Focus Article

# El Niño and our future climate: where do we stand?

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El Niño and La Niña comprise the dominant mode of tropical climate variability: the El Niño and Southern Oscillation (ENSO) phenomenon. ENSO variations influence climate, ecosystems, and societies around the globe. It is, therefore, of great interest to understand the character of past and future ENSO variations. In this brief review, we explore our current understanding of these issues. The amplitude and character of ENSO have been observed to exhibit substantial variations on timescales of decades to centuries; many of these changes over the past millennium resemble those that arise from internally generated climate variations in an unforced climate model. ENSO activity and characteristics have been found to depend on the state of the tropical Pacific climate system, which is expected to change in the 21st century in response to changes in radiative forcing (including increased greenhouse gases) and internal climate variability. However, the extent and character of the response of ENSO to increased in greenhouse gases are still a topic of considerable research, and given the results published to date, we cannot yet rule out possibilities of an increase, decrease, or no change in ENSO activity arising from increases in $CO_2$. Yet we are fairly confident that ENSO variations will continue to occur and influence global climate in the coming decades and centuries. Changes in continental climate, however, could alter the remote impacts of El Niño and La Niña.  *WIREs Clim Change* 2010 1 260–270

Climatological conditions in the equatorial Pacific[1–3] are characterized by a strong east–west (or zonal) asymmetry (Figure 1(a)), with an equatorially centered region of relatively cool waters in the eastern Pacific (the 'cold tongue') and a broad area of very warm sea surface temperature (SST) in the west (the 'warm pool'). The cold tongue is associated with weak rainfall, while the warm pool has strong rainfall. The surface winds in the equatorial Pacific tend to blow from east to west (easterly winds)—from the dry/high-pressure regions of the east to the wetter/low-pressure west. The equatorial oceanic thermocline (the region of the water column in which temperature varies strongly with depth between the warm near-surface waters and the cold abyssal waters) is shallower in the east than in the west due to the easterly surface winds, which push the warm surface waters westward and draw colder abyssal waters toward the surface in the east. The easterly winds are maintained by the zonal gradient in rainfall and surface pressure, which are in turn maintained by the SST gradient driven largely by the thermocline tilt that makes cool waters available to be upwelled in the east Pacific.[3,4]

An El Niño event is characterized by a warming of the cold tongue, an eastward shift of the warm pool and its rainfall (Figure 1(b)), a reduction of the equatorial easterly winds, and a flattening of the zonal thermocline slope.[1–4] La Niña is roughly the opposite of El Niño: La Niña leads to a stronger than normal zonal asymmetry in SST, rainfall, and the thermocline, and to stronger easterly winds.[2–4]

El Niño events drive changes in weather patterns (Figure 1(c,d)) around the world[3,5] and influence the frequency and intensity of tropical cyclone activity, including a decrease in Atlantic hurricane activity[6] and an eastward shift of western Pacific cyclone activity.[7,8] Changes in climate patterns and oceanic circulation during El Niño also influence terrestrial and marine organisms and ecosystems.[9,10] La Niña events tend to be associated with changes roughly opposite to those during El Niño events.[3]

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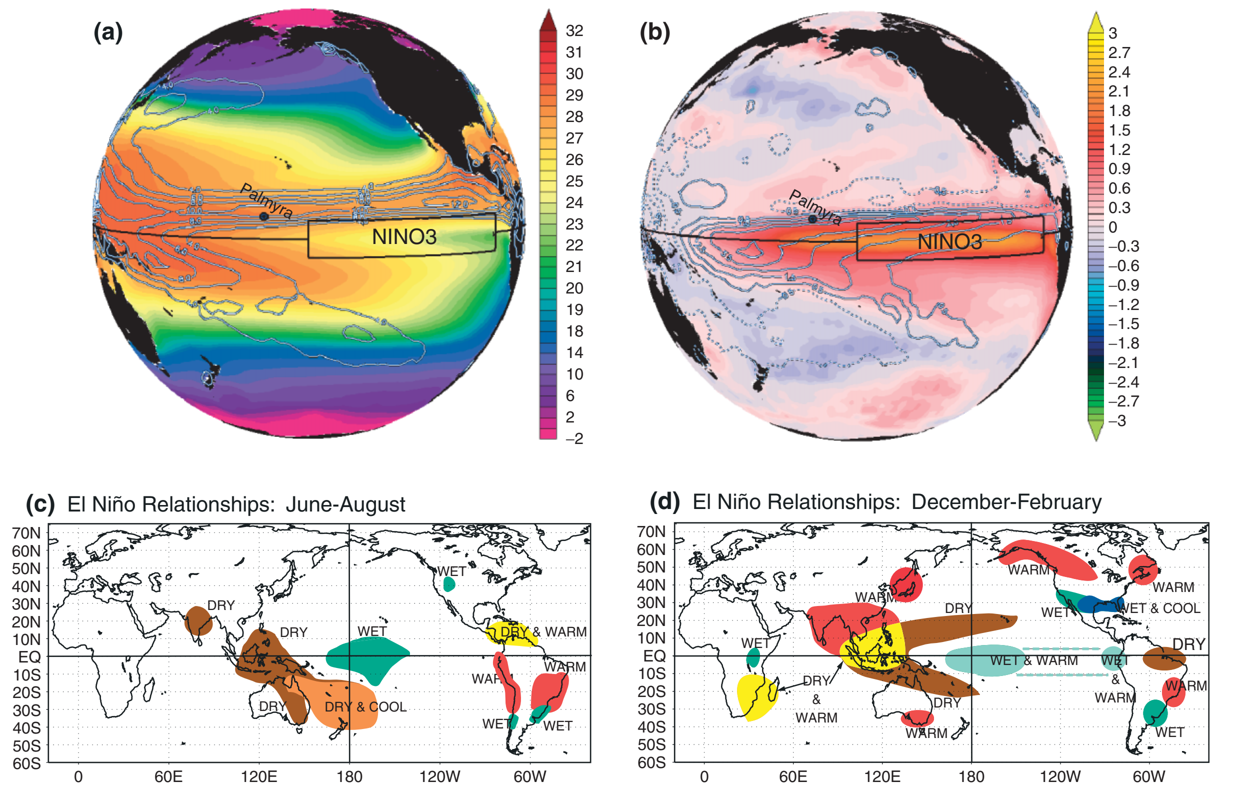


