nature portfolio

Peer Review File

Global climate mode resonance due to rapidly intensifying El Niño-Southern Oscillation

Corresponding Author: Professor Malte Stuecker

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Review of "Global climate mode resonance due to rapidly intensifying El Nino-Southern Oscillation" submitted to Nature Communications. This paper examines how greenhouse-gas–driven warming leads to highly regular, large-amplitude ENSO cycles by mid-21st century, in response to strengthened air–sea feedbacks and weakened thermocline damping. The paper also shows that this intensification of ENSO phase-locks and amplifies variability in the North Atlantic, Indian, and Pacific climate modes of variability (e.g. NAO, TNA, IOD), suggesting both enhanced predictability and heightened global hydroclimate risks under alternating El Niño/La Niña events.

This is a very good paper, with great implications for global climate risk forecasting on sub-seasonal to seasonal scales. I also really like the methodology, combining high-resolution coupled climate models (AWI-CM3) with reduced-order dynamical diagnostics. I am only concerned about the use of a single coupled climate models, and the absence of a control simulations with change in greenhouse gas emissions. Can we find the same patterns in lower resolution CMIP6 ScenarioMIP and/or HighResMIP models? Is the intensification of ENSO variability exceeding the maximum range of variability that could be simulated in piControl experiments? I was also wondering how the method used to analyse the amplitude and phase synchronization would compare with the methodology developed by Jajcay et al. (2018; https://doi.org/10.1038/s41612-018-0043-7).

I would therefore recommend major revisions.

Reviewer #2

(Remarks to the Author)

[Editorial Note: Please see Reviewer #2's attachment at the end of this file]

Reviewer #3

(Remarks to the Author)
Stuecker et al. investigates climate change experiments in a high resolution coupled GCM under a high-CO2-emissions scenario and finds a strong increase in the amplitude and periodicity in ENSO. Consequently, other climate modes phase lock onto the strong and periodic ENSO signal and increase in amplitude. They use a hierarchy of idealized models to diagnose the changes in ENSO amplitude and periodicity. The societal impacts of such a transition are manifest, but it remains unclear whether this feature is a peculiarity of the chosen model or whether it reflects reality.
The paper is clearly written, the results are well-presented, and the importance of the findings are clear. I consider the paper suitable for publication after minor revisions. However, the paper would be improved if the authors provide some additional commentary and analysis on why this model exhibits this unique ENSO behavior, but not any other models. I offer some

small suggestions to improve the manuscript.

Major Comments
The results of this paper are very interesting, but one important point is not addressed: why does the AWI-CM3 model simulate a rapid switch to a highly regular oscillation with high amplitude, while other climate models do not? Since this model is an outlier, the impact of the paper will be increased if an argument can be made that this model's ENSO response is in some respects more realistic than other models.
A few ideas are hinted at throughout the paper, such as intensifying tropical intraseasonal variability (Ln. 111), or the relaxation of the mean SST gradient and trade winds (Ln.130). But these changes are seen in other climate models as well (especially the weakening of the east-west SST gradient), so what makes AWI-CM3 an outlier? Is its high horizontal and vertical resolution important? If so, do we see this increase in other HiResMIP models?
If the authors can discuss possible reasons conventional CMIP6 models do not simulate the response, it would be great. Furthermore, if they can speculate on why this particular model might better reflect reality compared to other CMIP models, that would further improve the impact. But overall it is still a very nice result that is worth being published.

Minor Comments
Ln. 52-53. It could be interesting to show Fig 1B for some selected CMIP6 models for comparison, to demonstrate that this behavior of this model is unique.
Ln. 123 It's not obvious to me that ZA is very significant, it looks like it averages about zero over the annual cycle.
Ln. 174. I'm confused why, if the range of phase differences narrows, the standard deviation of the PDFs trends upwards (blue curve)? Intuitively, I would expect the standard deviation to become smaller.
Fig.4: The features on the figure are very small. Perhaps three rows and two columns will allow each sub-panel to be larger.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I believe the authors have now addressed all my comments. The paper is significantly stronger, and deserves to be accepted for publication in Nature Communications.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
I am satisfied with the authors' careful reply to my comments and consider the paper ready for publication. Congratulations on an excellent paper.

(Remarks on code availability)
Currently, the Github links to the code do not work.

Manuscript NCOMMS-25-44516

Point-by-point response to the reviewers

We thank the three reviewers for their valuable comments and suggestions, which have improved the manuscript significantly. We have included a point-by-point response to the comments below (Reviewer comments are in black font, our responses in blue font, changes in the revised text in *Times New Roman italics*).

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

Review of "Global climate mode resonance due to rapidly intensifying El Nino-Southern Oscillation" submitted to Nature Communications. This paper examines how greenhouse-gas–driven warming leads to highly regular, large-amplitude ENSO cycles by mid-21st century, in response to strengthened air–sea feedbacks and weakened thermocline damping. The paper also shows that this intensification of ENSO phase-locks and amplifies variability in the North Atlantic, Indian, and Pacific climate modes of variability (e.g. NAO, TNA, IOD), suggesting both enhanced predictability and heightened global hydroclimate risks under alternating El Niño/La Niña events.

This is a very good paper, with great implications for global climate risk forecasting on sub-seasonal to seasonal scales. I also really like the methodology, combining high-resolution coupled climate models (AWI-CM3) with reduced-order dynamical diagnostics.

Thank you for the assessment and valuable feedback. We address your specific comments below.

I am only concerned about the use of a single coupled climate models, and the absence of a control simulations with change in greenhouse gas emissions. Can we find the same patterns in lower resolution CMIP6 ScenarioMIP and/or HighResMIP models? Is the intensification of ENSO variability exceeding the maximum range of variability that could be simulated in piControl experiments?

Following your suggestion, we have added comparisons of the AWI-CM3 projections with a 150-yr control simulation with the same model as well as with observational and reanalysis data (new Fig. 2a,b in the revised manuscript). The AWI-CM3 model simulates ENSO amplitude and regularity within the observational range. Both ENSO amplitude and regularity show a significant increase when comparing the AWI-CM3 SSP5-8.5 projections with the internal variability of these metrics in the AWI-CM3 control simulation.

We also analysed ENSO regularity and amplitude in all 49 available CMIP6 models (Fig. 2c,d). As expected, the projected changes in ENSO regularity and amplitude exhibit a wide spread; however, AWI-CM3 is not an outlier. Several CMIP6 models produce similar results (Fig. 2c,d; Supplementary Fig. 1). The ENSO changes across all these models are shown in Fig. R1 below for your reference.

