The Impact of Anthropogenic Forcing on ENSO Amplitude

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Key Points:

- NCAR's CESM Large Ensemble predicts increase to Niño 3.4 variance over the 21^{st} century.
- Increase can mainly be attributed to greenhouse gas and aerosol emissions.
- Changes to ENSO amplitude are linked to changes to equatorial Pacific ocean stratification.

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Abstract

The El Niño/Southern Oscillation (ENSO) is the dominant mode of interannual climate variability, with substantial associated global socio-economic impacts. Due to their significance, shifts in ENSO under climate change also have the potential to substantial impact human society and natural ecosystems. However, it is currently unclear what effect greenhouse gas (GHG) and industrial aerosol (AER) emissions will have on ENSO and even less clear what effect a combination of these factors might have when changing in tandem. This study examines transient changes to ENSO variance under a variety of forcing scenarios using the CESM1 Large and Single-Forcing Ensembles. These multi-member ensembles span the historical record (1920-2005) and much of the 21st C (2006-2080 for GHG/AER). A 2000-year pre-industrial (PI) control simulation is used to account for model drift and 20-year running variance of the Niño 3.4 SST index is used as a proxy for ENSO variance. The ensemble mean and standard error of each ensemble is calculated, while the Probability Density Function (PDF) is computed for the PI control simulation to estimate the statistical significance of simulated changes. We identify significant increases in variance under full-forcing conditions during the historical record and attribute these mainly to changes in GHG, with the potential emergence of AER-driven increases in the decades to come. We calculate the correlation coefficient between ocean temperature in the equatorial Pacific and Niño 3.4 under various forcing conditions and .

Plain Language Summary

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1 Introduction

El Niño is the main mode of interanual climate variability, originating from an interaction between the atmosphere and water movement and temperature in the Pacific ocean (Bjerknes, 1969). The reasons for studying ENSO are clear, as ENSO drastically affects climate patterns worldwide, modulating rainfall and temperature in nearly every continent (Ropelewski & Halpert, 1987). For example, the recent 2015-2016 El Niño event contributed to record-breaking high temperatures and droughts in South America (Jiménez-Muñoz et al., 2016). At the same time, long-term anthropogenic greenhouse gas emissions are causing global temperatures to increase through a greenhouse effect . It remains unclear how greenhouse gasses and other factors will affect ENSO.

External forcing is defined as climate forcing caused by external factors, most notably greenhouse gasses, natural and artificial aerosol emissions, land use changes, and stratospheric ozone changes. Greenhouse gas emissions have a clear impact on the earth's climate, global warming. In contrast, internal variability is defined as changes to the earth's climate originating from natural climatic processes, such as ENSO, Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and others.

Research on the effect of external forcing on ENSO remains inconclusive, as results from similar studies conflict. Nowack et al. (2017) predicted an overall increase in Niño 3.4 standard deviation under a combination of 4xCO_2 and interactive ozone forcing using single-model simulations, showing that greenhouse gasses increase the frequency of extreme ENSO by favoring a more Niño-like in the tropical Pacific, while ozone dampens this effect. In contrast, a few studies have found that ENSO amplitude decreases under global warming in certain coupled models (Kohyama et al., 2018).

However, other studies have failed to find any statistically significant ENSO response to external forcing (Stevenson, 2012). Analysis using NCAR's CESM Large Ensemble shows an ensemble size of at least 15 models is necessary to attribute changes to Niño variance to external forcing and reject the null hypothesis that internal variability is responsible for changes to ENSO (Zheng et al., 2018). A number of modes of internal variability have been shown to modulate ENSO, including the AMO (Levine et al., 2017) and Tropical Pacific Decadal Variability (TPDV) (Zheng et al., 2018). An analysis of the Max Plank Institute's Grand Ensemble as well as NCAR's CESM Large Ensemble suggests that 80% of changes to ENSO amplitude can be attributed to internal variability, but given a large enough ensemble, significant changes due to forcing can be detected (Maher et al., 2018).