**FIGURE 1** | Tropical Pacific climatology, El Niño, and El Niño impacts. Upper panels show sea surface temperature (SST, shaded) and precipitation (contoured) for (a) the annual average and (b) monthly anomalies averaged June–December for five recent El Niño events (1982, 1987, 1991, 1997, 2002). SST is shown in units of degree Celsius and is computed from Ref 12, precipitation is shown in units of millimeter per day and is computed using the Ref 15 dataset. Dashed contours in (b) indicate regions of reduced rainfall. Also indicated are the NIÑO3 index region (150°W–90°W, 5°S–5°N) and the source location of fossil corals recovered from Palmyra Island (Ref 13 and Figure 2). Lower panels (courtesy of the United States National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center) are schematic representations of the typical climate response to El Niño during (c) austral winter and (d) boreal winter.

## PAST CHANGES IN ENSO

Instrumental records of atmospheric pressure and SST since the late 19th century allow us to explore changes in some aspects of El Niño and the Southern Oscillation (ENSO) over the span of a century.[11,12] For a longer term view, we can turn to noninstrumental ('proxy') records: for example, isotopic and chemical composition of oceanic and lake sediments, deposits from shells of corals and other marine organisms, and tree rings. With these tools, we can explore changes in ENSO for thousands of years into the past[13,14], though less directly than for the more recent instrumental records.

A commonly used index for ENSO variability is the NIÑO3 index, computed by averaging SST anomalies (i.e., departures of SST from normal monthly values) over a large region of the eastern equatorial Pacific (Figure 1) that is both the heart of the equatorial cold tongue and the region where El Niño events typically have their strongest SST variations. Strongly positive NIÑO3 values indicate El Niño events (upper panel of Figure 2). As can be seen from the yellow shading in the background of the instrumental NIÑO3 record, there has been a gradual increase in the availability of *in situ* SST measurements in the NIÑO3 region[10], along with the appearance of satellite-based measurements of SST around 1980 (red bar). Thus, as we can better characterize the state of ENSO today than earlier in the record, our assessment of how ENSO has changed since the late 19th century must be viewed with a level of caution. Nonetheless, these records of NIÑO3 SST indicate that there have been variations in the amplitude and frequency of ENSO—with the decades since the mid-1970s standing out as particularly active, and the 1950s to 1960s standing out as inactive. Accordingly, over the past 50–100 years, ENSO activity has apparently increased.

Isotopic proxy data from coral or other sources increase our view of long-term changes to ENSO.[13,14]

  