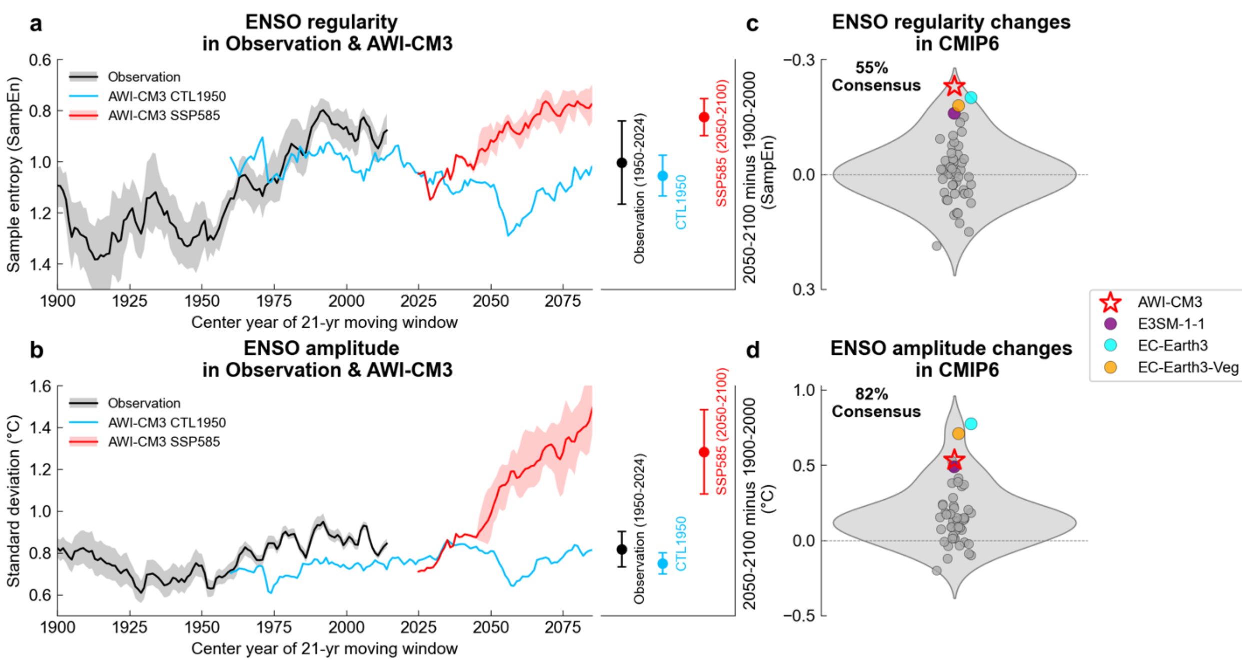
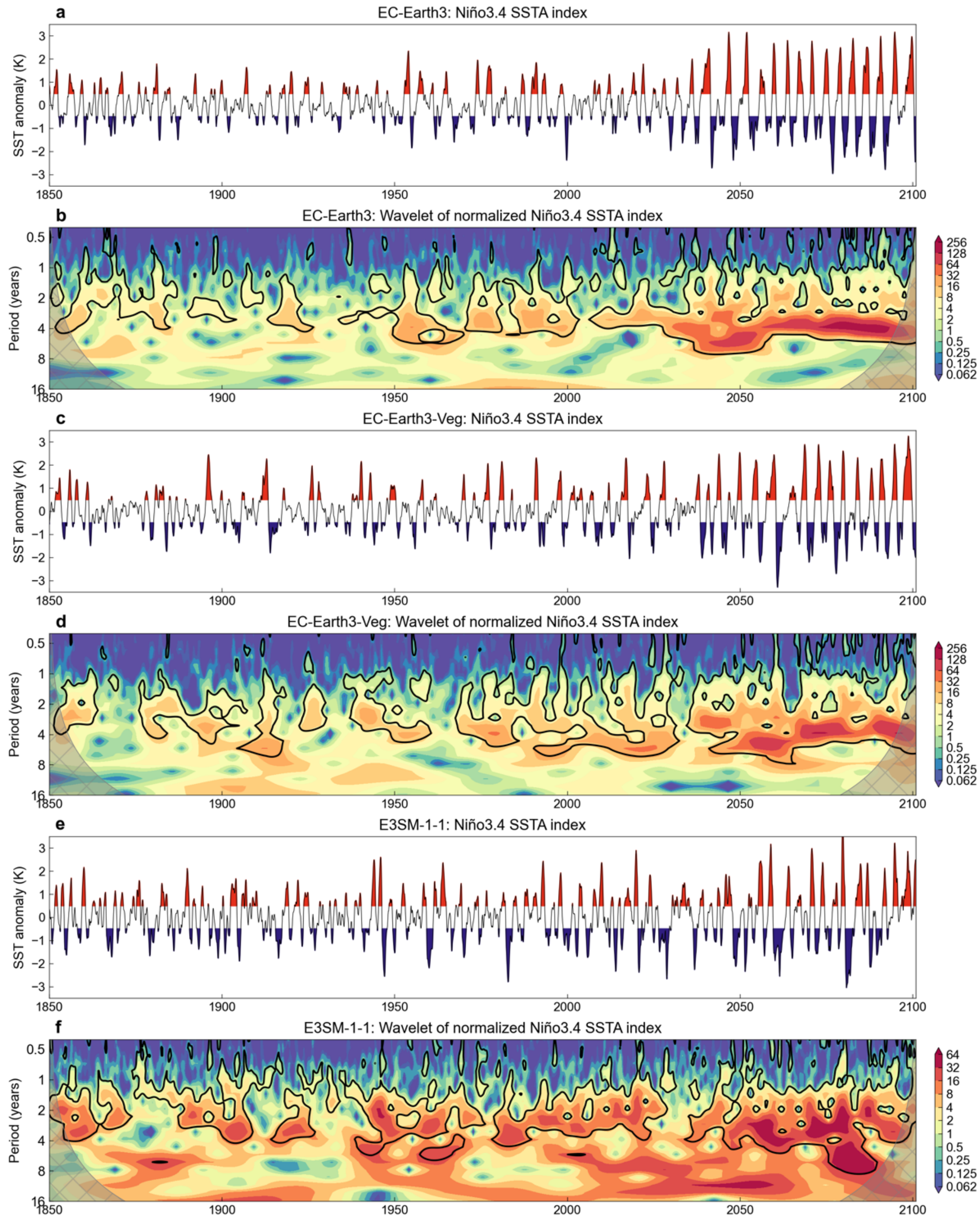
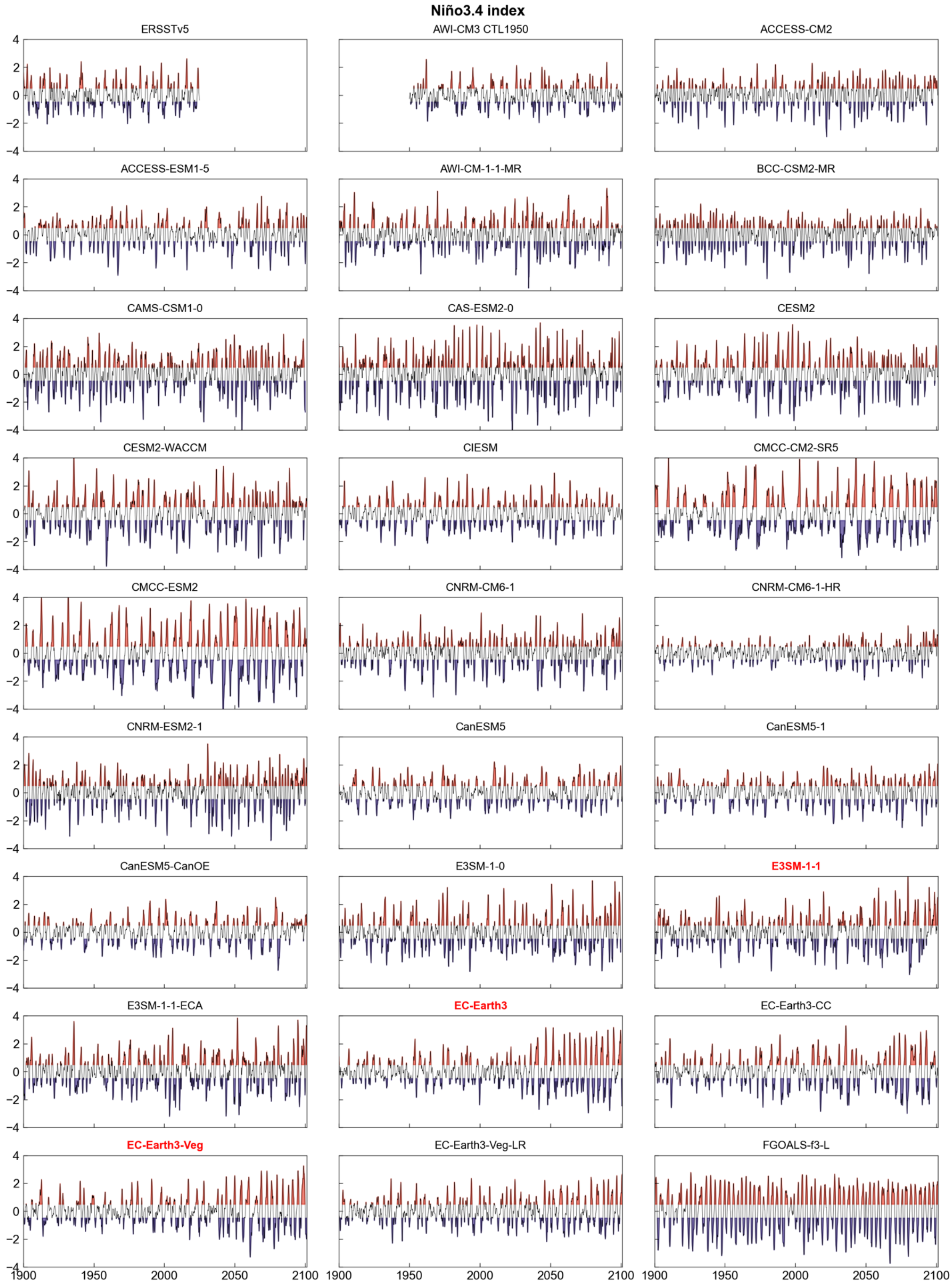


