El Niño Magnitude in CMIP6 Models

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Abstract

The magnitude of El Niño determines the level of its global impact. Yet, how well our state-of-the-art models simulate this key aspect of El Niño is not well documented. Previous studies tend to ignore ENSO asymmetry and equate the variance of ENSO to the magnitude of El Niño. Moreover, previous evaluations are more focused on the surface manifestation of El Niño. Here, we quantify the magnitudes of El Niño and La Niña separately, both at the surface and subsurface levels. At the surface, we find that while the magnitude of La Niña events in most models is generally stronger than observed, the magnitude of El Niño is more diverse to observations. In fact, in many models, El Niño is weaker than observed. This bias in the magnitude of El Niño is more pronounced in the subsurface. We attribute this weakness in the subsurface to the generally weaker coupling strength and the apparent stronger ENSO at the surface to a lack of sufficiently strong negative feedback from the surface heat flux in the models. When normalized by the variance of ENSO, the lack of exceptionally strong El Niño events in the models is more common and pronounced. The consequences of a generally weaker El Niño in the models are discussed.

Full Text

Preamble

El Niño Magnitude in CMIP6 Models

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Abstract

The magnitude of El Niño determines the level of its global impact, yet how well our state-of-the-art models simulate this key aspect of El Niño is not well documented. Previous studies tend to ignore ENSO asymmetry and equate the variance of ENSO to the magnitude of El Niño, focusing primarily on the surface manifestation of El Niño. Here, we quantify the magnitudes of El Niño and La Niña separately, both at the surface and subsurface levels. At the surface, we find that while most models generally produce stronger La Niña events than observed, the magnitude of El Niño shows greater diversity relative to observations. In fact, many models simulate El Niño as weaker than observed, and this bias is more pronounced in the subsurface. We attribute this subsurface weakness to generally weaker ocean-atmosphere coupling strength, while the apparent strength of ENSO at the surface stems from a lack of sufficiently strong negative feedback from surface heat flux in the models. When normalized by ENSO variance, the absence of exceptionally strong El Niño events in the models becomes even more common and pronounced. The consequences of this systematic underestimation of strong El Niño events are discussed.

Keywords: El Niño; Magnitude; Climate models; Coupling strength; Heat flux

1. Introduction

The El Niño-Southern Oscillation (ENSO) represents the most significant interannual climate fluctuation in the Earth's climate system, alternating between its warm phase (El Niño) and cold phase (La Niña) (Philander 1989; McPhaden et al. 2006). ENSO exerts profound global impacts (Ropelewski and Halpert 1987), with its influence depending strongly on magnitude. For example, extreme El Niño events such as those observed in 1982/1983, 1997/1998, and 2015/2016 have caused major natural hazards—including floods, droughts, and hurricanes (Philander 1983; Changnon 1999; McPhaden et al. 2006; Zhai et al. 2017; Ma et al. 2018)—and have drastically affected ecosystems and agriculture, resulting in considerable economic damage (Valle et al. 1987; Khandekar et al. 2000; Rosenzweig et al. 2001; Kogan and Guo 2017). There is also evidence that these events have significant adverse effects on public health (Anyamba et al. 2019; Anttila-Hughes et al. 2021). In general, the stronger the El Niño event, the greater the impact, ranging from more expansive drought areas over tropical land to increased likelihood of extreme precipitation in California (Lyon and Barnston 2005; Hoell et al. 2016; Jong et al. 2016). Additionally, El Niño strength influences the severity of rainfall-triggered landslides in countries where they cause substantial fatalities, such as India, Indonesia, Colombia, and the Philippines (Hendon 2003; Villafuerte et al. 2015; Emberson et al. 2012). Therefore, understanding and predicting El Niño magnitude is crucial for mitigating its profound environmental and economic impacts.

However, the factors controlling El Niño magnitude remain poorly understood. Although numerous studies have examined El Niño, most focus on explaining the phenomenon itself or its influence on global climate and weather rather than on magnitude (Philander 1990). The earliest exploration of El Niño’ s causes traces back to Bjerknes (1969), who proposed tropical ocean-atmosphere interaction as a possible mechanism. This was later supplemented by Wyrtki (1975), who introduced the theory of trade wind relaxation through observational data analysis, and subsequently linked the El Niño cycle to warm water buildup in the western Pacific (Wyrtki 1985). With the advent of simple and intermediate coupled models in the late 1980s, various theories emerged, including the “delayed oscillator” (Suarez and Schopf 1988), “recharge oscillator” (Jin 1997), “western Pacific oscillator” (Weisberg and Wang 1997), “advective-reflective oscillator” (Picaut et al. 1997), and Sun’ s (1997) diabatic and nonlinear theory, which attributes El Niño to a combined effect of internal nonlinearity and strong radiative heating. These theories improved understanding of El Niño dynamics but focused primarily on why El Niño occurs and how ENSO oscillates (Kessler 2002), rather than what controls its magnitude. While Sun’ s (1997) two-equilibrium states do provide a bound on ENSO amplitude, magnitude itself received limited attention.

