Increasing frequency of extreme La Niña events induced by greenhouse warming

Wenju Cai[1,2,], Guojian Wang[1,2], Agus Santoso[3], Michael J. McPhaden[3], Lixin Wu[2], Fei-Fei Jin[5], Axel Timmermann[6] , Mat Collins[7], Gabriel Vecchi[8], Matthieu Lengaigne[9], Matthew H. England[3], Dietmar Dommenget[10], Ken Takahashi[11], Eric Guilyardi[9,12]

1. CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia
2. Physical Oceanography Laboratory, Qingdao Collaborative Innovation Center of Marine Science and Technology, Ocean University of China, Qingdao, China
3. Australian Research Council (ARC) Centre of Excellence for Climate System Science, Level 4 Mathews Building, The University of New South Wales, Sydney 2052, Australia.
4. NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington, USA
5. Department of Meteorology, SOEST, University of Hawaii, Honolulu, Hawaii, USA
6. IPRC, Department of Oceanography, SOEST, University of Hawaii, Honolulu, Hawaii, USA
7. College of Engineering Mathematics and Physical Sciences, Harrison Building, Streatham Campus, University of Exeter, Exeter, UK
8. Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, New Jersey, USA
9. Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN), IRD/UPMC/CNRS/MNHN, Paris, France
10. School of Mathematical Sciences, Monash University, Clayton, VIC, Australia
11. Investigación en Variabilidad y Cambio Climático, Instituto Geofísico del Perú
12. NCAS-Climate, University of Reading, Reading, UK

Wenju Cai: Wenju.Cai@csiro.au
Guojian Wang: *guojian.wang@csiro.au*
Agus Santoso: *a.santoso@unsw.edu.au*
Michael J. McPhaden: *michael.j.mcphaden@noaa.gov*
Lixin Wu: *lxwu@ouc.edu.cn*
Fei-Fei Jin: *jff@hawaii.edu*
Axel Timmermann: *axel@hawaii.edu*
Mat Collins: *M.Collins@exeter.ac.uk*
Gabriel Vecchi: gabriel.a.vecchi@noaa.gov
Matthieu Lengaigne: *Matthieu.Lengaigne@locean-ipsl.upmc.fr*
Matthew England: *m.england@unsw.edu.au*
D. Dommenget *dietmar.dommenget@monash.edu*
Ken Takahashi: *ken.takahashi.igp@gmail.com*
Eric Guilyardi: *Eric.Guilyardi@locean-ipsl.upmc.fr*

The El Niño Southern Oscillation (ENSO) is Earth's most prominent source of interannual climate variability, switching irregularly between the El Niño warm phase and the La Niña cold phase, resulting in global disruption of weather patterns, ecosystems, fisheries, and agriculture (1Ropelewski and Halper 1987; 2Bove et al. 1998; 3Changnon 1999; 4Bell et al. 1999; 5McPhaden et al. 2006). The 1998/99 extreme La Niña that followed the 1997/98 super El Niño event (6McPhaden), switched extreme El Niño-induced severe droughts to devastating floods in western Pacific countries, and El Niño-induced catastrophic floods to severe drought in southwest of US (4Bell et al. 1999; 7Hoerling and Kumar 2003). Although recent discoveries have revealed robust changes in El Niño and its impacts under greenhouse warming (8Cai et al. 2014; 9Power et al. 2013; 10Santoso et al. 2013), the response of La Niña events are yet to be examined. Here we present climate modelling evidence for a near doubling in the frequency of extreme La Niña. About half of the projected increase occurs in the year following an extreme El Niño, thus projecting more frequent climatic swings of opposite extremes from one year to the next, analogous to the 1997-1998 extreme episodes. We estimate these changes by aggregating results from climate models in the Coupled Model Intercomparison Project phases 5 (CMIP5) multi-model databases (11Taylor 2013). During an extreme La Niña, coldest anomalies are situated in the central Pacific (12Dommenget), generating an enhanced east-minus-west anomalous sea surface temperature (SST) gradient along the equator, a commonality shared by an extreme El Niño. We find that this enhanced gradient is supported by a La Niña Modoki (13Ashok et al. 2007), with cold SST anomaly situated in the central equatorial Pacific and warm anomaly in the east. Greenhouse warming strengthens such a gradient in the mean state, thus facilitating increased occurrences of extreme La Niña, as well as extreme El Niño events.