Fig. 2| ENSO regularity and amplitude changes in observations, AWI-CM3, and CMIP6 models. a,b Moving 21-year changes of sample entropy (SampEn) (a) and standard deviation (SD) (b) of the Niño3.4 SST anomaly index in observations (black), the 150-year AWI-CM3 1950 control simulation (CTL1950, blue), and the AWI-CM3 SSP5-8.5 scenario simulation (red). Solid lines and shading indicate the multi-product/multi-member mean and the 1 SD spread of 10,000 inter-realizations using a bootstrap method, respectively. The error bars indicate the mean and 1 SD of values across all overlapping 21-year windows for the observations (1950-2024), CTL1950 (150-yr), and SSP5-8.5 (2050-2100). **c,d** Violin plots showing the probability density distribution of ENSO regularity change (c) and amplitude change (d) across 49 CMIP6 models. The change is calculated as the difference between 2050–2100 and 1900–2000. Dots represent individual model results, with E3SM-1-1, EC-Earth3, and EC-Earth3-Veg highlighted in distinct colours; the red star marks the AWI-CM3 result (2050-2100 minus CTL1950). In **a** and **c**, the y-axis is inverted to emphasize decreasing SampEn indicating increasing regularity.



Supplementary Fig. 1| Increased ENSO regularity in selected CMIP6 models. a Time evolution of the ENSO Niño3.4 SSTA index [K] for EC-Earth3 (3-month running-mean applied). **b** Wavelets of the normalized Niño3.4 SSTA index for EC-Earth3. Black contours enclose regions above 90% confidence level significance tested against a Lorentzian spectrum. **c,d** and **e,f** Same as **a,b** but for EC-Earth3-Veg and E3SM-1-1, respectively.



Niño3.4 index
ERSSTv5
AWI-CM3 CTL1950
ACCESS-CM2
ACCESS-ESM1-5
AWI-CM-1-1-MR
BCC-CSM2-MR
CAMS-CSM1-0
CAS-ESM2-0
CESM2
CESM2-WACCM
CIESM
CMCC-CM2-SR5
CMCC-ESM2
CNRM-CM6-1
CNRM-CM6-1-HR
CNRM-ESM2-1
CanESM5
CanESM5-1
CanESM5-CanOE
E3SM-1-0
E3SM-1-1
E3SM-1-1-ECA
EC-Earth3
EC-Earth3-CC
EC-Earth3-Veg
EC-Earth3-Veg-LR
FGOALS-f3-L
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1900
1950
2000
2050
2100