The magnitude issue gained prominence with the establishment of CMIP and the climate modeling community’ s interest in evaluating how well coupled general circulation models (GCMs) simulate El Niño (Meehl et al. 2001; Latif et al. 2001; AchutaRao and Sperber 2002; Guilyardi et al. 2004; van Oldenborgh et al. 2005; Guilyardi 2006; Wittenberg 2006). Using models available at that time, including those from IPCC AR4, Guilyardi (2006) noted that ENSO amplitude varied widely across coupled GCMs, with the weakest being about half of observed and the strongest twice as strong, though most models underestimated ENSO amplitude. Later examination of the full CMIP5 and CMIP3 archives showed that the spread in ENSO amplitudes was significantly reduced in CMIP5 relative to CMIP3, though still relatively large (Guilyardi et al. 2012; Bellenger et al. 2014). On average, ENSO amplitude in CMIP5 models was comparable to observations (Zhang and Sun 2014). In the most recent CMIP6 models, Zhao and Sun (2022) found that most models have amplitude comparable to observations, although several models show considerably larger ENSO amplitude than observed.

However, these evaluation studies did not separately assess El Niño and La Niña, instead measuring ENSO level by total variance of an index such as Niño-3 sea surface temperature (SST) anomalies (Guilyardi 2006). This lack of differentiation is problematic because El Niño and La Niña are strongly asymmetric in magnitude, and one cannot equate El Niño magnitude to half of ENSO amplitude (Burgers and Stephenson 1999; An et al. 2005; Zhang and Sun 2014; Zhao and Sun 2022). Studies that do evaluate El Niño separately have focused on simulating its spatial diversity—characterized by so-called EP and CP events (Kao and Yu 2009; Kug et al. 2009)—rather than magnitude (Yu and Kim 2010; Ham and Kug 2012; Kim and Yu 2012; Taschetto et al. 2014; Hou et al. 2022). Here, we focus on El Niño magnitude and address how this fundamental ENSO aspect is simulated in CMIP6 models. In addition to examining El Niño magnitude in the SST field as done previously (Lee et al. 2021; Planton et al. 2021), we also examine subsurface magnitude. Since surface warming is largely driven by subsurface warming (Zebiak and Cane 1988; Jin 1996; Sun 1997), differences between surface and subsurface biases may provide insight into the responsible processes and suggest pathways for model improvement.

This paper is organized as follows. Section 2 introduces data and methods. Section 3 evaluates El Niño magnitude in CMIP6 models, first using surface signatures—SST anomalies (Section 3.1)—then examining subsurface manifestation (Section 3.2). We show that subsurface evaluation yields a different impression from SST analysis: while models show diverse El Niño magnitude at the surface, they almost universally underestimate magnitude at the subsurface. Section 4 investigates possible causes for these biases, particularly the roles of heat flux feedback and coupling strength. Conclusions and discussion are provided in Section 5.

2. Data and Methods

a. Observations

SST data are from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST1, Rayner et al. 2003) for 1950-2014. Upper-ocean temperatures and zonal wind stress are from the Simple Ocean Data Assimilation Version 3.3.1 dataset (SODA v3.3.1, Carton et al. 2018) for 1980-2014. Net heat flux data are derived from the Woods Hole Oceanographic Institution dataset, also known as the OA Flux dataset (Yu and Weller 2007; Yu et al. 2008), covering 1983-2009. For all variables, anomalies are calculated by removing the long-term monthly climatology and linear trend over the entire period.

b. CMIP6 Models

Following previous studies (Zhang and Sun 2014; Zhao and Sun 2022), we select the same models to provide consistent analysis of ENSO simulation. Specific model configurations and affiliations are listed in Table 1 . We use historical runs from 19 CMIP6 models over 1950-2014, including SST, upper-ocean temperatures, zonal wind stress, and heat flux (Eyring et al. 2016). For CESM2, we use member r4i1p1f1; for CNRM-CM6-1, member r1i1p1f2; for HadGEM3 models, member r1i1p1f3; and for all remaining models, member r1i1p1f1. As with observations, we remove the long-term monthly climatology and linear trend when calculating anomalies.

c. Selection of El Niño Events

We follow Trenberth (1997) and use the Niño-3 index, defined as mean SST anomalies in the Niño-3 region (5°N-5°S, 120°E-170°W), to identify El Niño events. An El Niño (La Niña) event is identified when the Niño-3 index exceeds 0.5 times (falls below -0.5 times) the standard deviation for at least six consecutive months. This method has been widely used in El Niño studies (Levine et al. 2016).

TABLE 1. List of models from the CMIP6 analyzed in this study. The first column shows model acronyms, and the second column shows corresponding modeling centers.

Models	Institute
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization
ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organization
CAS-ESM2-0	China Academy of Sciences
CESM2	National Center for Atmospheric Research
CNRM-CM6-1	Centre National des Recherches Meteorologiques
CanESM5	Canadian Centre for Climate Modelling and Analysis
FGOALS-f3-L	Chinese Academy of Sciences
FGOALS-g3	Chinese Academy of Sciences
GFDL-ESM4	National Oceanic and Atmospheric Administration
GISS-E2-1-H	National Aeronautics and Space Administration
HadGEM3-GC31-LL	Met Office Hadley Centre
HadGEM3-GC31-MM	Met Office Hadley Centre
IPSL-CM6A-LR	Institute Pierre Simon Laplace
MIROC6	Model for Interdisciplinary Research on Climate
MPI-ESM1-2-HR	Max Planck Institute for Meteorology
MRI-ESM2-0	Meteorological Research Institute
NESM3	Nanjing University of Information Science and Technology
NorESM2-LM	Norwegian Climate Centre
NorESM2-MM	Norwegian Climate Centre

