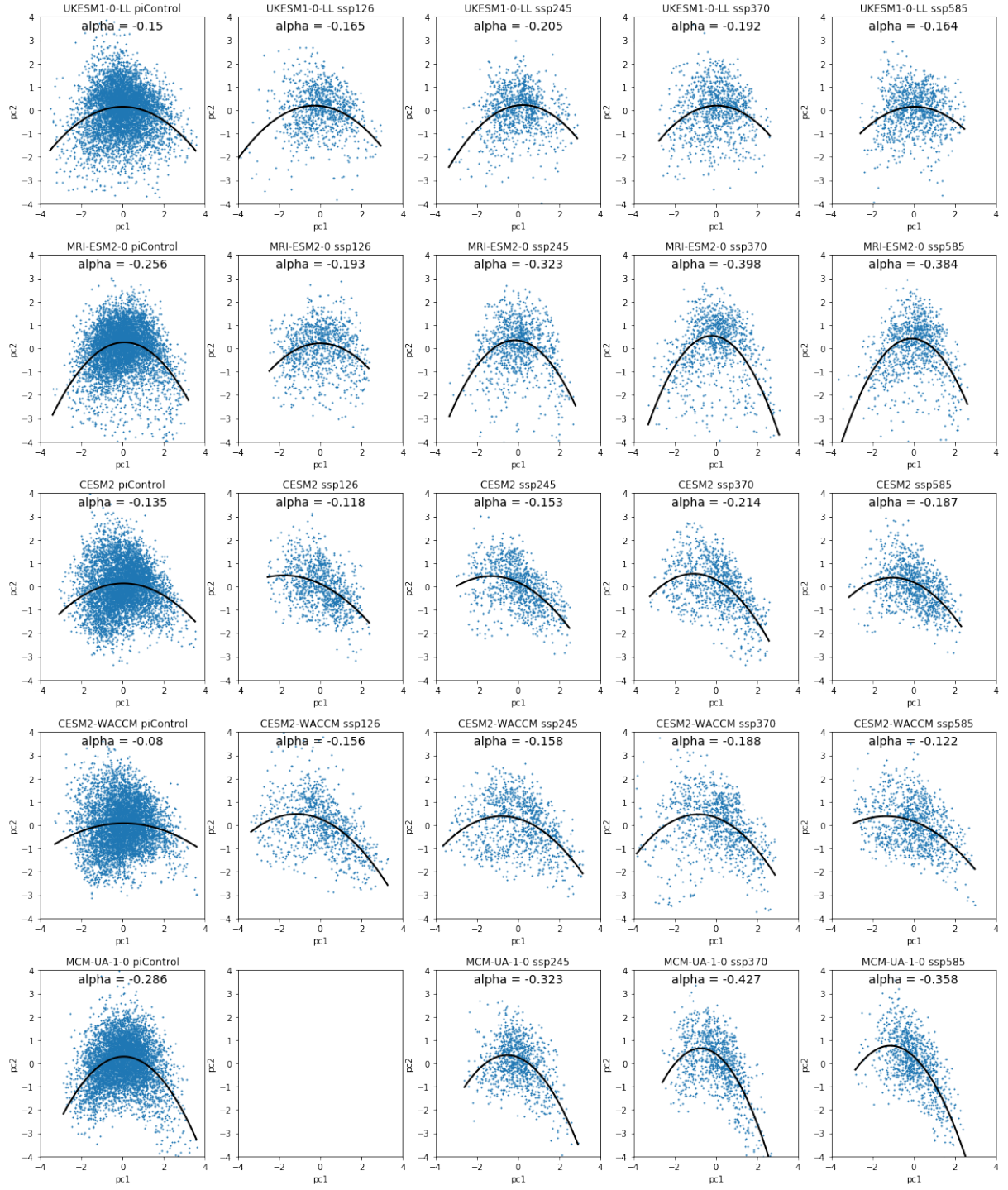


Figure S5 continued.