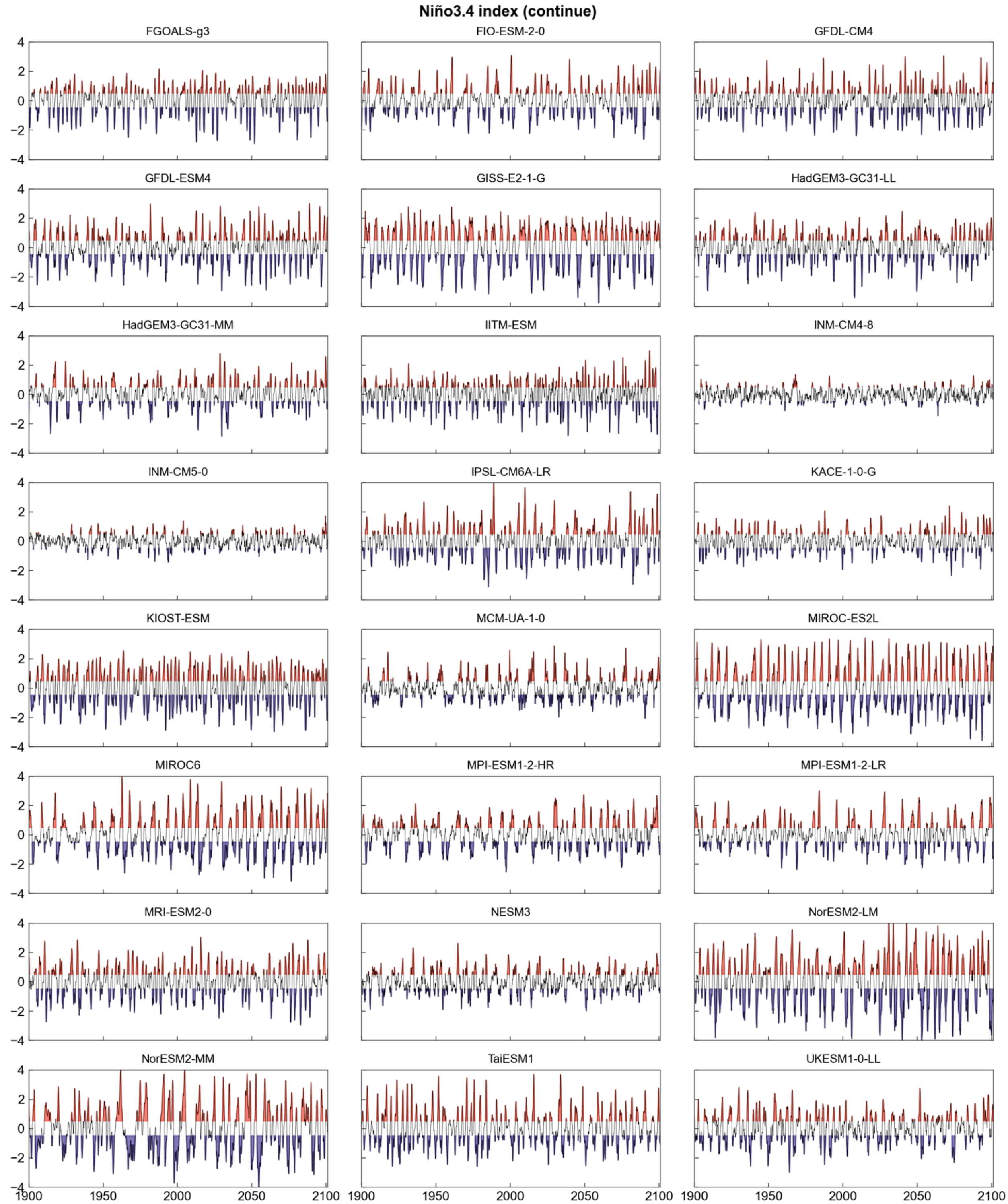


Fig. R1| ENSO time series in CMIP6 models. Time evolution of ENSO Niño3.4 SST anomaly index [K] (3-month running-mean applied) for ERSSTv5 (1900-2024), the 150-year AWI-CM3 CTL1950 simulation, as well as the historical+SSP5-8.5 simulations from 49 CMIP6 models (1900-2100).

Corresponding changes to the revised manuscript text (L92–106, a new section titled "Assessment of model fidelity."):

Assessment of model fidelity

Next, using sample entropy (SampEn; see Methods) of Niño3.4 SST anomalies as a metric for ENSO regularity together with the Niño3.4 SST anomaly standard deviation (SD), we show that a 1950 control simulation of AWI-CM3 TCo319 exhibits both ENSO regularity (Fig. 2a) and ENSO amplitude (Fig. 2b) similar to the observations and that the increase of both metrics in the AWI-CM3 TCo319 future projections cannot be explained by internal variability. Furthermore, analysis of the CMIP6 model archive demonstrates that while there is a wide range of possible changes in future ENSO regularity (Fig. 2c) and amplitude (Fig. 2d), 55% of CMIP6 models show an increase in ENSO regularity (Fig. 2c) and 82% an increase in ENSO SST anomaly amplitude (Fig. 2d) by the second half of this century under the SSP5-8.5 scenario. In addition, a few models (i.e., E3SM-1-1, EC-Earth3, and EC-Earth3-Veg) show similar increased ENSO regularity and amplitude as AWI-CM3 TCo319 (Fig. 2c,d, Supplementary Fig. 1). We emphasize that we do not expect strong inter-model agreement of ENSO projections across the CMIP6 archive given that considerable biases of climate mean states and ENSO dynamics result in different ENSO regimes across models [8,24].

I was also wondering how the method used to analyse the amplitude and phase synchronization would compare with the methodology developed by Jajcay et al. (2018; https://doi.org/10.1038/s41612-018-0043-7).
I would therefore recommend major revisions.

Thank you for raising this point. The methodology of Jajcay et al. (2018) primarily examines *intra-series* phase interactions by analysing how different time scales within the same time series (e.g., Niño3.4 at different wavelet periods) interact using a phase-dynamics framework combined with conditional mutual information and statistical randomization. This approach is well-suited for identifying scale–scale interactions or cross-frequency coupling within a single process.

In contrast, our analysis targets *inter-series* phase synchronization — that is, how two distinct processes (e.g., Niño3.4 and other climate mode indices) exhibit joint phase locking. We employ Hilbert-transform–based analytic signals and directly test for *m:n* phase synchronization through the evolution and statistical distribution of phase differences, rather than through scale-resolved mutual information. Our method emphasizes dynamical phase locking between separate time series, whereas the Jajcay et al. approach emphasizes interactions among different oscillatory components of the same signal. In short, Jajcay et al. investigate cross-scale interactions within a single process, while our method examines phase synchronization between different processes. Both methods are complementary but designed to address different scientific questions.

Reviewer #2 (Remarks to the Author):

The authors present a well-written, timely study on future ENSO intensification and global synchronization under greenhouse warming, using a high-resolution climate model. The abstract clearly communicates key findings, especially the shift to a highly regular, high-amplitude ENSO regime and its impacts on other climate modes. This addresses an important unresolved question, and the proposed mechanism linking air-sea feedbacks, atmospheric noise, and teleconnection synchronization is compelling. I recommend the manuscript for publication, provided the authors address some important points.

Thank you for the assessment and valuable feedback. We address your specific comments below.

• A major limitation is the reliance on a single climate model (AWI-CM3) to infer future changes in ENSO amplitude, teleconnection strength, and global hydroclimate impacts. Given well-known inter-model differences in ENSO characteristics, the lack of multi-model comparison raises concerns about the robustness and generalizability of results.

• Additionally, the study lacks validation of modeled trends against observational or reanalysis data. Without benchmarking AWI-CM3's current ENSO behavior and atmospheric responses, confidence in future projections is reduced. Incorporating multi-model analyses and observational validation would greatly enhance credibility and applicability.

Thank you for raising these important points. To address these issues, we included in the revised version:

(i) A detailed model evaluation, showing that a 150-yr AWI-CM3 1950 control simulation reproduces both the observed climate mean state and SST variability reasonably well (new Supplementary Fig. 11) as well as reasonably reproduces key ENSO metrics, such as its seasonal synchronization, spectral characteristics, and its teleconnections (new Supplementary Fig. 12). These results are presented in the revised manuscript (L294–299):

A 150-year TCo319 control simulation with fixed 1950 forcing (CTL1950) was also analysed to characterize internal climate variability and to serve as a baseline comparison. The CTL1950 simulation reproduces the observed SST and precipitation mean state and SST variability reasonably well (Supplementary Fig. 11). The CTL1950 simulation also reproduces the observed characteristics of ENSO including its *seasonal synchronization, spectral characteristics, and teleconnections (Supplementary Fig. 12).*

(ii) A comparison of future changes of both ENSO regularity and amplitude in the AWI-CM3 model with the CMIP6 model archive (new Fig. 2). While the CMIP6 models show a large range of projected changes (new Fig. 2c,d), a few models exhibit similar behaviour as AWI-CM3 (new Supplementary Fig. 1), providing support that the AWI-CM3 results are not spurious. Corresponding changes to the revised manuscript text (L92–106, a new section titled "Assessment of model fidelity."):

Assessment of model fidelity

Next, using sample entropy (SampEn; see Methods) of Niño3.4 SST anomalies as a metric for ENSO regularity together with the Niño3.4 SST anomaly standard deviation (SD), we show that a 1950 control simulation of AWI-CM3 TCo319 exhibits both ENSO regularity (Fig. 2a) and ENSO amplitude (Fig. 2b) similar to the observations and that the increase of both metrics in the AWI-CM3 TCo319 future projections cannot be explained by internal variability. Furthermore, analysis of the CMIP6 model archive demonstrates that while there is a wide range of possible changes in future ENSO regularity (Fig. 2c) and amplitude (Fig. 2d), 55% of CMIP6 models show an increase in ENSO regularity (Fig. 2c) and 82% an increase in ENSO SST anomaly amplitude (Fig. 2d) by the second half of this century under the SSP5-8.5 scenario. In addition, a few models (i.e., E3SM-1-1, EC-Earth3, and EC-Earth3-Veg) show similar increased ENSO regularity and amplitude as AWI-CM3 TCo319 (Fig. 2c,d, Supplementary Fig. 1). We emphasize that we do not expect strong inter-model agreement of ENSO projections across the CMIP6 archive given that considerable biases of climate mean states and ENSO dynamics result in different ENSO regimes across models [8,24].