3. Results

a. ENSO Magnitude at the Surface

Although most models tend to overestimate the overall amplitude of ENSO variability (Fig. 1a [Figure 1: see original paper]), El Niño magnitudes vary considerably across models (Fig. 1b). In contrast, La Niña magnitudes are generally overestimated (Fig. 1c). We measure ENSO amplitude by the standard deviation of interannual variability in Niño-3 SST (Zhao and Sun 2022), and quantify event magnitude by the peak (lowest) Niño-3 index value during El Niño (La Niña) events (Rao and Ren 2014; Meng et al. 2020). The observed ENSO amplitude is 0.81°C, whereas most models show larger amplitude with an ensemble mean of 1.08°C. However, unlike this general overestimation of ENSO amplitude, El Niño magnitudes are diverse across models (Fig. 1b). The observed El Niño magnitude is 1.67°C, while the model ensemble mean is 1.83°C. Some models (e.g., CAS-ESM2-0, CESM2, FGOALS-f3-L, MIROC6, NorESM2-LM, NorESM2-MM) strongly overestimate El Niño magnitude (up to 2.0°C), while nine out of 19 models simulate weaker El Niño than observed. In contrast, La Niña magnitudes are generally overestimated (Fig. 1c), with a model ensemble mean of -1.82°C, clearly stronger than the observed -1.33°C.

The spatial patterns of El Niño SST anomalies reinforce this impression of diverse magnitudes across models (Fig. 2 [Figure 2: see original paper]). Observed peak SST anomalies during El Niño exceed 2.0°C, and most models are comparable with a warm center around 2.0°C. However, models such as CanESM5 and MPI-ESM1-2-HR show significantly weaker warm patterns, while CAS-ESM2-0 and NorESM2-MM display much stronger warming with peak SST anomalies exceeding 4°C. Compared to observations, positive (negative) SST anomalies extend too far west into the western Pacific during El Niño events in the models—a known bias in coupled GCMs from CMIP3 through CMIP5 (Bellenger et al. 2014; Taschetto et al. 2014) that persists in CMIP6 models (Chen et al. 2021; Brown et al. 2020).

Larger Niño-3 SST anomalies during El Niño events in some models result from greater overall ENSO variability, and the normalized magnitudes of El Niño are generally weaker in the models (Fig. 3 [Figure 3: see original paper]). Normalized magnitude is calculated as the magnitude divided by ENSO amplitude. On average, the normalized magnitude of El Niño events is 2.05 SD in observations and 1.72 SD in the ensemble mean. After normalization, all models underestimate El Niño magnitude, though they still generally overestimate La Niña magnitude with some exceptions (CESM2, FGOALS-f3-L, MIROC6, NorESM2-MM). This suggests that extreme El Niño events in observations are more prominent relative to background variability (i.e., ENSO amplitude).

b. ENSO Magnitude in the Subsurface

In contrast to the surface, underestimation of magnitude exists for both El Niño and La Niña events in the subsurface, with greater underestimation for El Niño (Fig. 4 [Figure 4: see original paper]). In the subsurface, the depth of the main thermocline, estimated using the depth of the 20°C isotherm (D20), correlates well with subsurface temperature (Meinen and McPhaden 2000; Kim and Jin 2011). We measure ENSO amplitude by the standard deviation of zonal D20 contrast between the eastern equatorial Pacific (5°S–5°N, 155°W–70°W) and western equatorial Pacific (5°S–5°N, 120°E–155°W), and measure event magnitude by the zonal D20 contrast anomaly when the Niño-3 index reaches its peak (lowest) value during El Niño (La Niña). During El Niño, the zonal D20 contrast anomaly is usually positive, indicating a deepening thermocline in the eastern Pacific and shoaling in the western Pacific, with larger values indicating stronger subsurface El Niño magnitude (the opposite for La Niña).

For subsurface ENSO amplitude, the model ensemble mean is 19.93 m, close to observations (20.68 m), though most models have smaller amplitude than observed. Furthermore, a systematic bias exists in El Niño magnitude, with 17 out of 19 models simulating weaker El Niño than observed (43.82 m). The model ensemble mean El Niño magnitude is only 27.62 m, far weaker than observed. La Niña magnitude is also underestimated; except for MIROC6 (-34.06 m), NorESM2-LM (-41.32 m), and NorESM2-MM (-42.90 m), all models simulate weaker La Niña than observed (-33.51 m). The model ensemble mean (-27.02 m) is also weaker than observed, though the discrepancy is smaller than for El Niño.

Weaker El Niño in the models is also evident in the spatial patterns of equatorial upper-ocean temperature anomalies (Fig. 5 [Figure 5: see original paper]). In observations, positive anomalies in the eastern upper tropical Pacific reach 3.5°C, while negative anomalies in the western upper tropical Pacific fall below -3.0°C. Most models show weaker east-west temperature anomaly contrast than observed. For example, MPI-ESM2-1-HR, which simulates the weakest El Niño (10.10 m), shows only about 1°C warming (cooling) in the eastern (western) upper tropical Pacific.