Impact of La Niña in general. During moderate La Niña events, the eastern equatorial Pacific is colder than normal, opposite to that of El Niño events. This inhibits formation of rain-producing clouds there, but enhancing atmospheric convection and rainfall elsewhere, particularly in the equatorial western Pacific. The associated atmospheric circulation changes, such as in 1985 (Fig. 1a), spurred extreme weather in many parts of the world, including droughts in Southwest United States (1Ropelewski and Halper 1987; 14Kiladis and Diaz; 1989) and eastern equatorial Pacific regions, floods in the western Pacific and central American countries (1Ropelewski and Halper 1987; 15Hoyos et al. 2013), and increased land-falling West Pacific cyclones and Atlantic hurricanes (16Wu el al. 2004; 2Bove et al. 1998; 17Gray 1984).

Impacts of extreme La Niña. The SST anomaly patterns, and the associated impacts, however, differ vastly from event to event. The difference in pattern between the moderate La Niña in 1985 and the 1998 extreme event, for instance, is striking (Fig. 1a, b). During the 1998 event, the cold SST anomalies peak notably farther west, in the central equatorial Pacific, generating an east-minus west SST gradient, accompanied by a stronger and meridionally broader western tropical Pacific warm pool (Fig. 1b, Extended Fig. 1). Consequently, the centre of dry anomalies is situated in the western and central Pacific and wet anomalies expand meridionally (Extended Data Fig. 1). The impact of the associated convection changes is global in scale. There was complete disappearance of rainfall across the east-central equatorial Pacific. Southwest US experienced one of the most severe droughts in history (7Hoerling and Kumar 2003; 4Bell et al. 1999; 18Cole 2002). Venezuela endured flash flood and landslide that killed an estimated 25,000 to 50,000 people (19Takahashi et al. 2001). In China, river floods and storms led to the death of thousands, and displacement of over 200 million people (20Jonkman 2005). Bangladesh experienced one of the most destructive flooding events in modern world history, with over 50% of the land flooded, severe food shortage and massive water-borne epidemic diseases, killing several thousand people and affecting over 30 million more (21Kunii et al. 2002; 22del Ninno 2001; 23Mirza, 2001). The 1998 North Atlantic hurricane season was far more active than normal, and saw one of the deadliest and strongest hurricanes (Mitch) in the historical record (4Bell et al. 199); in Honduras and Nicaragua, the associated extreme floods and mudslides claimed more than 11,000 lives (24Kerle et al. 2002).

Transition to Science. The 1998 La Niña event occurred in the year following the 1997 extreme El Niño event – an event considered as the climate event of the 20th Century (3Changnon 1999), followed immediately in 1999 by another extreme La Niña, causing prolonged impacts. Another extreme La Niña occurred earlier in 1988 following the two-year long moderate 1986-88 El Niño, with dire consequences. Recent studies have shown a greenhouse warming-induced increase in extreme El Niño events (8Cai et al. 2014), El Niño with eastward-propagating SST anomalies (10Santoso et al. 2013), or with a drastic swing of the South Pacific Convergence Zone toward the equator (25Cai et al. 2012), but how La Niña events will change in a warming climate has not been systematically examined. The severe impacts described above call for an examination of this issue. Here we show that greenhouse warming leads to a near doubling in the frequency of extreme La Niña.

Characterization of extreme La Niña. The vastly different anomaly pattern between an extreme and moderate La Niña (Figs 1a-b) suggests that ENSO dynamics is nonlinear and its depiction requires more than one index (11Dommenget, 26Takahashi,). Only considering the Niño3 index (SST anomalies over 150^{o}W-90^{o}W, 5^{o}S-5^{o}N) would imply an identical anomaly pattern differing only in the intensity. To capture the nonlinearity, we apply an Empirical Orthogonal Function (EOF) analysis to deconvolve the spatio-temporal SST variability into orthogonal modes, each described by a principal spatial pattern and an associated principal component time series (See Methods Lorenz 1956). We focus on satellite-era observations

(See Methods, Adler, Balmaseda), and austral summer (December to February) when a La Niña peaks.