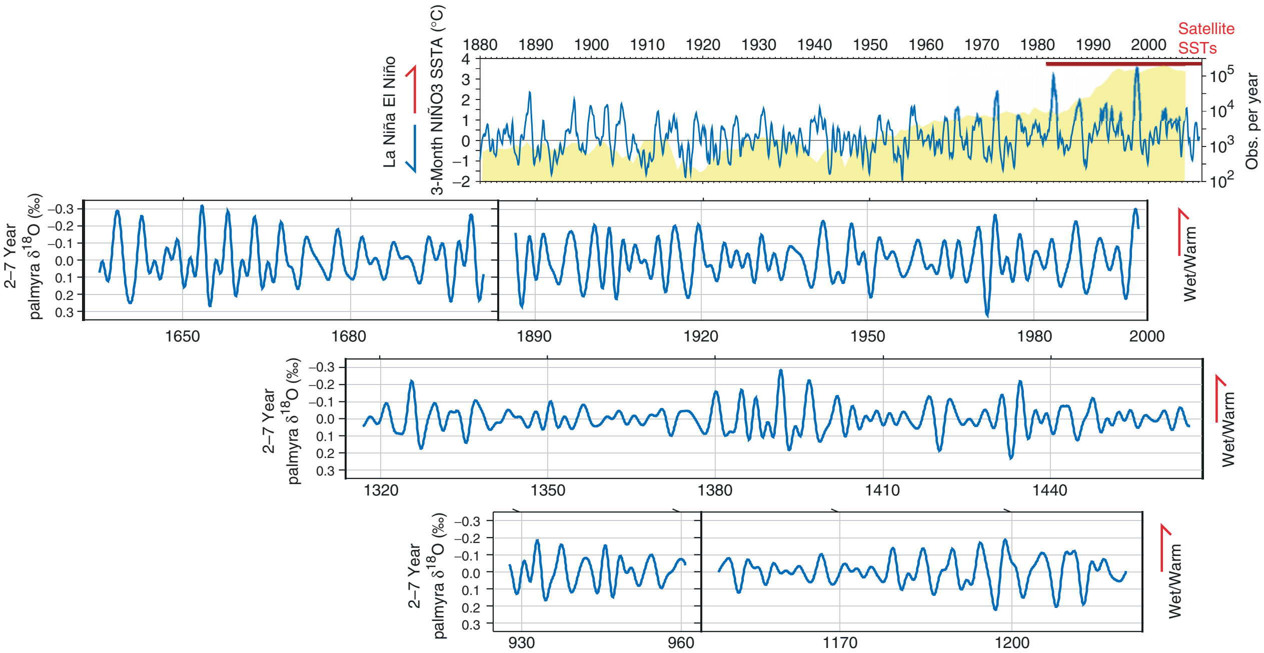


**FIGURE 2** | Instrumental and coral-based records of El Niño/La Niña. Upper time series shows the monthly NIÑO3 sea surface temperature (SST) anomaly index from Ref 12 (blue line, left scale), the logarithm of the number of SST observations per year in the NIÑO3 region based on Ref 11 (yellow shading, right scale), and the era in which satellite estimates of SST are available (red horizontal line). Lower time series show the 2–7-year filtered ratio of Oxygen-18 to Oxygen-16 isotope concentrations from corals taken from Palmyra Island—with positive values indicating warmer, wetter conditions associated with El Niño—after Ref 13. See Figure 1(a,b) for location of Palmyra Island and the NIÑO3 region. (Lower panels are reprinted with permission from Ref 13. Macmillan Publishers Ltd. Copyright 2003).

Interpretation of the proxy data that exist is complicated by the fact that multiple environmental conditions can result in similar isotopic signals, and by the sparseness of the records that have been taken. However, these records provide a rich view of the character of preinstrumental El Niño events—for example, the lower panels in Figure 2 show records from various fossil corals from the Island of Palmyra, which along with other records help to place the variations in the past century in context. We interpret high values of the ratio of Oxygen-18 to Oxygen-16 isotopes in coral shells as indicative of El Niño events in the Pacific—as they indicate either wetter, or warmer, or less biologically productive conditions in Palmyra (Figure 1). It appears that ENSO has exhibited substantial variability over the past millennium, with centuries of strong activity (e.g., the mid-1600s and late-1300s) and others of much weaker activity (e.g., the mid-1100s, mid-1300s, and 1400s). These changes are not connected in an obvious manner to changes in radiative forcing.

On even longer timescales, there are indications that aspects of ENSO have changed in response to changes in the shape of Earth's orbit. Proxy measurements and some climate model simulations suggest that the strength of ENSO had a pronounced minimum around 6000 years ago, apparently in response to changes in orbital forcing.[16–18] There are not many proxy measurements for the character of ENSO during the Last Glacial Maximum (LGM), partly because sea level changes have hidden many of the relevant corals deep in the ocean; a study[19] that examined fossil corals—some as old as 130,000 years—uplifted near New Guinea, found evidence that ENSO variability existed over past glacial cycles. Global climate models[20] indicate that ENSO may have been stronger during the LGM, yet considerable uncertainty still exists in modeling the tropical climate of the LGM.[18,21] Nonetheless, two important messages from the distant past are (1) ENSO can exist even during the very anomalous glacial periods, and (2) its character can respond to changes in radiative (orbital) forcing.

## MECHANISMS FOR CHANGE IN ENSO

The mechanisms behind these observed changes in ENSO on decadal to centennial timescales remain an area of active research and color our expectation of future ENSO activity. The tropical Pacific could generate variations in ENSO frequency and intensity on its own (via chaotic behavior), respond to external radiative forcings (e.g., changes in greenhouse gases, volcanic eruptions, atmospheric aerosols, etc.), or both.

A state-of-the-art global climate model[22,23] (Figure 3) suggests that changes like those over the past millennium (Figure 2) could occur without changes to radiative forcing. The model has a rich spectrum of ENSO variability—there are epochs with almost no variability (e.g., M5); with very strong El Niños five or more years apart (e.g., M7); with milder El Niños 2–3 years apart (e.g., M2); or with a little of everything (e.g., M6). Though the model generally has stronger El Niños than observed, the amplitude in segment M1 is quite similar to observations. The model timescales of El Niño modulation can be long: M3 shows 200 years with very strong El Niños, followed just one century later by 200 years with weak El Niños (M4). If the real world behaves like this model, two questions arise: (1) How long would we need to observe ENSO before we could accurately describe its 'background' state? And (2) if there is a component to ENSO change that arises due to changes in greenhouse gases, will we be able to detect it in the face of this strong unforced component of the variability?