In addition, we revised the text in the abstract, introduction, and discussion making it clear that the results are one possible scenario within a wide range of possible ENSO future behaviours:

Abstract (with tracked changes):

Abstract

The El Niño-Southern Oscillation (ENSO) ~~impacts~~influences climate variability ~~across the globe, including many~~globally, encompassing various other modes of variability, ~~thereby representing the~~and thus represents a key predictable climate signal on seasonal timescales. Yet, its response to greenhouse warming remains uncertain, with models projecting ~~various~~a range of outcomes. Here, we ~~show~~demonstrate that in response to warming, a state-of-the-art high-resolution climate model simulates a rapid ~~switch~~transition from a moderate~~ -~~-amplitude irregular regime, as observed in the current climate, to a highly regular oscillation with intensifying amplitude. This behaviour can be attributed to increasing air-sea feedbacks, which approach criticality in the second half of this century, and growing atmospheric noise. As ENSO intensifies in this model, it synchronizes with other prominent climate modes, such as the North Atlantic Oscillation and the Indian Ocean Dipole, thereby imprinting its regular, predictable variability on them. ~~This~~If realized, this global climate mode resonance would have wide-ranging whiplash impacts on regional hydroclimates.

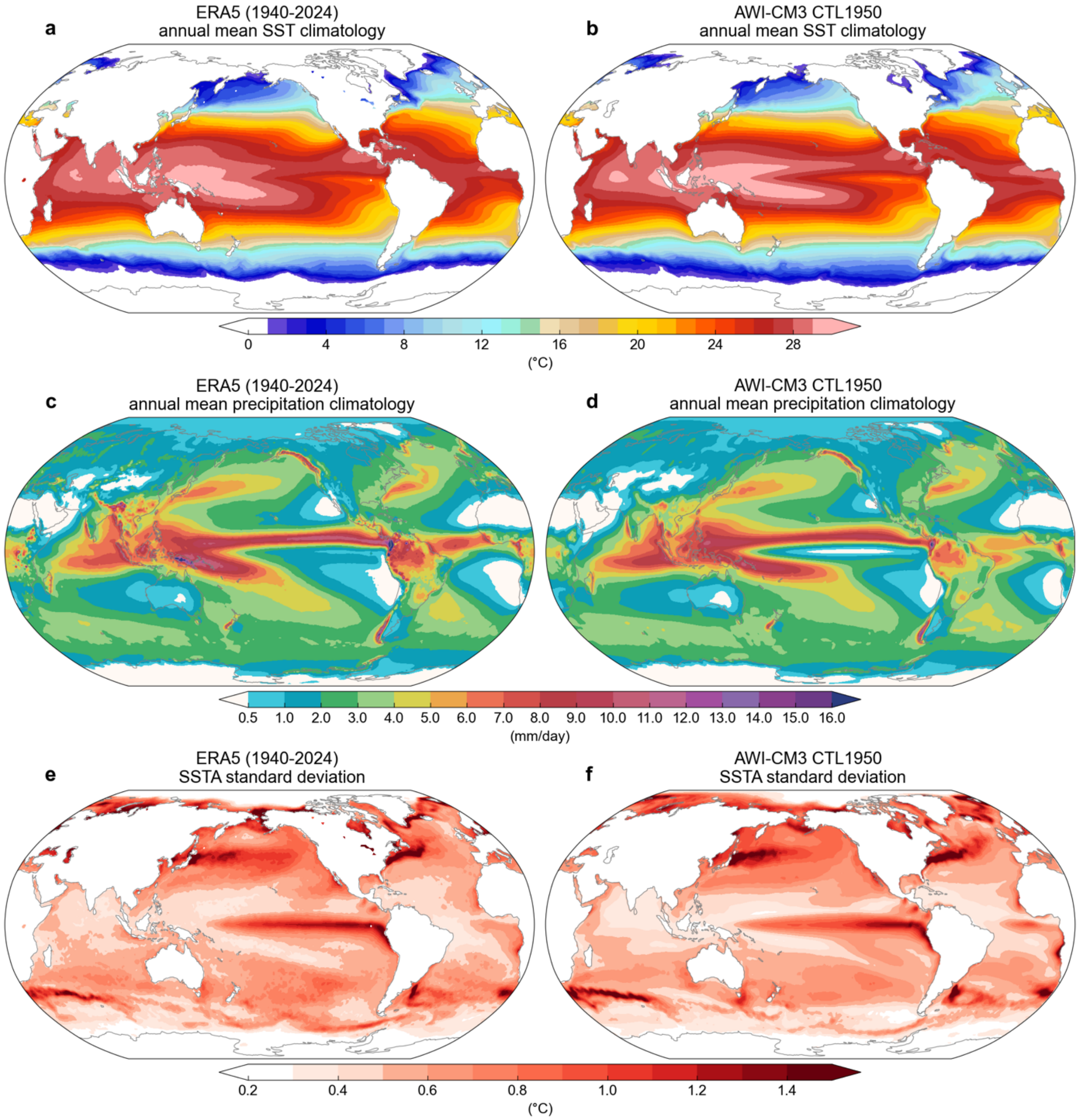
Changes to the text in the in introduction and discussion sections *in italics*:

L65-70:

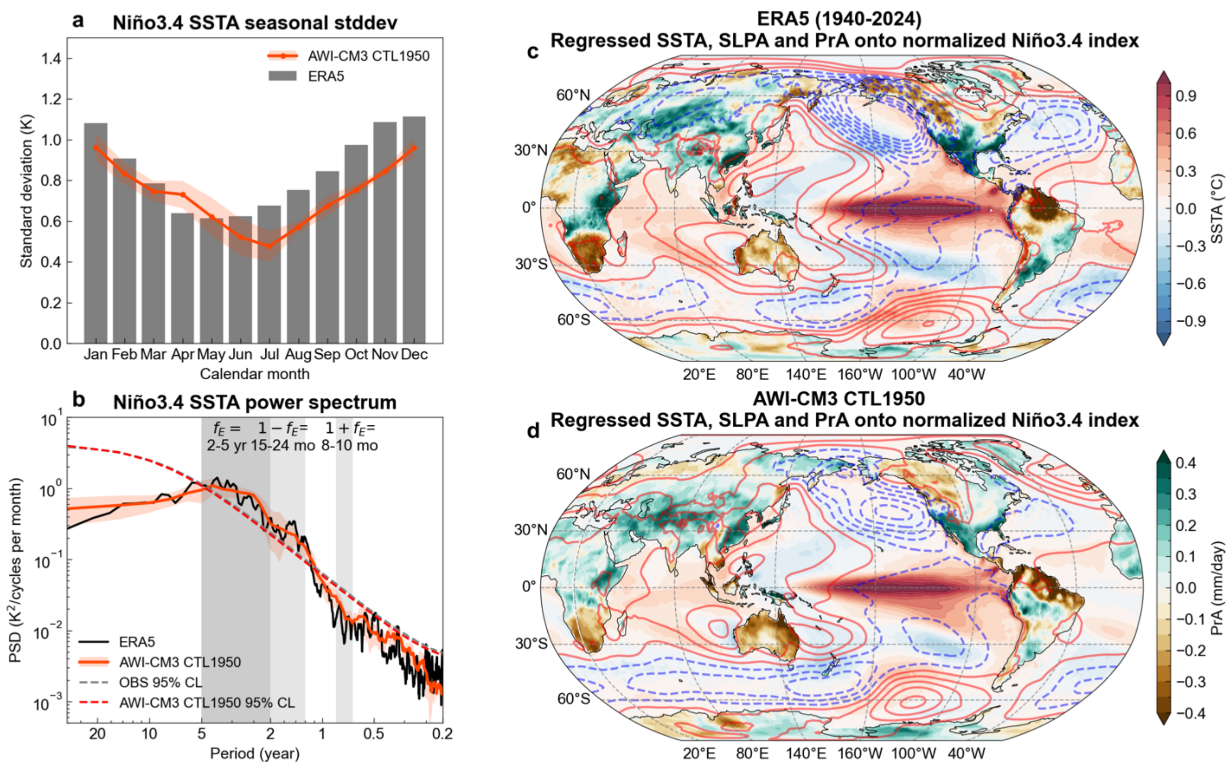
While models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) show a wide range of possible future ENSO regularity and amplitude projections, a few models show qualitatively similar behaviour to AWI-CM3. If this peculiar ENSO dynamical scenario were to materialize in the future, it could lead to both increased ENSO predictability, due to greater regularity, and, at the same time, to warming-amplified "whiplash impacts" [28] on regional climates.

L272-274:

While similar increases in ENSO regularity and amplitude can be found in some CMIP6 model projections (Fig. 2), future work needs to assess the detailed dynamics across these models and assess the likelihood of the ENSO regime changes seen in AWI-CM3.



Supplementary Fig. 11| Fidelity of AWI-CM3 in simulating the mean state and SST variability. a,b Annual mean SST climatology in ERA5 (1940-2024) and the AWI-CM3 CTL1950 simulation; **c,d** Annual mean precipitation climatology in ERA5 (1940-2024) and the AWI-CM3 CTL1950 simulation; **e,f** Monthly SST anomaly standard deviation in ERA5 (1940-2024) and the AWI-CM3 CTL1950 simulation.



Supplementary Fig. 12| Fidelity of AWI-CM3 in simulating ENSO and its teleconnections. a Seasonal standard deviation of the Niño3.4 SST anomaly index in ERA5 (gray bars) and the AWI-CM3 CTL1950 simulation (red line); **b** Power spectral density (PSD) estimated using the Multi-Taper Method, of the Niño3.4 SSTA index for ERA5 (1940-2024, black curve) and the AWI-CM3 CTL1950 simulation (red curve). The confidence levels (CL) for the spectral peaks were derived from the percentile distributions at each frequency across 10,000 synthetic power spectra generated from discrete AR(1) processes for the Niño3.4 index with the same lag(-1 month) autocorrelation, variance, and data length to the corresponding time series (See Methods). The red shading in a and **b** is one standard deviation spreads across five non-overlapping 30-yr segments of the 150-yr CTL1950 simulation. **c,d** Regressed December-January-February (DJF) anomalies onto the normalized Niño3.4 index for ERA5 (1940-2024) and the AWI-CM3 CTL1950 simulation for SST (°C), land precipitation (mm day^{-1}), SLP (contour interval of 0.3 hPa) anomalies.

• The suggestion that future ENSO will become more regular, intense, and predictable—synchronizing other major climate modes like the North Atlantic Oscillation and Indian Ocean Dipole—is speculative. ENSO predictability as well as teleconnections exhibit substantial variability influenced by internal dynamics and background state changes. Assuming a more regular ENSO leads to improved predictability or consistent control over other modes oversimplifies the complex climate system. Without supporting observational or multi-model evidence, this conclusion should be framed more cautiously, clearly distinguishing model results from real-world implications. The authors may consider referencing relevant literature on ENSO predictability for discussion or introduction.

https://www.nature.com/articles/s41612-024-00845-5

Thank you for these comments. We revised the text (see reply to your comments above) to emphasize that the results discussed here are a possible scenario but that we do not assess its likelihood. We demonstrate in the revised manuscript using an analysis of ENSO regularity and amplitude changes in the CMIP6 archive that a few other models exhibit an increase in both ENSO amplitude and regularity. In addition, we now also include a reference to a previous study (Berner et al. 2020), which found an increase in ENSO regularity and amplitude in the CMIP5 model CESM1.

Thank you for pointing out the Ehsan et al. (2024) study. We now cite this paper in addition to two other papers on decadal variations of ENSO predictability when we discuss how sample entropy captures observed decadal variations in ENSO forecast skill:

L381-383:

The observed SampEn effectively captures the decadal variations in ENSO forecast skill, including the modest decrease in predictability after the 2000s (black curve in Fig. 2a, refs [59-61]).

Reviewer #3 (Remarks to the Author):

Stuecker et al. investigates climate change experiments in a high resolution coupled GCM under a high-CO2-emissions scenario and finds a strong increase in the amplitude and periodicity in ENSO. Consequently, other climate modes phase lock onto the strong and periodic ENSO signal and increase in amplitude. They use a hierarchy of idealized models to diagnose the changes in ENSO amplitude and periodicity. The societal impacts of such a transition are manifest, but it remains unclear whether this feature is a peculiarity of the chosen model or whether it reflects reality.

The paper is clearly written, the results are well-presented, and the importance of the findings are clear. I consider the paper suitable for publication after minor revisions. However, the paper would be improved if the authors provide some additional commentary and analysis on why this model exhibits this unique ENSO behavior, but not any other models. I offer some small suggestions to improve the manuscript.

Thank you for the assessment and valuable feedback. We address your specific comments below.

Major Comments

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A few ideas are hinted at throughout the paper, such as intensifying tropical intraseasonal variability (Ln. 111), or the relaxation of the mean SST gradient and trade winds (Ln.130). But these changes are seen in other climate models as well (especially the weakening of the east-west SST gradient), so what makes AWI-CM3 an outlier? Is its high horizontal and vertical resolution important? If so, do we see this increase in other HiResMIP models?

If the authors can discuss possible reasons conventional CMIP6 models do not simulate the response, it would be great. Furthermore, if they can speculate on why this particular model might better reflect reality compared to other CMIP models, that would further improve the impact. But overall it is still a very nice result that is worth being published.

We added an analysis of the CMIP6 archive to address this important point (see new Fig. 2 in the revised manuscript and also our response to reviewer #1). We find while models show a large range of possible projections, a few models show qualitatively similar behaviour of future projected ENSO regularity and amplitude changes to AWI-CM3.