At their positive phase, the first EOF (Fig. 1c), showing a canonical La Niña pattern, and the second EOF, a La Niña Modoki pattern (13Ashok et al. 2007) (Fig. 1d), are highly correlated with Niño3 (r=0.98) and with an ENSO Modoki index (13Ashok et al. 2007) (r=0.82), respectively. The two time series display a strong "V-shaped" nonlinear relationship (Fig. 1e).

The 1998 extreme La Niña manifested as a strong La Niña Modoki (EOF2) superimposed on a canonical La Niña (EOF1) (Extended Data Fig. 2), such that maximum cold anomalies in the west and central Pacific are accompanied by large and broad positive SST anomalies over the far western Pacific (Fig.1b). In contrast, the 1985 moderate La Niña is the difference between the appropriately weighted EOF1 and EOF2 (Extended Fig. 2), such that the maximum cool anomalies are situated in the eastern equatorial Pacific (Fig. 1b). The 1982/83 and 1997/98 extreme El Niño events manifested as a superimposition of a strong canonical El Niño (EOF1) and a strong La Niña Modoki (EOF2) (Fig. 1e), with warm anomalies in far eastern equatorial Pacific, such that the warmest SST is located in the eastern equatorial Pacific (8Cai).

Thus, the La Niña Modoki equatorial SST gradient emerges as a commonality embedded in both an extreme El Niño and extreme La Niña, which, as we will show, acts as an amplifier to canonical El Niño and La Niña, turning them into extreme events. A La Niña Modoki features cold anomalies in the central Pacific but warm SST anomalies in the eastern Pacific (Fig. 1d). SST and wind anomalies of a canonical La Niña are offset in the eastern but strengthened in the central equatorial Pacific by La Niña Modoki anomalies, giving rise to a cold anomaly that peaks in the western and central Pacific and an ***enhanced east-minus-west***

***SST gradient*,** characterising an extreme La Niña (Fig. 2a). Conversely, warm anomalies of a canonical El Niño are offset in the central Pacific, but strengthened in the eastern Pacific, giving rise to a warm anomaly peaking in the eastern Pacific (Fig. 2b) and an ***enhanced east-minus-west SST gradient**,* the hallmark of an extreme El Niño (8Cai et al. 2014). By contrast, an El Niño Modoki damps a canonical El Niño or La Niña (Fig. 2c, d), and a strong El Niño Modoki tends to occur independently of canonical ENSO events. These features are evidenced by the "V-shaped" nonlinear relationship (Fig. 1e).

This functionality of a La Niña Modoki amplifying a La Niña or El Niño can be directly depicted by an equatorial zonal SST anomaly gradient (Fig. 1f), defined as SST anomalies averaged over the eastern (5^oS-5^oN, 80^oW-90^oW) minus that over the central (5^oS-5^oN, 160^oE-210^oE) equatorial Pacific. This ENSO "Amplifier" index, has a correlation with the SST EOF2 of 0.97 (Fig. 1f): a large positive value corresponding to a strong La Niña Modoki. Under greenhouse warming, this index trends upward due to a faster warming in the eastern than the western equatorial Pacific (27Xie 2010).

We define an extreme La Niña as one for which the amplitude of EOF1 is greater than a one-standard deviation value, and EOF2 greater than a 0.75-standard deviation value. This definition captures the three extreme La Niña austral summers of 1988, 1998, and 1999. Since a La Niña tends to last for more than one year (18Cole 2000), the 1998 and 1999 conditions are counted as one event, as they are both preceded by a discharged equatorial Pacific upper ocean heat content due to the 1997/98 El Niño (28Jin 1997). Indeed, most La Niña events, consecutive or otherwise occur following a discharged heat marked by a shallowing of thermocline depth across the equatorial Pacific. The same EOF definition identifies the two well-known extreme El Niños of 1982/83 and 1997/98.