The amplitude, frequency, onset, growth, maintenance, decay, and reemergence of El Niño and La Niña events involve positive and negative feedbacks that depend on the state of the climate system[4–27]. In climate models, the north–south width of the wind changes during ENSO influences the frequency of El Niño.[28] Relative to present day, ENSO tends to weaken as the zonal-mean depth of the equatorial thermocline increases, but strengthen as the zonal thermocline tilt or the near-surface vertical temperature contrast increase.[26,28–33] The sensitivity of winds and clouds to changes in SST influences El Niño amplitude: if winds respond strongly to SST, ENSO tends to be more active; if eastern equatorial Pacific clouds respond strongly to SST, El Niño tends to be less active.[24,31,32] Finally, because El Niño events can be triggered by atmospheric 'noise' (the component of atmospheric wind variability not deterministically predictable beyond a month or so),[31,32] the response of atmospheric noise to climate change could well influence the future sensitivity of ENSO. Research into ENSO sensitivity continues to uncover new influences of the background state, feedbacks, and

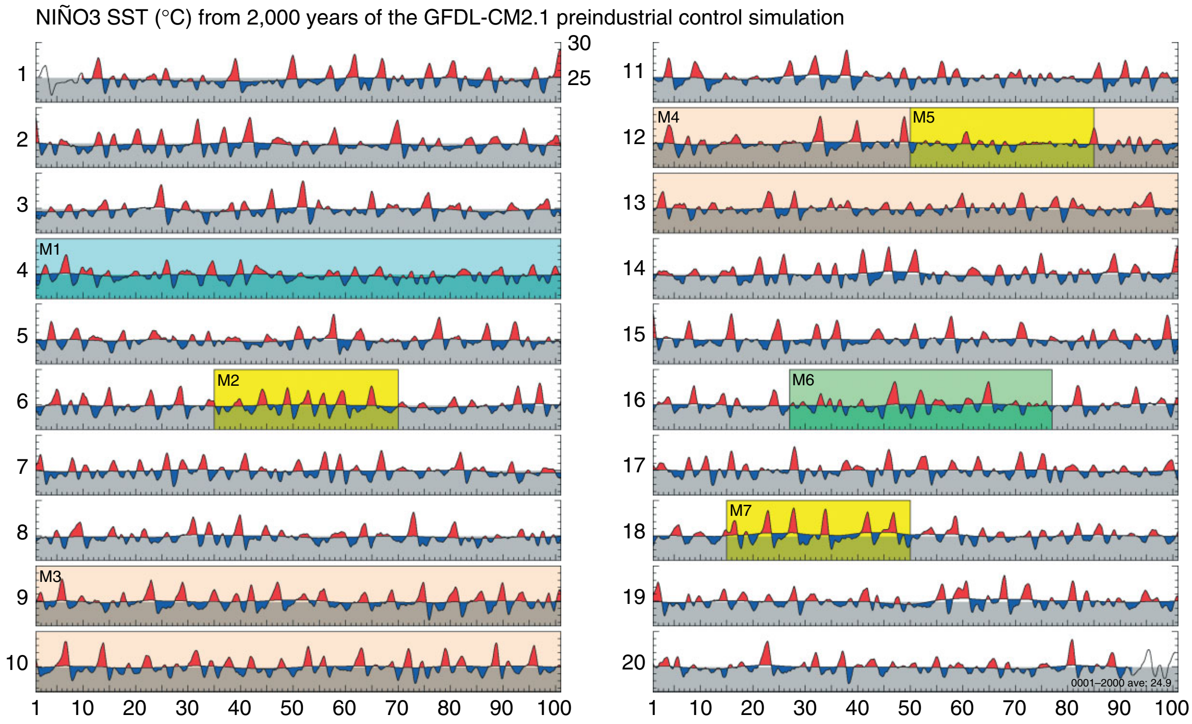


**FIGURE 3** | Simulated decadal and centennial variations in El Niño in the absence of radiative forcing changes. Running annual-mean values of NIÑO3 sea surface temperature (Figure 1) from a 2000-year simulation using a 'state-of-the-art' global climate model with invariant radiative forcing (i.e., no changes in greenhouse gases or insolation, and so on). Red (blue) shading indicates El Niño (La Niña) events. Notice the strong internally generated variations in the character of El Niño on multidecadal and centennial timescales. (Adapted with permission from Ref 22. Copyright 2009).

  

stochastic forcings on ENSO, illustrating the complexity of attributing and predicting changes in ENSO to climate change; often multiple factors can offset each other.