As expected, after normalization, El Niño magnitudes in the models are smaller than observed in the subsurface (Fig. 6a [Figure 6: see original paper]), consistent with surface results (Fig. 3a). Moreover, La Niña is also weaker in the models in the subsurface (Fig. 6b). The normalized magnitude of El Niño events averages 2.11 SD in observations but only 1.38 SD in the ensemble mean, significantly lower than observed. All models show weaker normalized El Niño magnitude than observed, suggesting that extreme El Niño events are more prominent relative to background variability not only at the surface but also in the subsurface.

c. Possible Causes for Biases in El Niño Magnitude

Our surface and subsurface analyses reveal that while El Niño magnitudes vary across models at the surface, subsurface results are completely different: models generally underestimate El Niño magnitude. One possible reason is weaker dynamic coupling strength between ocean and atmosphere (Fig. 7 [Figure 7: see original paper]). Coupling strength measures how strongly atmospheric winds respond to SST anomalies (Guilyardi et al. 2006; Kim and Jin 2011; Chen et al. 2021). Figure 7 shows the spatial pattern of regression of zonal wind stress anomalies onto Niño-3 SST anomalies, calculated by regressing zonal wind stress anomalies at each point onto Niño-3 SST anomalies to highlight wind stress sensitivity to Niño-3 SST.

In observations, a significantly positive center (exceeding 0.015 N m^{-2} $°C^{-1}$) appears in the Niño-4 region, indicating that positive (negative) SST anomalies associate with strong zonal westerly (easterly) wind stress anomalies. Based on Sverdrup balance (Sverdrup 1947), zonal westerly (easterly) wind stress anomalies cause anomalous upwelling (downwelling) in the western (eastern) Pacific, deepening (shoaling) the thermocline in the equatorial eastern (western) Pacific (Kim and Jin 2011), leading to strong El Niño (La Niña) magnitude in the subsurface. Most models also simulate westerly (easterly) wind stress anomalies in the Niño-4 region related to positive (negative) Niño-3 SST anomalies, but regression slopes are generally smaller than observed. Only MIROC6 has a center (exceeding 0.015 N m^{-2} $°C^{-1}$) comparable to observations. Since the maximum response of zonal wind stress to Niño-3 SST anomalies occurs mainly in the Niño-4 region in both observations and CMIP6 models, we argue that the regression slope between Niño-3 SST anomalies and zonal wind stress anomalies in the Niño-4 region (Fig. 8 [Figure 8: see original paper]) represents coupling strength between oceanic forcing and atmospheric response, following earlier studies (Yeh et al. 2014). The observed coupling strength is 0.0104 N m^{-2} $°C^{-1}$, while the ensemble mean is 0.0074 N m^{-2} $°C^{-1}$, with model values ranging from 0.0043 to 0.0135 N m^{-2} $°C^{-1}$. Except for MIROC6 (0.0135 N m^{-2} $°C^{-1}$), all models show significantly weaker coupling strength. A positive correlation (R = 0.55) at the 99% confidence level exists between subsurface El Niño magnitude and coupling strength (Fig. 9 [Figure 9: see original paper]), strongly suggesting that underestimation of subsurface El Niño magnitude relates to weaker coupling strength in the models.

Since subsurface warming of El Niño drives surface warming (Sun 1997), weaker subsurface El Niño events should generally produce weaker surface events. Indeed, a significant correlation coefficient (0.85) exists between surface and subsurface El Niño magnitudes (Fig. 10 [Figure 10: see original paper]). However, notably, for a range of subsurface El Niño magnitudes similar to observations, models show stronger surface El Niño. To understand this puzzle, we consider the role of net surface heat flux feedback. This feedback is generally negative: a positive (negative) SST anomaly produces decreased (increased) net heat flux, increasing (decreasing) ocean heat loss and reducing (increasing) the SST anomaly (Lloyd et al. 2009). Figure 11 [Figure 11: see original paper] shows the spatial pattern of regression of net heat flux anomalies onto Niño-3 SST anomalies, calculated by regressing net heat flux anomalies at each point onto Niño-3 SST anomalies to highlight heat flux sensitivity to Niño-3 SST (Kim and Jin 2011; Chen et al. 2021). In observations, strong negative feedback (exceeding -25 W m^{-2} $°C^{-1}$) centers in the Niño-3 region, indicating that positive (negative) SST anomalies associate with strong negative (positive) heat flux anomalies. Most models also simulate negative feedback in the Niño-3 region, but generally weaker than observed, particularly in CanESM5 and NorESM2-LM. Only two models (FGOALS-f3-L and MIROC6) have feedback strength comparable to observations. The regression slope between Niño-3 SST anomalies and net heat flux anomalies in the Niño-3 region measures net heat flux feedback strength (Fig. 12 [Figure 12: see original paper]). The observed net heat flux feedback is -16.38 W m^{-2} $°C^{-1}$, while the ensemble mean is -8.61 W m^{-2} $°C^{-1}$, only half the observed value. Model values range from -0.58 to -15.14 W m^{-2} $°C^{-1}$. Except for CAS-ESM2-0 (-14.86 W m^{-2} $°C^{-1}$), FGOALS-f3-L (-15.14 W m^{-2} $°C^{-1}$), and MIROC6 (-13.32 W m^{-2} $°C^{-1}$), all models show significantly weaker net heat flux feedback. Thus, weaker negative feedback from net surface heat flux into the ocean may partly explain the discrepancy between surface and subsurface bias directions.