We conjecture that multiple criteria likely need to be fulfilled for a model to exhibit a similar ENSO regime shift:

(i) relatively weak biases in the climate mean state and its variability (new Supplementary Figs. 11 and 12)

(ii) relatively weak biases in ENSO's interaction with other climate modes. We showed in the supplementary material of Zhao et al. (2024) using the XRO framework that CMIP models tend to have large biases in these interaction terms.

See the following new additions to the results (including a new "assessment of model fidelity" section) summarizing these points (changes marked in *italics*):

L65-70:

While models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) show a wide range of possible future ENSO regularity and amplitude projections, a few models show qualitatively similar behaviour to AWI-CM3. If this peculiar ENSO dynamical scenario were to materialize in the future, it could lead to both increased ENSO predictability, due to greater regularity, and, at the same time, to warming-amplified "whiplash impacts" [28] on regional climates.

L92-106:

Assessment of model fidelity

"Next, using sample entropy (SampEn; see Methods) of Niño3.4 SST anomalies as a metric for ENSO regularity together with the Niño3.4 SST anomaly standard deviation (SD), we show that a 1950 control simulation of AWI-CM3 TCo319 exhibits both ENSO regularity (Fig. 2a) and ENSO amplitude (Fig. 2b) similar to the observations and that the increase of both metrics in the AWI-CM3 TCo319 future projections cannot be explained by internal variability. Furthermore, analysis of the CMIP6 model archive demonstrates that while there is a wide range of possible changes in future ENSO regularity (Fig. 2c) and amplitude (Fig. 2d), 55% of CMIP6 models show an increase in ENSO regularity (Fig. 2c) and 82% an increase in ENSO SST anomaly amplitude (Fig. 2d) by the second half of this century under the SSP5-8.5 scenario. In addition, a few models (i.e., E3SM-1-1, EC-Earth3, and EC-Earth3-Veg) show similar increased ENSO

regularity and amplitude as AWI-CM3 TCo319 (Fig. 2c,d, Supplementary Fig. 1). We emphasize that we do not expect strong inter-model agreement of ENSO projections across the CMIP6 archive given that considerable biases of climate mean states and ENSO dynamics result in different ENSO regimes across models [8,24]."

We emphasize that more work is needed to investigate inter-model differences that are beyond the scope of this paper. We added the following statement in the discussion section:

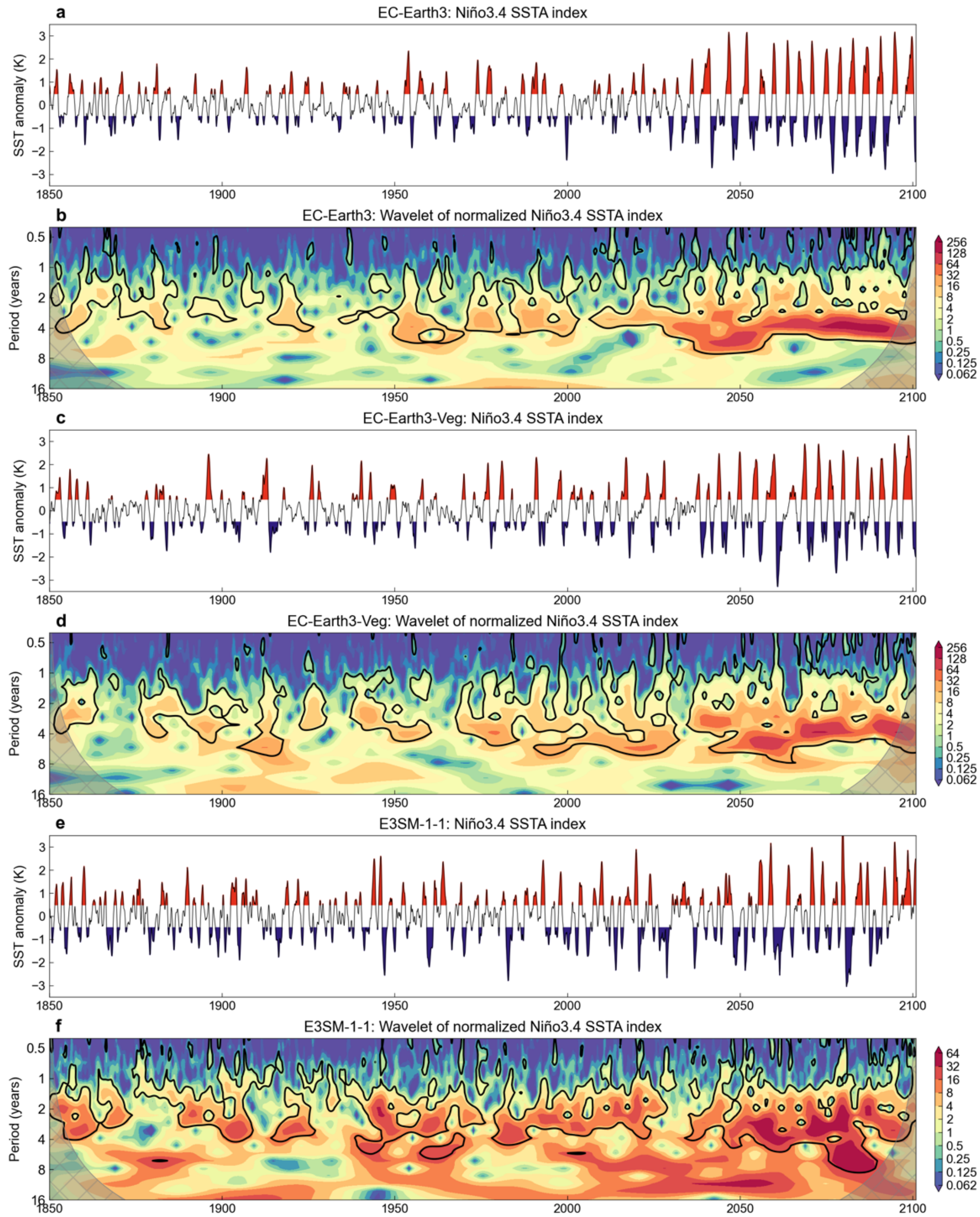
L272-274:

While similar increases in ENSO regularity and amplitude can be found in some CMIP6 model projections (Fig. 2), future work needs to assess the detailed dynamics across these models and assess the likelihood of the ENSO regime changes seen in AWI-CM3.

Minor Comments

Ln. 52-53. It could be interesting to show Fig 1B for some selected CMIP6 models for comparison, to demonstrate that this behavior of this model is unique.

Following your suggestion, we have selected the few models that show a qualitatively similar behaviour (new Supplementary Fig. 1). Most of the models do not exhibit this behaviour (see Fig. R1 in response to reviewer #1).



Supplementary Fig. 1| Increased ENSO regularity in selected CMIP6 models. a Time evolution of the ENSO Nino3.4 SSTA index [K] for EC-Earth3 (3-month running-mean applied). **b** Wavelets of the normalized Nino3.4 SSTA index for EC-Earth3. Black contours enclose regions above 90% confidence level significance tested against a Lorentzian spectrum. **c,d** and **e,f** Same as **a,b** but for EC-Earth3-Veg and E3SM-1-1, respectively.

Ln. 123 It’s not obvious to me that ZA is very significant, it looks like it averages about zero over the annual cycle.