Some analyses of observations and particular climate models[34,35] interpret the increase in El Niño activity over the past 50–100 years as resulting from increased $CO_2$, yet formal 'detection/attribution' studies for the observed changes in ENSO are still lacking. In fact, it is not clear that the change in El Niño activity is 'detectable,' with many studies suggesting that the increase in ENSO activity over the past 50–100 years may be within the range of natural variations.[13,22,36–38] It is currently ambiguous, moreover, to 'attribute' a change in ENSO activity to greenhouse gas increases; as we shall see in the next section, the sign of the sensitivity of ENSO amplitude and frequency to increased greenhouse gases remains highly uncertain.[32,39]

## PROJECTIONS OF THE FUTURE

Global general circulation models (GCMs) are powerful tools to assess how future changes in $CO_2$ and other radiative forcing may influence ENSO. GCMs explicitly represent the interactions that control climate, its variability and sensitivity to forcing through computer representations of the basic laws of fluid dynamics, radiative transfer and thermodynamics—along with parameterizations to represent unresolved processes. The skill of these models has been steadily improving,[39,41] and there are ongoing efforts to understand and improve the representation of ENSO in these models.[42] The physical feedbacks that lead to El Niño can vary between models[42] and may be different from those in observations, so caution must be exercised in interpreting their sensitivity of ENSO to climate change. GCMs' current abilities to represent global climate (including ENSO)—though far from perfect—encourage their use as test beds for the sensitivity of ENSO to projected changes in radiative forcing.

### Changes in the Mean State

In addition to internal variations of the climate system, increases in greenhouse gases are projected to lead to changes in the temperature and precipitation patterns across the globe in the coming decades and centuries (Figure 4). SST warming is projected to be relatively uniform, though the equatorial regions are projected to warm more than subtropical regions.[43] Atmospheric circulation is projected to weaken, resulting from global energy and mass constraints,[44] and this weakening is projected to manifest itself primarily as a reduction of the zonal overturning of air across the tropics—known as the Walker Circulation.[44–46] This reduction of atmospheric circulation, along with other feedbacks, is projected to lead to an eastward expansion of the Pacific warm pool, an increase of central and eastern equatorial Pacific rainfall, and a reduction of the zonal winds across the equatorial Pacific.[44]

Taken together, these changes have been described as 'El Niño-like global warming.'[47–49] However, the usefulness and validity[50] of the phrase 'El Niño-like' may be limited because of the following reasons: the zonal asymmetry in the projected warming across the equatorial Pacific is much smaller than that arising during El Niño,[43,51] the mechanisms for these changes are distinct from those of El Niño,[44–46] there are many changes in the Pacific that do not resemble those of El Niño,[46,50,51] and—most importantly—there are many climate anomalies over land that do not resemble those during El Niño.[52,53] For example, under increased greenhouse gases, the Maritime Continent and Indian Subcontinent are projected to become wetter and southwestern North America drier (Figure 4(b))—all of which are unlike the impacts of El Niño (Figure 1).

There is evidence for a weakening of the Pacific Walker Circulation in observations since the mid-19th century[36,54,55] and since the 1950s.[39] Ocean reanalysis data indicate that both the depth and the zonal tilt of the equatorial Pacific thermocline have reduced since the 1950s,[48] in rough agreement with GCMs. However, it is still unclear that whether the century-scale trend in tropical Pacific SST has been 'El Niño-like' or 'La Niña-like.'[14,46,49,55–57]

### Changes in ENSO Variations

There is no consensus across the current crop of 'state-of-the-art' GCMs as to the sign of the sensitivity of El Niño intensity to greenhouse gas increase.[29,58–61] While current GCMs tend to generally suggest a pattern of change that roughly resembles El Niño in tropical Pacific sea level pressure,[32,46] these same models project anywhere from a −30% decrease to a 30% increase in ENSO variability[32] (Figure 5(a)). Even in a single climate model, the response of El Niño to increasing $CO_2$ can be complex: a study exploring the impact of various levels of atmospheric $CO_2$ found that ENSO activity increased slightly from doubling and quadrupling of $CO_2$, while at an extreme 16× $CO_2$, the activity of ENSO decreased considerably.[61]

  