A linear relationship (R = -0.56) between Niño-4 coupling strength and Niño-3 net heat flux feedback (Fig. 13 [Figure 13: see original paper]) suggests error compensation between the two—a common problem in current climate models (Lloyd et al. 2009; Bellenger et al. 2014; Bayr et al. 2017). We argue this error compensation is a major contributor to the diversity of surface El Niño magnitudes. Models with stronger surface El Niño fall into two categories: those with strong coupling strength and strong heat flux feedback, and those with weak heat flux feedback and weak coupling strength.

4. Conclusions and Discussion

This study assesses El Niño simulation in state-of-the-art CMIP6 models, focusing on magnitude as captured by both surface and subsurface observations and the 19 models. Previous studies emphasized overall ENSO amplitude (Guilyardi 2006) and often did not evaluate El Niño magnitude separately. Studies that did evaluate El Niño separately focused on spatial diversity rather than magnitude (Yu and Kim 2010; Ham and Kug 2012; Kim and Yu 2012; Taschetto et al. 2014; Hou et al. 2022), and evaluation was typically limited to the surface. By examining El Niño and La Niña events separately and quantifying their magnitudes using both surface and subsurface data, we have uncovered several novel findings.

First, El Niño magnitudes are diverse at the surface, but La Niña biases are more systematic, indicating that ENSO amplitude cannot serve as a surrogate for El Niño magnitude. Second, El Niño events are almost universally weaker in the subsurface, a very different impression from the surface. Additionally, after normalization, El Niño magnitudes are smaller than observed in both the subsurface and at the surface, suggesting that extreme El Niño events are more prominent relative to background variability (i.e., ENSO amplitude). Finally, consistent with earlier studies (Bellenger et al. 2014; Bayr et al. 2018), both coupling strength and net surface flux are weaker in the models. Underestimation of subsurface El Niño magnitude relates to weaker coupling strength, while the lack of strong surface underestimation—particularly compared to the subsurface—mainly results from error compensation between these two factors.

Future work should more extensively examine processes known to affect El Niño strength. In addition to coupling strength and net surface heat flux feedback, we plan to examine thermocline depth and temperature gradients across the thermocline. Addressing these issues could lead to more accurate simulation of ENSO magnitude, enhancing our ability to predict and understand these critical climate phenomena.

Overall, this study addresses whether El Niño events are strong enough in models compared to observations. Due to underestimation of strong El Niño events, particularly in the subsurface, we suspect that oceanic dynamic processes are not fully simulated, requiring more comprehensive dynamic process diagnostics to improve ENSO metrics (Planton et al. 2021). Furthermore, we caution against using these models to study El Niño changes in a warming climate (Kim et al. 2014; Fredriksen et al. 2020; Cai et al. 2021), as predictions of El Niño magnitude will have greater uncertainty in future climate scenarios than in the present climate (Beobide-Arsuaga et al. 2021).

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Data Availability Statement. CMIP6 coupled model data can be downloaded from https://esgf-node.llnl.gov/projects/cmip6/. HadISST data are available at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The SODA dataset is from http://iridl.ldeo.columbia.edu/SOURCES/.CARTON/.SODA3/.SODA3.3.1/. OAFlux data are from https://oaflux.whoi.edu/data-access/.

Author Contribution Statement

De-Zheng Sun: Proposed the research propositions; reviewed manuscript drafts and provided constructive feedback and editorial suggestions.

Ronghui Zhang: Designed the research framework and methodology; conducted literature review, case collection, and organized the overall research process; collected, cleaned, and processed data; performed in-depth analysis; drafted the initial manuscript and finalized revisions and approval of the submitted version.

References

AchutaRao, K., and K. Sperber, 2002: Simulation of the El Niño Southern Oscillation: Results from the Coupled Model Intercomparison Project. *Climate Dyn.*, 19, 191-209, https://doi.org/10.1007/s00382-001-0221-9.

An, S. I., Y. G. Ham, J. S. Kug, F. F. Jin, and I. S. Kang, 2005: El Niño-La Niña asymmetry in the Coupled Model Intercomparison Project Simulations. *J. Climate*, 18, 2617-2627, https://doi.org/10.1175/JCLI3433.1.

Anttila-Hughes, J. K., A. S. Jina, and G. C. McCord, 2021: ENSO impacts child undernutrition in the global tropics. *Nat. Commun.*, 12, 5785, https://doi.org/10.1038/s41467-021-26048-7.

Anyamba, A., and Coauthors, 2019: Global Disease Outbreaks Associated with the 2015-2016 El Niño Event. *Sci. Rep.*, 9, https://doi.org/10.1038/s41598-018-38034-z.

Bayr, T., M. Latif, D. Dommenget, C. Wengel, J. Harlass, and W. Park, 2018:

Mean-state dependence of ENSO atmospheric feedbacks in climate models. *Climate Dyn.*, 50, 3171–3194, https://doi.org/10.1007/s00382-017-3799-2.

Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation in climate models: from CMIP3 to CMIP5. *Climate Dyn.*, 42, 1999–2018, https://doi.org/10.1007/s00382-013-1783-z.