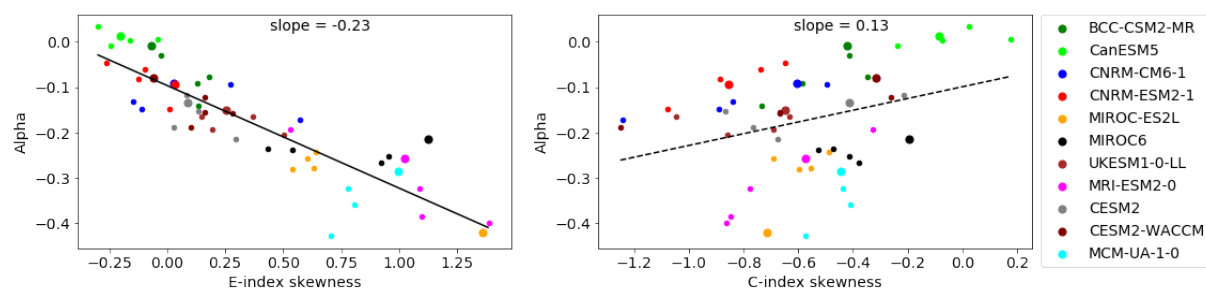


Figure S6: Estimates of alpha vs skewness of E-index and C-index. The five estimates for each model represent different experiments: large circles are from piControl, and used to sort models in main Figure 3, and the smaller circles are from SSP scenarios.

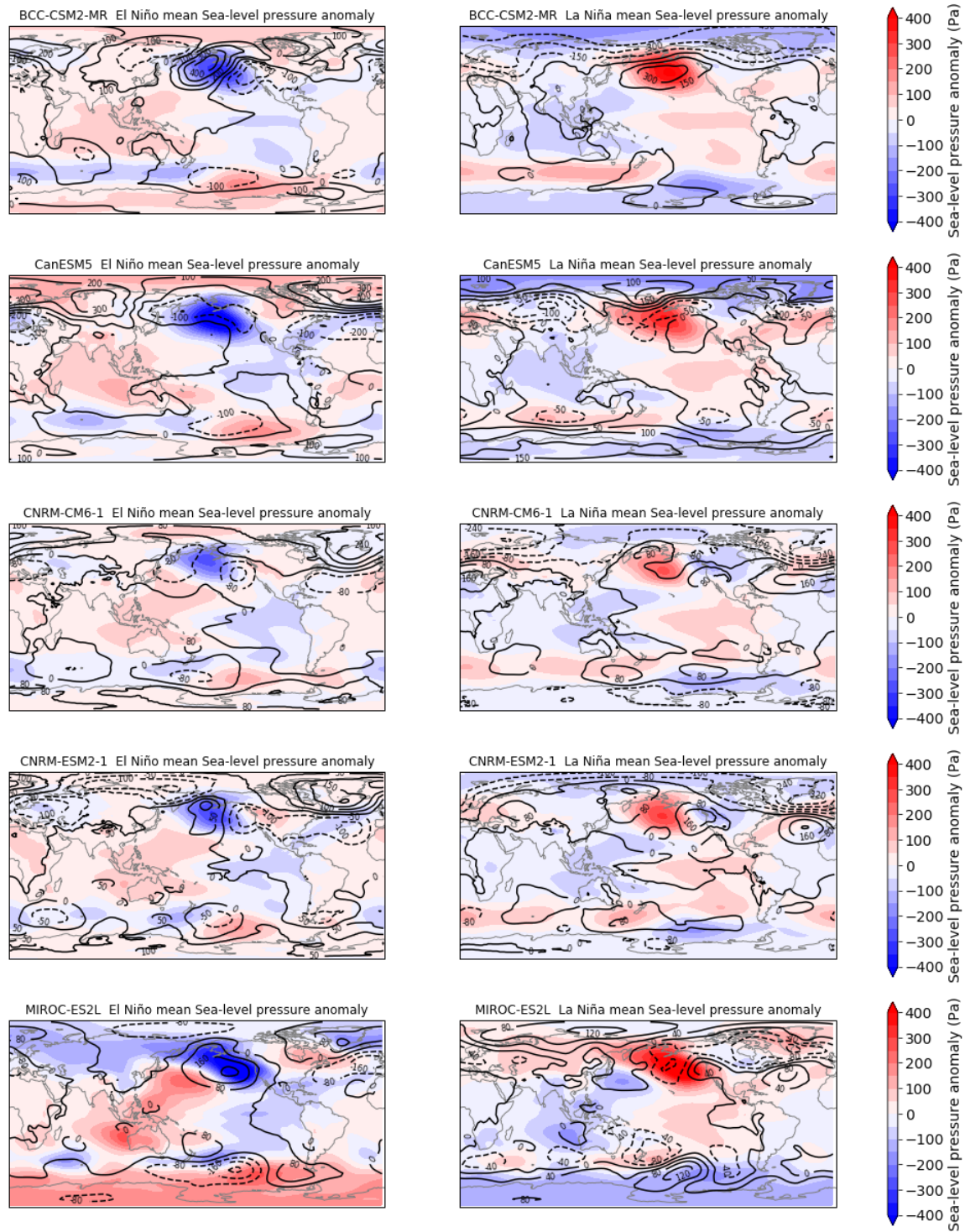


Figure S7: Showing the same as main Figure 4 a) and b), but for each model.