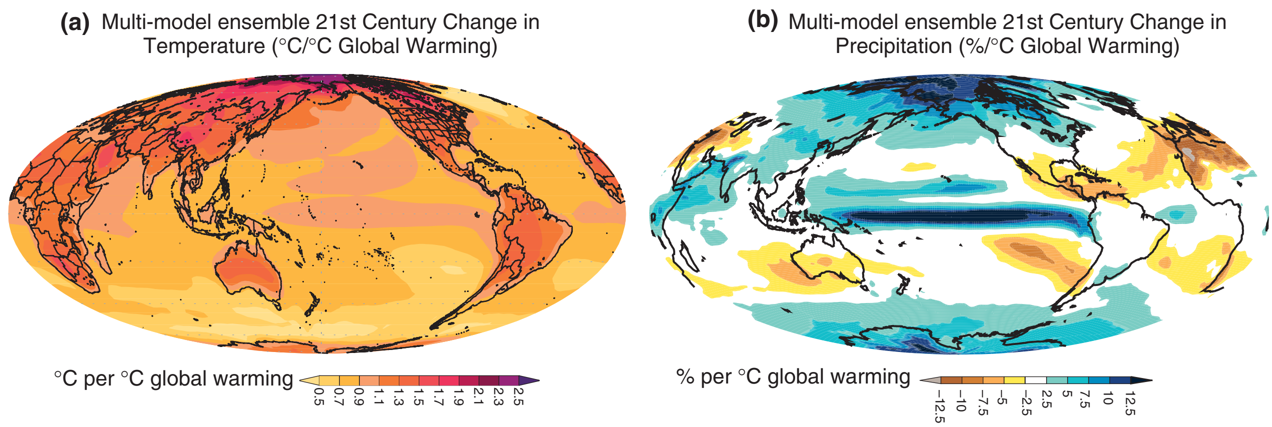


**FIGURE 4** | Twenty-first century projected changes in climatology due to increasing greenhouse gases. Multimodel averages of the (a) change in surface temperature and (b) fractional change in precipitation in the 21st century relative to the late-20th century, using the 21 general circulation models that participated in the CMIP3 intercomparison. In both panels, the changes have been normalized by each model's global-mean surface temperature change prior to averaging across models. (Adapted with permission from Ref 46. Copyright 2007 American Meteorological Society).

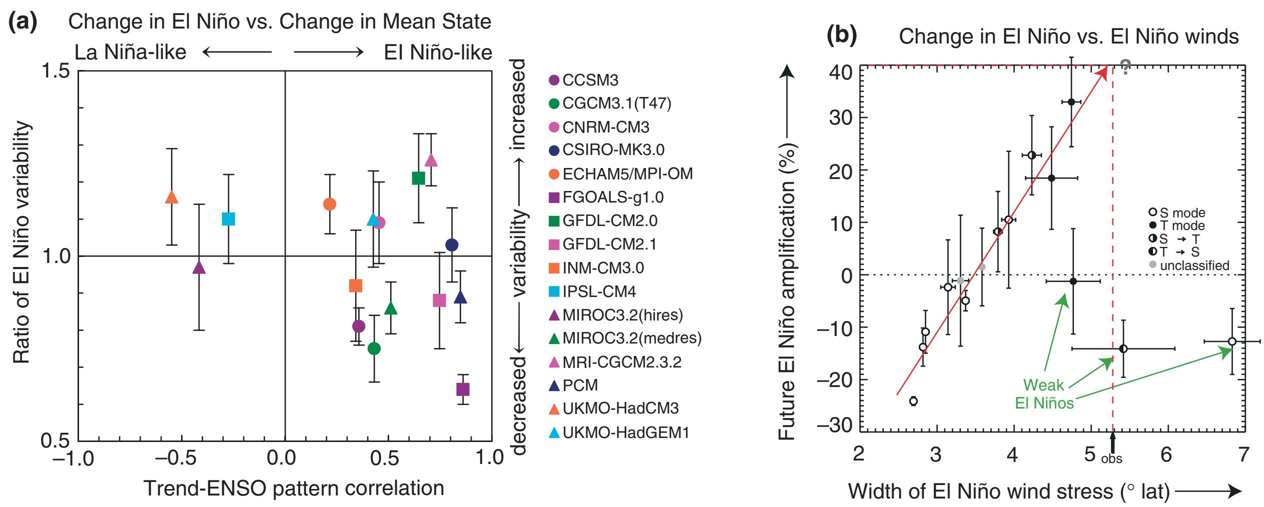


**FIGURE 5** | Twenty-first century projected changes in El Niño characteristics. (a) Multimodel projections of changes in tropical Pacific sea level pressure mean state (horizontal axis) versus change in El Niño sea surface temperature variability (vertical axis); the 'mean state' change in each model is characterized by its similarity to the pattern of El Niño variability. Changes in mean state and El Niño are computed by comparing the end of the 21st century projections with the end of the 20th century from the analysis of Ref 32. (b) Change in El Niño amplitude (vertical axis) versus the meridional (north–south) width of the preindustrial near-equatorial westerly wind anomalies associated with El Niño, in response to increasing levels of atmospheric $CO_2$, from the CMIP3 ensemble of global climate models; different symbols indicate character of model response as characterized in Ref 58. The three models highlighted by green Ref 47 arrows have 20th century El Niño variations that are much weaker than the observed and are considered less reliable. (Left panel adapted with permission from Ref 48. Copyright 2009; Right panel adapted with permission from Ref 60. Copyright 2006 American Meteorological Society).

With increased $CO_2$, current GCMs project both a reduced depth and a reduced zonal tilt of the equatorial Pacific thermocline,[46,51] which have rather opposing impacts on ENSO variability.[26] Because increased greenhouse gases act to warm the ocean from above, GCMs also project increased vertical ocean temperature stratification that should help to amplify ENSO.[4,29,32,46,53,62,63] However, these same GCMs project a reduced atmospheric sensitivity to SST which tends to offset the influence of increased oceanic temperature stratification.[31] Thus, the net effect on ENSO is the result of numerous large and canceling influences, making it a challenge to simulate and resulting in ambiguous projections for El Niño change in climate models.