Beobide-Arsuaga, G., T. Bayr, A. Reintges, and M. Latif, 2021: Uncertainty of ENSO-amplitude projections in CMIP5 and CMIP6 models. *Climate Dyn.*, 56, 3875–3888, https://doi.org/10.1007/s00382-021-05673-4.

Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, 97, 163–172, https://doi.org/10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2.

Brown, J. R., and Coauthors, 2020: Comparison of past and future simulations of ENSO in CMIP5/PMIP3 and CMIP6/PMIP4 models. *Climate Past*, 16, 1777–1805, https://doi.org/10.5194/cp-16-1777-2020.

Burgers, G., and D. B. Stephenson, 1999: The "normality" of El Niño. *Geophys. Res. Lett.*, 26, 1027–1030, https://doi.org/https://doi.org/10.1029/1999GL900161.

Cai, W., and Coauthors, 2021: Changing El Niño–Southern Oscillation in a warming climate. *Nat. Rev. Earth Environ.*, 2, 628–644, https://doi.org/10.1038/s43017-021-00199-z.

Carton, J. A., G. A. Chepurin, and L. G. Chen, 2018: SODA3: A New Ocean Climate Reanalysis. *J. Climate*, 31, 6967–6983, https://doi.org/10.1175/JCLI-D-18-0149.1.

Changnon, S. A., 1999: Impacts of 1997–98 El Niño-generated weather in the United States. *Bull. Amer. Meteor. Soc.*, 80, 1819–1827, https://doi.org/10.1175/1520-0477(1999)080<1819:IOENOG>2.0.CO;2.

Chen, H. C., F. F. Jin, S. Zhao, A. T. Wittenberg, and S. C. Xie, 2021: ENSO Dynamics in the E3SM-1-0, CESM2, and GFDL-CM4 Climate Models. *J. Climate*, 34, 9365–9384, https://doi.org/10.1175/JCLI-D-21-0355.1.

Emberson, R., D. Kirschbaum, and T. Stanley, 2021: Global connections between El Niño and landslide impacts. *Nat. Commun.*, 12, https://doi.org/10.1038/s41467-021-23830-8.

Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016.

Fredriksen, H.-B., J. Berner, A. C. Subramanian, and A. Capotondi, 2020: How Does El Niño–Southern Oscillation Change Under Global Warming —A First Look at CMIP6. *Geophys. Res. Lett.*, 47, e2020GL090640, https://doi.org/https://doi.org/10.1029/2020GL090640.

Guilyardi, E., 2006: El Niño–mean state–seasonal cycle interactions in a multi-model ensemble. *Climate Dyn.*, 26, 329–348, https://doi.org/10.1007/s00382-005-0084-6.

—–, and Coauthors, 2004: Representing El Niño in coupled ocean-atmosphere GCMs: The dominant role of the atmospheric component. *J. Climate*, 17, 4623-4629, https://doi.org/10.1175/JCLI-3260.1.

—–, A. Wittenberg, A. Fedorov, M. Collins, C. Wang, A. Capotondi, G. J. van Oldenborgh, and T. Stockdale, 2009: Understanding El Niño in Ocean–Atmosphere General Circulation Models: Progress and Challenges. *Bull. Amer. Meteor. Soc.*, 90, 325–340, https://doi.org/https://doi.org/10.1175/2008BAMS2387.1.

Ham, Y.-G., and J.-S. Kug, 2012: How well do current climate models simulate two types of El Niño? *Climate Dyn.*, 39, 383–398, https://doi.org/10.1007/s00382-011-1157-9.

Hendon, H. H., 2003: Indonesian rainfall variability: Impacts of ENSO and local air-sea interaction. *J. Climate*, 16, 1775–1790, https://doi.org/10.1175/1520-0442(2003)016<1775:IRVIOE>2.0.CO;2.

Hoell, A., and Coauthors, 2016: Does El Niño intensity matter for California precipitation? *Geophys. Res. Lett.*, 43, 819–825, https://doi.org/10.1002/2015GL067102.

Hou, M. Y., and Y. M. Tang, 2022: Recent progress in simulating two types of ENSO—from CMIP5 to CMIP6. *Front. Mar. Sci.*, 9, https://doi.org/10.3389/fmars.2022.986780.

Hua, L. J., D. Z. Sun, and Y. Q. Yu, 2019: Why do we have El Niño: quantifying a diabatic and nonlinear perspective using observations. *Climate Dyn.*, 52, 6705-6717, https://doi.org/10.1007/s00382-018-4541-4.

Jin, F. F., 1996: Tropical ocean-atmosphere interaction, the Pacific cold tongue, and the El Niño Southern Oscillation. *Science*, 274, 76–78, https://doi.org/10.1126/science.274.5284.76.

—–, 1997: An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.*, 54, 811–829, https://doi.org/10.1175/1520-0469(1997)054<0811:AEORPF>2.0.CO;2.

Jong, B. T., M. F. Ting, and R. Seager, 2016: El Niño’ s impact on California precipitation: seasonality, regionality, and El Niño intensity. *Environ. Res. Lett.*, 11, https://doi.org/10.1088/1748-9326/11/5/054021.

Kao, H.-Y., and J.-Y. Yu, 2009: Contrasting Eastern-Pacific and Central-Pacific Types of ENSO. *J. Climate*, 22, 615–632, https://doi.org/https://doi.org/10.1175/2008JCLI2309.1.