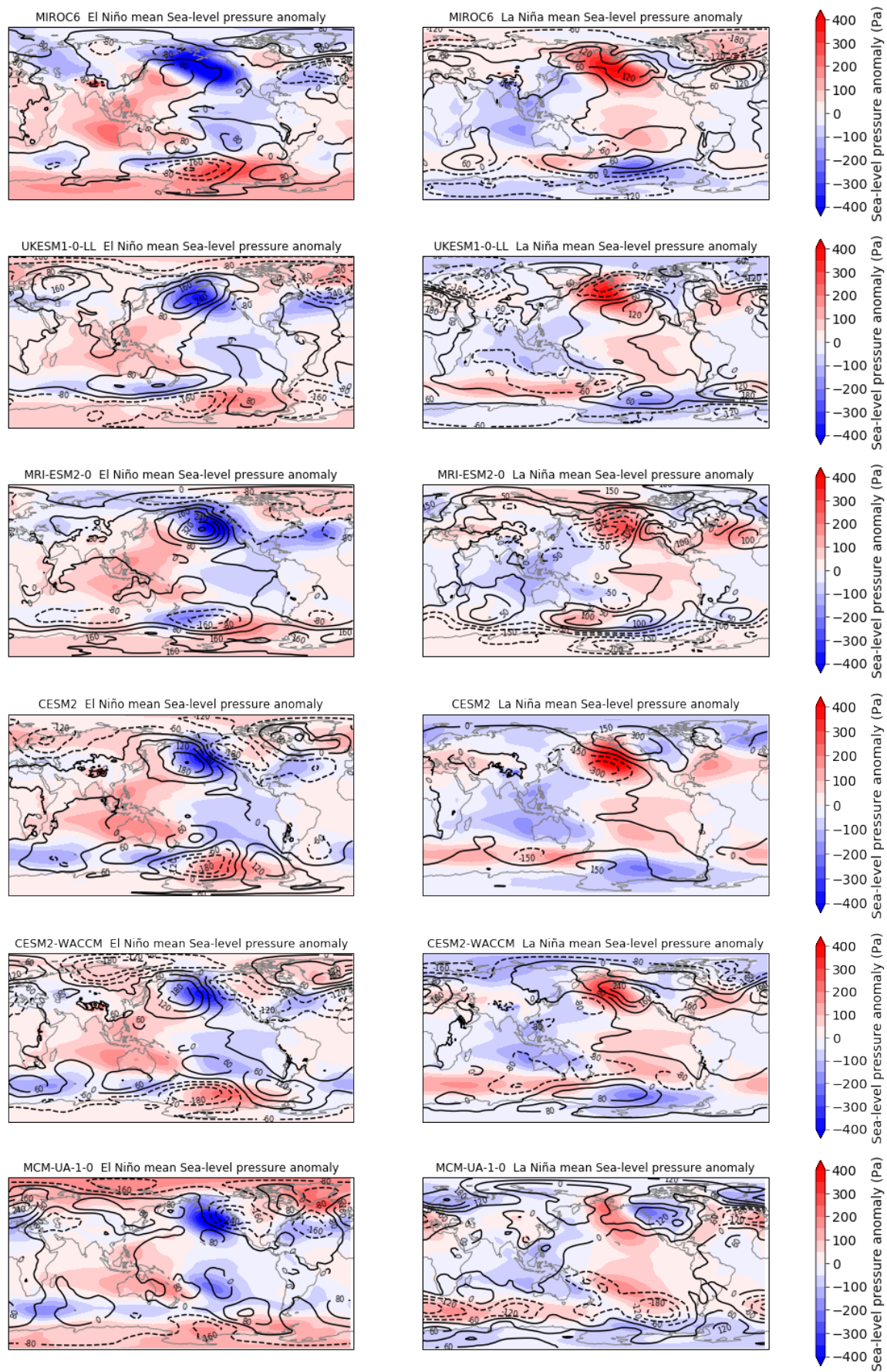


Figure S7 continued.