In this study, we show that NCAR's CESM predicts significant increase in ENSO amplitude in the 21st century, and that greenhouse gasses and aerosol emissions play important roles in causing this increase. As in previous studies, we examine the role of internal variability in conjunction with forcing. We hypothesize that increased stratification in the future plays a large role in causing this predicted increase.

2 Data

The primary data source for this study is NCAR's Community Earth System Model Large Ensemble and Single Forcing Ensemble (CESM1-LE). The Large Ensemble contains 40 simulations of the CESM1 coupled model, forced with historic radiative forcing from 1920 to 2005 and according to the RCP 8.5 protocol from 2006 to 2100 (Kay et al., 2015). The single forcing ensemble is a collection of sub-ensembles for various climate factors (greenhouse gas, aerosols, biomass burning, land use, ozone). Each simulation is forced by a combination of all factors except for one, allowing the impact of a single factor to be deduced by subtracting the ensemble mean from the fully-forced ensemble mean (Deser et al., 2020). For example, the xghg (greenhouse gas) ensemble is forced by aerosol emissions, biomass burning, land use, and ozone. There is also a preindustrial control simulation, with all radiative forcing fixed at 1850 levels.

3 Methods and Results

We estimate 20th and 21st century ENSO amplitude for each model in the fully-forced, single-forced, and PI control CESM1 ensembles using the variance of the Niño 3.4 region of the Pacific ocean (5N-5S, 170W-120W). We measure variance on 20-year centered sliding windows. We calculate the multi-model mean for each ensemble, as well as the ensemble standard error. The results of this calculation are shown in figure 1.

The fully-forced ensemble exhibits moderate increase in variance, with the other ensembles showing less meaningful changes. In the fully-forced ensemble, the variance of the Niño 3.4 region increases beyond 2 standard errors of the control, increasing until the mid-21st century, and then decreasing gradually. The excluded greenhouse, aerosol, and biomass-burning ensembles also contain a slight increase, which may be statistically insignificant. Although the excluded land use ensemble mean has a strong increase in variance, this result is unlikely to be meaningful due to the xlulc ensemble's low sample size.

The fully-forced ensemble exhibits reduced variance in the mid-late 20th century, below that of the PI control. The most likely explanation for this phenomenon is internal variability. To test the likelihood of this explanation, we test the influence of the Atlantic Multidecadal Oscillation (AMO) and Atlantic Meridional Overturning Current (AMOC) on ENSO in the control simulation. The AMO has been shown to have an influence on ENSO strength and seasonal growth rate (Levine et al., 2017). We filter the control Niño 3.4 variance data according to the strength of the AMO and AMOC, using records of AMO/C strength in the Climate Variability Diognostics Package (CVDP) (Phillips et al., 2014). The Probability Distribution Function of Niño 3.4 variance is estimated for AMO/C $> 1/2\sigma$ and $<$ -1/-2σ using a Kernel Density Estimation. No meaningful dif-