An identical analysis on observed rainfall anomalies produces two EOFs that are similarly nonlinearly related, and identifies the same extreme El Niño and La Niña events (Extended Data Fig. 3). The first and second rainfall EOFs correspond to the first and second SST EOFs, with a correlation between the two corresponding EOFs at 0.94 and 0.88, respectively Further, the rainfall EOF2 also varies coherently with the Amplifier index, with a correlation of 0.89 (Extended Data Fig. 3f).

Response to greenhouse warming. We select 17 CMIP5 models that are able to simulate nonlinear process associated with extreme ENSO events, identified using rainfall skewness and ability to generate extreme El Niño events (8Cai et al. 2014) (see Methods). These coupled general circulation models (CGCMs) are forced with historical anthropogenic and natural forcings, and future greenhouse gas emission scenarios, covering the 1900-2099 period. The models reproduce the nonlinear relationship between the two EOFs, confirming their ability to simulate extreme El Niño and extreme La Niña events. We define an extreme La Niña event in the same manner as in the observed, and compare the frequency in the first (1900–1999) and second (2000–2099) 100-year periods, referred to as the *Control* and *Climate Change* periods, respectively.

Based on rainfall EOFs, the frequency of extreme La Niña events doubles from about one event every 24 years (70 events in 1,700 years) in the *Control,* to one every 12 years (143 events in 1,700 years) in the *Climate Change* period (Fig. 3a-3d). The increase is statistically significant according to a bootstrap test (Austin), underscored by a strong inter-model consensus (see Methods), with 1 out of 17 models simulating a decrease (Extended Data Tables 1). Sensitivity tests to varying definitions of extreme La Niña (e.g., using different combination of EOF1 and EOF2 value) further support the robustness of this result (Extended Table 1). In terms of extreme El Niño events, our definition consistently produces a 67% increase in occurrences with 12 out of 17 models producing an increase, a reasonably strong inter-model consensus. Thus under greenhouse warming, both extreme La Niña and extreme El Niño increases in frequency. 42% of the increased extreme La Niña events occur in the year following an extreme El Niño event.

Results based on SST EOFs are similar (Fig. 3e-h) (Extended Data Fig. 4), though the increase is smaller, by 53%, with 12 out 17 (70%) models agreeing for extreme La Niña events, compared to an increase of 35% with 11 out of 17 models (65%) agreeing for extreme El Niño events (Extended Data Table 4). About 60% of the increased La Niña events occur in the year following an extreme El Niño event. The smaller increases compared to those based on rainfall EOFs are expected, since under greenhouse warming rainfall anomalies are more sensitive to SST anomalies (29Chung and Power, 8Cai et al. 2014) (Extended Data Fig. 4). In terms of impact most relevant to society, rainfall is a better indicator for ENSO activity (Cai et al. 2014). Thus, the rainfall-based results should be highlighted in the consideration for future projections.

Telconnection. In most regions, differences in extreme La Niña rainfall teleconnection pattern between the *Control* and *Climate Change* period (left column, Extended Data Fig. 5) are not statistically significant, with the exception of some western Pacific regions, e.g., northern Australia (Extended Data Fig. 6), where anomalies are greater in the *Climate Change* period. Given the large increase in frequency, this suggests that in general the impacts of extreme La Niña events experienced in the *Control* period will repeat more frequently in the *Climate Change* period.

Mechanism. The increased frequency of extreme El Niño and extreme La Niña relies on an increase in occurrences of strong Modoki La Niña (EOF2), that is, an increase in events with a strong Amplifier. Time series of Amplifier index (east-minus-west SST gradient) across the models display a strong correlation (r=0.73, with 3400 samples) with SST EOF2 (Fig.

4a). Large values tend to occur with extreme El Niño and La Niña events and are located in the same quadrant. Thus the model SST EOF2 can be represented by the Amplifier index, as in the observations (Fig. 1f). The raw index shows an increase in the frequency of large values (Extended Data Fig. 7a, b), because under greenhouse warming, the equatorial east-minus-west zonal SST gradient intensifies (Fig. 4b), due to a faster warming in the eastern equatorial Pacific than in the west (27Xie et al. 2010). This trend translates into more frequent occurrences of events with a strong Amplifier (Fig. 4c) and with a larger SST and rainfall EOF2, see Extended Data Fig. 7), hence more-frequent extreme La Niña events (Fig. 4c). In other words, as the eastern Pacific mean climate warms faster than the west, it takes a smaller change in SST to generate an equal amount of rainfall or zonal SST gradient associated with extreme La Niña in the *Control* period. There is also a tendency for an increase in the frequency of strong canonical La Niña events that can be amplified into extremes, as evidenced by a spread toward large positive EOF1 values (Fig. 3e, f). For example, events with EOF1 >1.5 increase by 14%. The increase is in part associated with a shallowing trend in the mean thermocline (30Vecchi et al. 2007), which leads to a higher sensitivity of SST to the thermocline anomalies (Extended Data Fig. 8).