Some order may yet emerge from this seemingly confused picture: (1) the GCMs with better representation of some aspects of the physics of ENSO tend to show a greater tendency toward increasing intensity[58] (although this connection is not fully understood) and (2) the sensitivity of the response of ENSO to the character of ENSO in these models may suggest a way to extrapolate the model results to that of the real climate system[60] (Figure 5(b)). However, our understanding of the basic physics of ENSO in these models must improve[41] before confidence can be placed on such extrapolation. Based on our current GCM evidence, we cannot yet make confident assessments of even the sign of the change in activity, though we note that all of the models show continued existence of El Nino for the coming century.

## Changes in Impacts of El Niño/La Niña

Of most direct societal significance is the extent to which the climate and ecosystems variations in response to El Niño and La Niña might change in the future. These responses to ENSO could change due to three main mechanisms: (1) changes in ENSO characteristics, (2) changes in the way remote regions respond to ENSO, or (3) through a superposition of large-scale changes which could either reinforce or mask the impacts of El Niño or La Niña events.

The remote impacts of El Niño and La Niña events are influenced by the amplitude of the event in the equatorial Pacific, so if—say—ENSO variability increases in the future, we may expect enhancement to its remote impacts.[64] Furthermore, differences in the location and seasonal timing of the strongest equatorial Pacific SST anomalies during an El Niño event drive different impacts in remote regions[5]; thus, if the dominant character of El Niño changes in the future, to being dominated by fewer or more events that are strongest in the central equatorial Pacific or stronger in a particular season, we may see a change in the remote responses associated with El Niño. Two recent multimodel studies of projected changes in interannual SST variability[65,66] suggest a possible shift to the central Pacific of the strongest SST variability, though the maximum rainfall variability shifts eastward[65] (Figure 6(a)). It may be some time before a confident assessment of the change—if any—can be made.

The changes in the mean state of the tropical Pacific can also impact the character of interannual variability of rainfall in the tropical Pacific, even if the interannual variability of SST does not change considerably.[65] Regions in which rainfall increases (decreases) strongly (Figure 4(b)) show strong increases (decreases) in projected interannual rainfall variability (Figure 6(d)) even though interannual SST variability does not change that much (Figure 6(c)). Also, the character of the atmospheric circulation sets the way the information is transmitted from the tropics to higher latitudes, and one may expect changes in the remote response to ENSO in a warmer climate, even in the absence of changes in the tropical Pacific signature of ENSO.[67]

Finally, because some of the changes in response to increasing greenhouse gases may resemble the climate response to El Niño events, one may expect that the impact of El Niño(La Niña) could appear enhanced (masked) in these regions,[64,68] and vice versa for La Niña-like changes. For example, the drying of southwestern North America typically associated with La Niña events coincides with a projected drying from increased greenhouse gases[46,68]—so that the drying (wetting) associated with La Niña (El Niño) in the future may appear enhanced (muted). Similarly, the projected drying of Australia for the next century (Figure 4(b)) may act to enhance (mask) the signature of El Niño (La Niña), even without changes to ENSO. The projection that Atlantic wind shear may increase in the 21st century[69] could make the suppression of hurricanes during El Niño more prominent in the coming century—although the strong decadal variability impacting wind shear[70] could overwhelm these signals, and because increased $CO_2$ should increase peak hurricane intensities,[71] it is possible that the increased intensities during La Niña events may become more prominent. The key is that ENSO variability will exist in the coming century and will act to temporarily enhance or mask some radiatively forced signals.

# FUTURE SCIENTIFIC FRONTIERS AND CONCLUDING REMARKS

In the near future, refinements to our understanding as well as entirely new horizons are within grasp. Because GCM studies indicate that ENSO characteristics can be influenced by ocean biology,[72–74] as the climate science community uses Earth System Models[73,74] (which include representation of biological and chemical systems in addition to the physical climate system), we can explore the sensitivity of ENSO to changes in biology, as well as the influence of changes in ENSO on the global carbon cycle. An enhanced focus on the climate impact of aerosols (soot, dust, and other particles suspended in the atmosphere that impact the radiative heating of the planet) should lead to better understanding the impact

  