Kessler, W. S., 2002: Is ENSO a cycle or a series of events? *Geophys. Res. Lett.*, 29, https://doi.org/10.1029/2002GL015924.

Khandekar, M. L., T. S. Murty, D. Scott, and W. Baird, 2000: The 1997 El Niño, Indonesian forest fires and the Malaysian smoke problem: A deadly combination of natural and man-made hazard. *Nat. Hazards*, 21, 131-144, https://doi.org/10.1023/A:1008141003518.

Kim, S. T., and F. F. Jin, 2011: An ENSO stability analysis. Part I: results from a hybrid coupled model. *Climate Dyn.*, 36, 1593-1607, https://doi.org/10.1007/s00382-010-0796-0.

—–, and J. Y. Yu, 2012: The two types of ENSO in CMIP5 models. *Geophys. Res. Lett.*, 39, https://doi.org/10.1029/2012GL052006.

—–, W. Cai, F.-F. Jin, A. Santoso, L. Wu, E. Guilyardi, and S.-I. An, 2014: Response of El Niño sea surface temperature variability to greenhouse warming. *Nat. Climate Change*, 4, 786-790, https://doi.org/10.1038/nclimate2326.

Kogan, F., and W. Guo, 2017: Strong 2015-2016 El Niño and implication to global ecosystems from space data. *Int. J. Remote Sens.*, 38, 161-178, https://doi.org/10.1080/01431161.2016.1259679.

Kug, J.-S., F.-F. Jin, and S.-I. An, 2009: Two Types of El Niño Events: Cold Tongue El Niño and Warm Pool El Niño. *J. Climate*, 22, 1499-1515, https://doi.org/https://doi.org/10.1175/2008JCLI2624.1.

Latif, M., and Coauthors, 2001: ENSIP: the El Niño simulation intercomparison project. *Climate Dyn.*, 18, 255-276, https://doi.org/10.1007/s003820100174.

Lee, J., Y. Y. Planton, P. J. Gleckler, K. R. Sperber, E. Guilyardi, A. T. Wittenberg, M. J. McPhaden, and G. Pallotta, 2021: Robust Evaluation of ENSO in Climate Models: How Many Ensemble Members Are Needed? *Geophys. Res. Lett.*, 48, e2021GL095041, https://doi.org/https://doi.org/10.1029/2021GL095041.

Levine, A., F. F. Jin, and M. J. McPhaden, 2016: Extreme Noise-Extreme El Niño: How State-Dependent Noise Forcing Creates El Niño-La Niña Asymmetry. *J. Climate*, 29, 5483-5499, https://doi.org/https://doi.org/10.1175/JCLI-D-16-0091.1.

Lloyd, J., E. Guilyardi, H. Weller, and J. Slingo, 2009: The role of atmosphere feedbacks during ENSO in the CMIP3 models. *Atmos. Sci. Lett.*, 10, 170-176, https://doi.org/10.1002/asl.227.

Lyon, B., and A. G. Barnston, 2005: ENSO and the spatial extent of interannual precipitation extremes in tropical land areas. *J. Climate*, 18, 5095-5109, https://doi.org/10.1175/jcli3598.1.

Ma, F., A. Z. Ye, J. J. You, and Q. Y. Duan, 2018: 2015-16 floods and droughts in China, and its response to the strong El Niño. *Sci. Total Environ.*, 627, 1473-1484, https://doi.org/10.1016/j.scitotenv.2018.01.280.

McPhaden, M. J., S. E. Zebiak, and M. H. Glantz, 2006: ENSO as an integrating concept in Earth science. *Science*, 314, 1740-1745, https://doi.org/10.1126/science.1132588.

Meehl, G. A., P. R. Gent, J. M. Arblaster, B. L. Otto-Bliesner, E. C. Brady, and A. Craig, 2001: Factors that affect the amplitude of El Niño in global coupled climate models. *Climate Dyn.*, 17, 515-526, https://doi.org/10.1007/PL00007929.

Meinen, C. S., and M. J. McPhaden, 2000: Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña. *J. Climate*, 13, 3551-3559, https://doi.org/10.1175/1520-0442(2000)013<3551:OOWWVC>2.0.CO;2.

Meng, J., and Coauthors, 2020: Complexity-based approach for El Niño magnitude forecasting before the spring predictability barrier. *Proc. Natl. Acad. Sci. USA.*, 117, 177-183, https://doi.org/10.1073/pnas.1917007117.

Philander, S. G. H., 1983: Meteorology: Anomalous El Niño of 1982-83. *Nature*, 305, 16-16, https://doi.org/10.1038/305016a0.

—–, 1990: *El Niño, La Niña, and the Southern Oscillation.* Academic Press, San Diego, CA, Int. Geophys. Ser., 46, 293 pp., https://doi.org/10.1126/science.248.4957.904.

Picaut, J., F. Masia, and Y. duPenhoat, 1997: An advective-reflective conceptual model for the oscillatory nature of the ENSO. *Science*, 277, 663-666, https://doi.org/10.1126/science.277.5326.663.

Planton, Y. Y., and Coauthors, 2021: Evaluating Climate Models with the CLIVAR 2020 ENSO Metrics Package. *Bull. Amer. Meteor. Soc.*, 102, E193-E217, https://doi.org/10.1175/bams-d-19-0337.1.