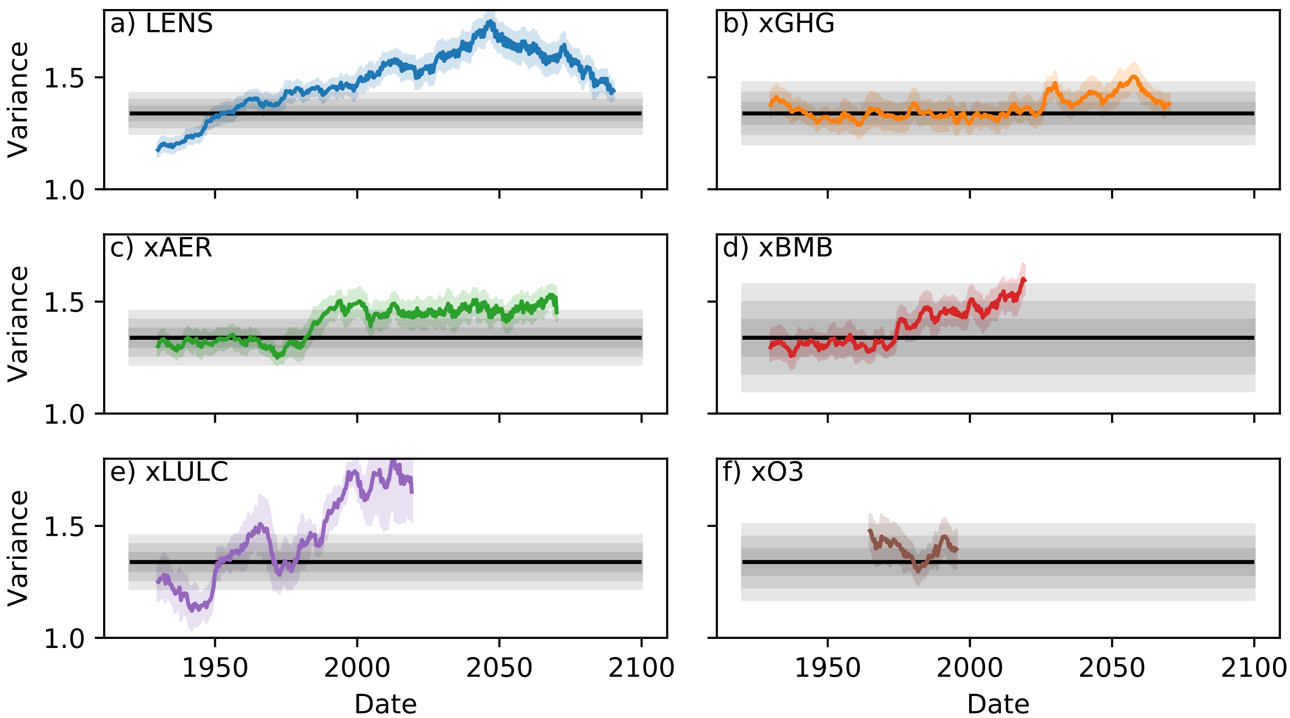

Figure 1. 20-year windowed variance of the Niño 3.4 region SST, for ensembles a) full-forcing, b) xghg, c) xaer, d) xbmb, e) xlulc, f) fixedO3. Grey bars are PI control mean and 1x, 2x, 3x standard error. Colored bars represent ensemble standard error.