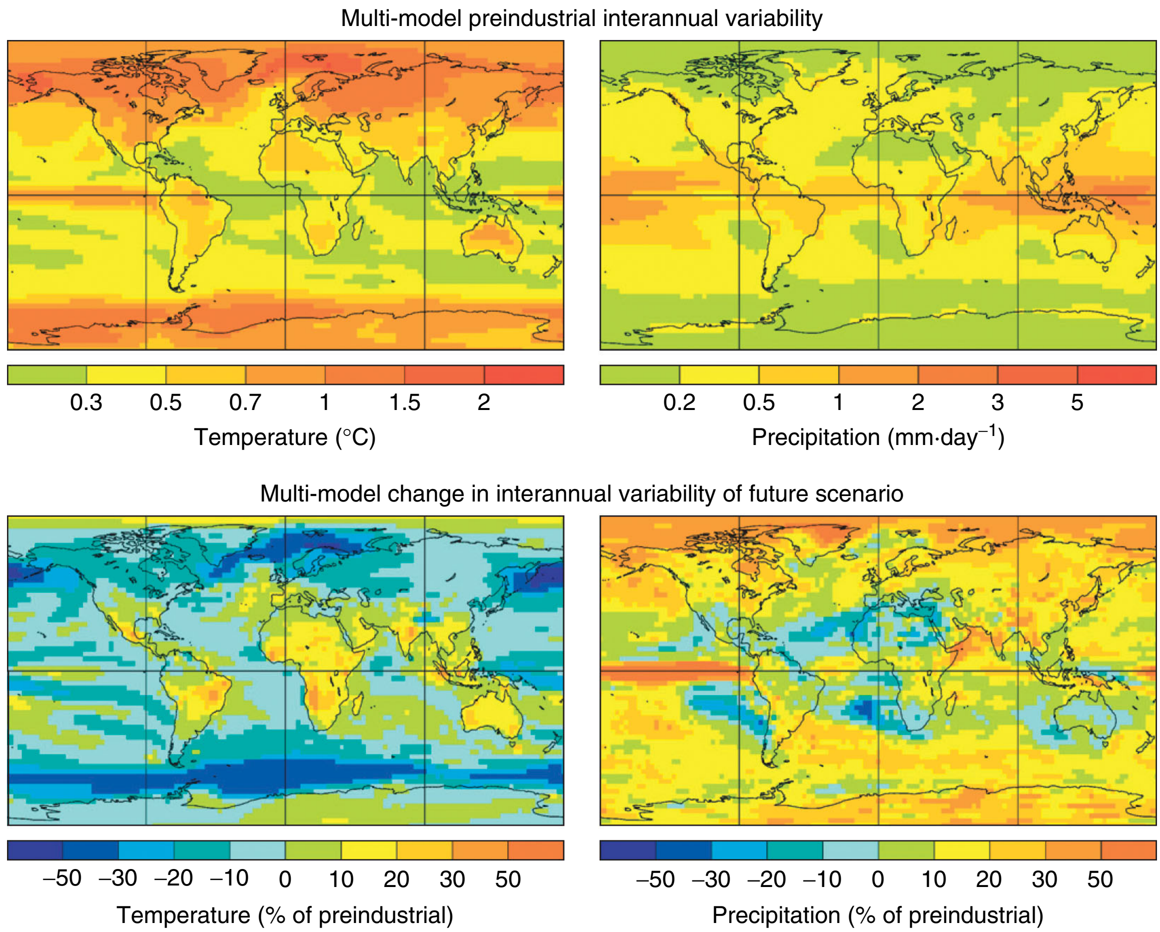


**FIGURE 6** | Multimodel variability of surface temperature and rainfall, and the projected sensitivity of the variability. Top panels show a multimodel estimate of interannual standard deviation of (a) surface temperature and (b) precipitation. Lower panels show the fractional change in interannual standard deviation in (c) surface temperature and (d) precipitation projected from a mid-range emissions scenario after stabilization. In the lower panels, blue colors indicate a reduction in variability, orange and yellow shading indicate an increase in variability. Figure adapted from Ref 65. Notice the strongest increase (reduction) in tropical rainfall variability in panel (d) occurs in regions where the mean rainfall increases (decreases) most strongly (Figure 4(b)). (Reprinted with permission from the American Meteorological Society).

of atmospheric aerosol changes—in addition to those of greenhouse gases—on ENSO. Broad efforts are underway to assess and exploit decadal predictability of the climate system's internal variability using initialized GCMS[75–77]; a key question is the extent to which the decadal modulation of ENSO may be predictable. Generally, as we continue to enhance our observational record (both instrumental and proxy), develop our fundamental understanding of ENSO and the earth's climate, and build better GCMs, we should be in a better position to project changes in ENSO, along with quantitative and comprehensive measures of uncertainty.

The character of ENSO variations has changed in the past, with some of those changes associated with changes in radiative forcing and some possibly due to internal climatic variability. We expect the radiative forcing in the atmosphere to continue changing in the future—due to greenhouse gas increases, atmospheric aerosol changes, and continued solar and volcanic variability. Also, we expect the climate system to keep exhibiting large-scale internal variations. Thus, we expect that the ENSO variations we see in decades to come may be different than those seen in recent decades—yet we are not currently at a state to confidently project what those changes will be.

On the other hand, we are rather confident of three things (1) El Niño and La Niña events will likely continue to occur; (2) El Niño and La Niña events will continue to influence weather and climate away from the tropical Pacific; and (3) there will continue to be variations in the character of El Niño and La Niña events on a variety of timescales. Thus, efforts to adapt to future climate changes must include an explicit understanding of the continued existence, variation, and influence on the global climate system of El Niño and La Niña.

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