Thank you for catching this. We revised the text accordingly.

Ln. 174. I'm confused why, if the range of phase differences narrows, the standard deviation of the PDFs trends upwards (blue curve)? Intuitively, I would expect the standard deviation to become smaller.

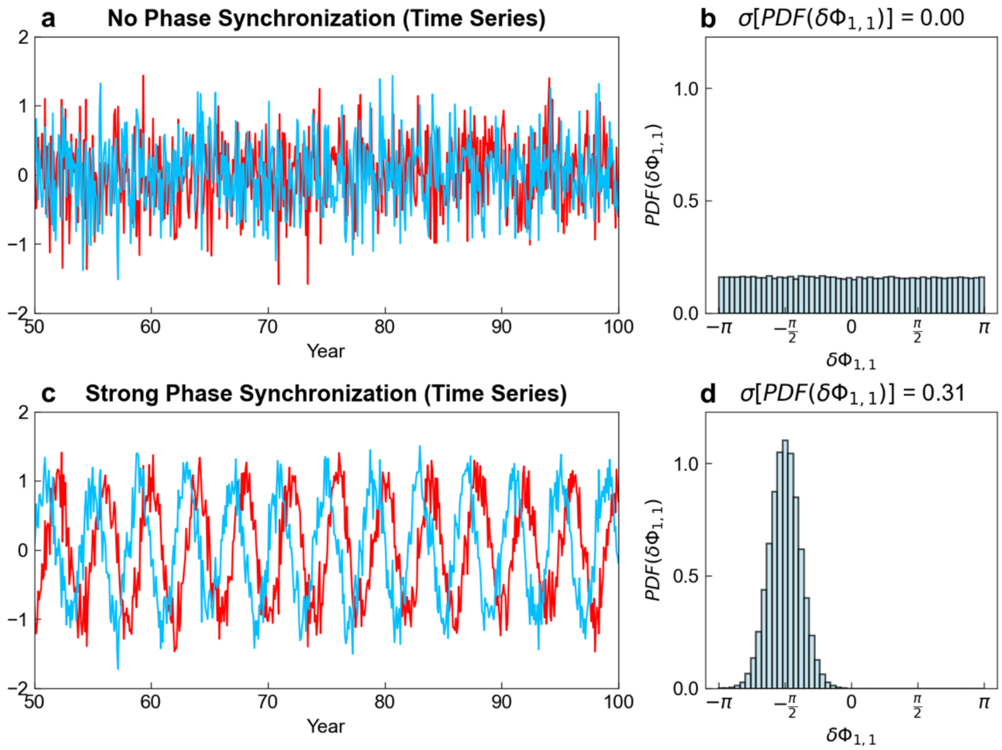
We apologize for the unclear description. We revised the methods and main text to clarify this point (L552-561; note that the previous version of the manuscript incorrectly stated 2:1 instead of 1:1 phase synchronization, which has been corrected in the revised version). In addition, we added a new supplementary figure (Supplementary Fig. 8) to illustrate the phase synchronization metric.

L184-186:

A bounded phase difference indicates stronger phase-coupling between the climate modes under consideration (Supplementary Fig. 8). Here we focus on 1:1 phase synchronization, meaning that the oscillators maintain a (near-)constant phase difference.

L552-561:

We use this approach to calculate the 1:1 difference of unwrapped phases between timeseries characterizing different climate modes simulated by the AWI-CM3 model. All timeseries were bandpass filtered between 2.5-months and 10-years using a Butterworth filter prior to the analysis to focus on annual to interannual variability and to satisfy Bedrosian's theorem. We use the standard deviation of the phase difference PDF, $\sigma[PDF(\delta\Phi_{1,1})]$*, as a measure of the synchronization strength. If there is no synchronization, the phase differences are uniformly distributed, yielding a flat PDF and* $\sigma[PDF(\delta\Phi_{1,1})]) \approx 0$ *(Supplementary Fig. 8a,b). In contrast, if there is strong synchronization, the phase differences concentrate around a preferred value (*$-\pi/2$ *for the example shown in Supplementary Fig. 8c,d), producing a sharply peaked PDF, resulting in a larger* $\sigma[PDF(\delta\Phi_{1,1})]$ *(Supplementary Fig. 8c,d).*



Supplementary Fig. 8| Illustration of phase synchronization analysis. a,b No phase synchronization case: Two independent white-noise time series (**a**) and the probability density function (PDF) of their phase difference (**b**). **c,d** Strong phase synchronization case: two idealized 4-year cosine time series with small white-noise perturbation (**c**) and the PDF of their phase difference (**d**). In **b** and **d**, the synchronization strength defined by the standard deviation of the phase difference PDF (σ[PDF($\delta\Phi_{1,1}$)]).

Fig.4: The features on the figure are very small. Perhaps three rows and two columns will allow each sub-panel to be larger.

Revised as suggested. Thanks for the helpful suggestion.

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Point-by-point response to the reviewers

We have included a point-by-point response to the comments below (Reviewer comments are in black font, our responses in blue font).

Reviewer #1 (Remarks to the Author):

I believe the authors have now addressed all my comments. The paper is significantly stronger, and deserves to be accepted for publication in Nature Communications.

We sincerely thank you for the positive assessment and supportive recommendation.

Reviewer #3 (Remarks to the Author):

I am satisfied with the authors' careful reply to my comments and consider the paper ready for publication. Congratulations on an excellent paper.

Thank you again for the constructive comments throughout the review process.

Reviewer #3 (Remarks on code availability):

Currently, the Github links to the code do not work.

The code is now publicly available, and the links along with permanent DOIs have been updated in the revised manuscript.

Global climate mode resonance due to rapidly intensifying El Niño Southern Oscillation by Malte F. Stuecker et al.

The authors present a well-written, timely study on future ENSO intensification and global synchronization under greenhouse warming, using a high-resolution climate model. The abstract clearly communicates key findings, especially the shift to a highly regular, high-amplitude ENSO regime and its impacts on other climate modes. This addresses an important unresolved question, and the proposed mechanism linking air-sea feedbacks, atmospheric noise, and teleconnection synchronization is compelling. I recommend the manuscript for publication, provided the authors address some important points.

- A major limitation is the reliance on a single climate model (AWI-CM3) to infer future changes in ENSO amplitude, teleconnection strength, and global hydroclimate impacts. Given well-known inter-model differences in ENSO characteristics, the lack of multi-model comparison raises concerns about the robustness and generalizability of results.
- Additionally, the study lacks validation of modeled trends against observational or reanalysis data. Without benchmarking AWI-CM3's current ENSO behavior and atmospheric responses, confidence in future projections is reduced. Incorporating multi-model analyses and observational validation would greatly enhance credibility and applicability.
- The suggestion that future ENSO will become more regular, intense, and predictable—synchronizing other major climate modes like the North Atlantic Oscillation and Indian Ocean Dipole—is speculative. ENSO predictability as well as teleconnections exhibit substantial variability influenced by internal dynamics and background state changes. Assuming a more regular ENSO leads to improved predictability or consistent control over other modes oversimplifies the complex climate system. Without supporting observational or multi-model evidence, this conclusion should be framed more cautiously, clearly distinguishing model results from real-world implications. The authors may consider referencing relevant literature on ENSO predictability for discussion or introduction.

  https://www.nature.com/articles/s41612-024-00845-5