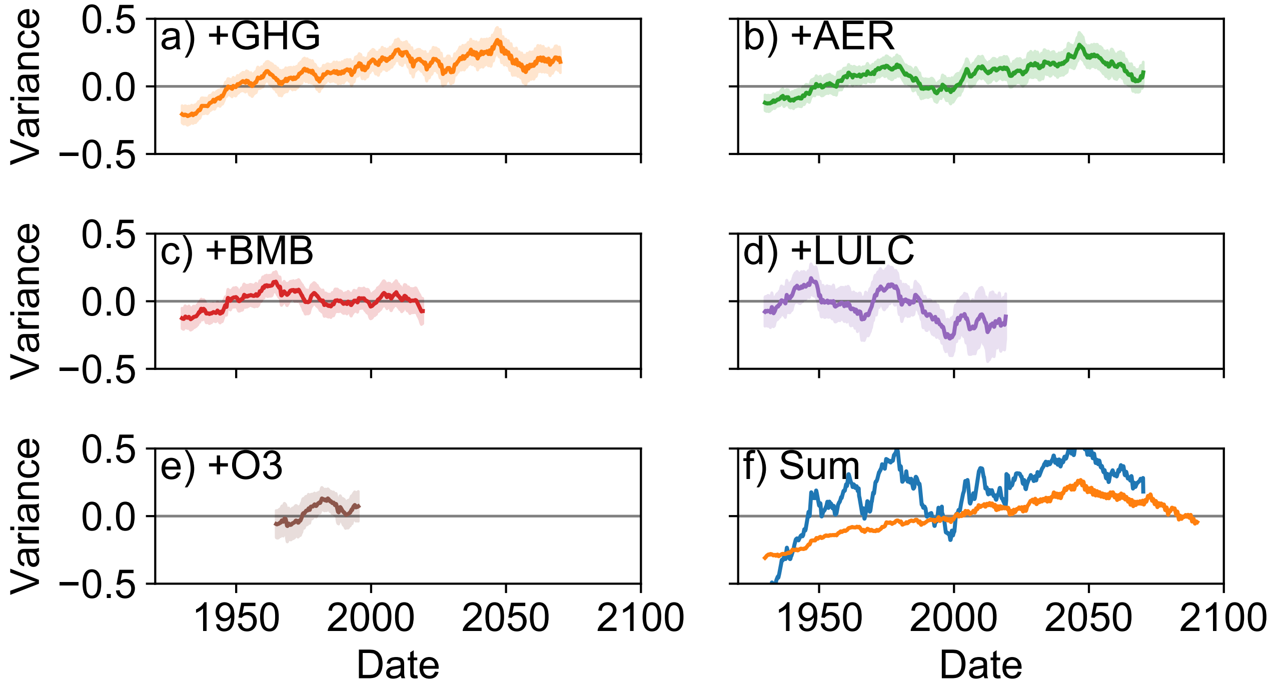

Figure 2. Difference between fully forced and single forced ensembles derived from the bootstrap process for a) greenhouse gas, b) aerosol emissions c) biomass burning, d) land use/cover, e) ozone; f) compares the sum of the bootstrapped ensemble means for the single forcing ensembles (blue) and the ensemble mean for the full forcing ensemble, detrended by a constant to center on zero (orange).

ferences were found in the distribution of ENSO intensity under any of these conditions (See Suplementary information figure 1).

We analyze the role of individual factors using the CESM Single Forcing Ensembles. To separate the influence of a single factor from the fully-forced ensemble, we employ a bootstrap test. For each single-forcing ensemble, a single simulation is randomly selected, and the Niño 3.4 20-year variance record is subtracted from that from a randomly selected fully-forced simulation. We repeat this process 1000 times for each ensemble, and then calculate the mean and standard error for each ensemble. These results are shown in figure 2. The greenhouse-only ensemble as well as the aerosol-only ensemble exhibit increased variance, signaling that greenhouse and aerosol emissions likely both play a significant role in ENSO's forced response in the full-forcing ensemble. Interestingly, the influence of greenhouse gasses and aerosols are non-conflicting, in contrast with previous studies that show opposite effects of greenhouse gas and aerosol forcing on ENSO (Stevenson et al., 2019). All the other single forcing ensembles exhibit insignificant differences from the fully-forced ensemble. The biomass burning case shows very small deviations from the fully-forced case, while the ozone ensemble's period of recording is too small to draw meaningful conclusions. However, Nowack et al. (2017) showed that ozone forcing may dampen the effect of greenhouse-forced increases to ENSO amplitude by reducing changes to Pacific sea temperature and the Walker Circulation. The land use/cover case, while it does show large deviations from the fully-forced case, has an ensemble size (5 members) too small to lend any credibility to these changes.

In both the fully-forced scenario, and the greenhouse and aerosol only simulations, there is noticeably reduced Niño 3.4 variance in the mid-20tĥ century, below 2 standard errors of the control. We hypothesize that this discrepancy may be the result of anomalous initial conditions caused by internal variability of the control, as the control conditions are used to initialize all the forced runs. To test this hypothesis, we analyze the impact of the Atlantic Multidecadal Oscillation (AMO) and the Atlantic Meridional Overturning Current (AMOC) on Niño 3.4 variance in the control simulation using records of the AMO and AMOC from the Climate Variability Diagnostics Package (CVDP) (Phillips et al., 2014). We filter the 20-year variance of the Niño 3.4 sea surface temperature in the control based on the strength of the AMO/AMOC, separating ENSO variance into groups where AMO $<$ -1σ, AMO $<$ -2σ, AMO $>$ 1σ, AMO $>$2σ, and the same for AMOC. We then estimate the probability density function for each group using a kernel density estimator. !!!!!!Suplementary info!!!!! We observe no consistent difference in the distribution of Niño 3.4 variance between any group. So far the question of reduced variance is unanswered, but it is a future goal of this study.

4 Conclusions and Discussion

Acknowledgments

Enter acknowledgments, including your data availability statement, here.

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