Rao, J., and R. Ren, 2014: Statistical Characteristics of ENSO Events in CMIP5 Models. *Atmos. Oceanic Sci. Lett.*, 7, 546-552, https://doi.org/10.3878/AOSL20140055.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, 108, https://doi.org/10.1029/2002JD002670.

Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño Southern Oscillation. *Mon. Wea. Rev.*, 115, 1606-1626, https://doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2.

Suarez, M. J., and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.*, 45, 3283-3287, https://doi.org/10.1175/1520-0469(1988)045<3283:ADAOFE>2.0.CO;2.

Sun, D.-Z., 1997: El Niño: A coupled response to radiative heating? *Geophys. Res. Lett.*, 24, 2031-2034, https://doi.org/https://doi.org/10.1029/97GL01960.

Sverdrup, H. U., 1947: Wind-driven currents in a baroclinic ocean; with application to the equatorial currents of the eastern Pacific. *Proc. Natl. Acad. Sci. USA*, 33, 318-326, https://doi.org/10.1073/pnas.33.11.318.

Taschetto, A. S., A. S. Gupta, N. C. Jourdain, A. Santoso, C. C. Ummenhofer, and M. H. England, 2014: Cold Tongue and Warm Pool ENSO Events in CMIP5: Mean State and Future Projections. *J. Climate*, 27, 2861-2885, https://doi.org/https://doi.org/10.1175/JCLI-D-13-00437.1.

Trenberth, K. E., 1997: The Definition of El Niño. *Bull. Amer. Meteor. Soc.*, 78, 2771-2778, https://doi.org/https://doi.org/10.1175/1520-0477(1997)078<2771:TDOENO>2.0.CO;2.

van Oldenborgh, G. J., S. Y. Philip, and M. Collins, 2005: El Niño in a changing climate: a multi-model study. *Ocean Sci.*, 1, 81-95, https://doi.org/10.5194/os-1-81-2005.

Valle, C. A., F. Cruz, J. B. Cruz, G. Merlen, and M. C. Coulter, 1987: The impact of the 1982-1983 El Niño-Southern Oscillation on seabirds in the Galapagos Islands, Ecuador. *J. Geophys. Res.*, 92, 14,437-14,444, https://doi.org/10.1029/JC092iC13p14437.

Villafuerte, M. Q., J. Matsumoto, and H. Kubota, 2015: Changes in extreme rainfall in the Philippines (1911-2010) linked to global mean temperature and ENSO. *Int. J. Climatol.*, 35, 2033-2044, https://doi.org/10.1002/joc.4105.

Weisberg, R. H., and C. Z. Wang, 1997: A western Pacific oscillator paradigm for the El Niño Southern Oscillation. *Geophys. Res. Lett.*, 24, 779-782, https://doi.org/10.1029/97GL00689.

Wittenberg, A. T., A. Rosati, N. C. Lau, and J. J. Ploshay, 2006: GFDL' s CM2 global coupled climate models. Part III: Tropical Pacific climate and ENSO. *J. Climate*, 19, 698-722, https://doi.org/10.1175/JCLI3631.1.

Wyrtki, K., 1975: El Niño—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, 5, 572-584, https://doi.org/10.1175/1520-0485(1975)005<0572:ENTDRO>2.0.CO;2.

—, 1985: Water displacements in the Pacific and the genesis of El Niño cycles. *J. Geophys. Res.*, 90, 7129-7132, https://doi.org/10.1029/JC090iC04p07129.

Yeh, S. W., Y. G. Ham, and B. P. Kirtman, 2014: A possible explanation on the changes in the spatial structure of ENSO from CMIP3 to CMIP5. *Geophys. Res. Lett.*, 41, 140-145, https://doi.org/10.1002/2013GL058478.

Yu, J.-Y., and S. T. Kim, 2010: Identification of Central-Pacific and Eastern-Pacific types of ENSO in CMIP3 models. *Geophys. Res. Lett.*, 37, L15705, https://doi.org/https://doi.org/10.1029/2010GL044082.

Yu, L. S., and R. A. Weller, 2007: Objectively analyzed air-sea heat fluxes for the global ice-free oceans (1981–2005). *Bull. Amer. Meteor. Soc.*, 88, 527-540, https://doi.org/10.1175/BAMS-88-4-527.

Zebiak, S. E., and M. A. Cane, 1987: A Model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, 115, 2262-2278, https://doi.org/https://doi.org/10.1175/1520-0493(1987)115<2262:AMENO>2.0.CO;2.

Zhai, P., and Coauthors, 2016: The strong El Niño of 2015/16 and its dominant impacts on global and China' s climate. *J. Meteor. Res.*, 30, 283-297, https://doi.org/10.1007/s13351-016-6101-3.

Zhang, T., and D.-Z. Sun, 2014: ENSO Asymmetry in CMIP5 Models. *J. Climate*, 27, 4070-4093, https://doi.org/10.1175/JCLI-D-13-00454.1.

Zhao, Y. D., and D. Z. Sun, 2022: ENSO Asymmetry in CMIP6 Models. *J. Climate*, 35, 5555-5572, https://doi.org/10.1175/JCLI-D-21-0835.1.

Note: Figure translations are in progress. See original paper for figures.