In summary, our result of a greenhouse-induced increase in occurrences of extreme La Niña events is consistent with previous findings of an increase in extreme El Niño events because they are both facilitated by the same amplifier, a Modoki-La Niña, embedded in the equatorial east-minus-west SST gradient. Greenhouse warming leads to an increase in the gradient of the mean state, hence more occurrences for a given amplification strength. The overall increased frequency, and the large portion of the increase that occur in the year after an extreme El Niño, means that there will be more occurrences of devastating weather events, and more-frequent swings of opposite extremes from one year to the next, with profound implications for the 21st century.

Methods Summary

The extreme La Niña events were diagnosed using a suite of distinctive process-based indicators, such as the position of maximum equatorial easterly, cold, and low rainfall anomalies, which is situated at the western Pacific during an extreme La Niña, as opposed to the eastern equatorial Pacific during moderate La Niña. For observations, we focus on historical events in the satellite era (1979–present) monthly precipitation analysis SSTs and other circulation fields from a global reanalysis (see Methods). We focus on austral summer, December-February (DJF) in which a La Niña typically peaks. The vastly different anomaly pattern between moderate and extreme La Niña suggests that the traditional index, e.g., Niño3 defined SST anomalies over (150°W-90°W and 5°S-5°N) is not sufficient to differentiate an extreme La Niña from a moderate one. Thus, we propose an identification method for extreme La Niña, in which we apply EOF analysis to rainfall and SST anomalies in the equatorial Pacific Ocean. This produces two principal variability patterns, one depicting a canonical La Niña and the other resembling a La Niña Modoki (13Ashok), display a nonlinear relationship. An extreme La Niña event is defined as when the first principal time series is greater than one standard deviation and the second greater than a 0.75 standard deviation. This definition captures the 1988 and 1998 observed extreme La Niña events. To select CGCMs, we use criteria of positive rainfall skewness in the eastern equatorial Pacific greater 1 and ability to simulate extreme events as in Ref. 8 (8Cai et al. 2014). The method selects 17 CMIP5 CGCMs, each covering 105 years of a pre-21st century climate change simulation using historical anthropogenic and natural forcings (1901-2005) and a further 95 years (2006-2100) under the RCP8.5 forcing scenario (12Taylor2014).

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Author Contributions

W.C. conceived the study and directed the analysis. G. W. performed the model output analysis. W. C. wrote the initial draft of the paper. All authors contributed to interpreting results, discussion of the associated dynamics, and improvement of this paper.

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Figure Legends

Figure 1 | (to be inserted)

Methods

Data, reanalyses, and EOF analysis

We utilised data in the satellite era (1979–present) which include Global Precipitation Climatology Project monthly precipitation analysis (31Adler) http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html, global analyses of SSTs (32Balmaseda), and circulation fields from the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) global reanalysis (33JKalnay). We use a multivariate signal processing method referred to as EOF analysis (34Lorenz) to deconvolve the spatio-temporal variability into orthogonal modes, each described by a principal spatial pattern and an associated principal component time series.

The EOF analysis is applied to both rainfall and SST anomalies, referenced to the mean since 1979 for the observed, and mean the *Control* period for the model outputs with anomalies covering the entire 200-year period. For SST, we use an equatorial domain (15°S-15°N, 140°E-280°E), but for rainfall, an equatorial domain (5°S-5°N, 140°E-280°E) to highlight concentrated convective variability along the equator (Fig. 1b). Model SST anomalies display a distinctive warming trend manifested as the first EOF mode and this is removed first. To facilitate easy discussion, SST EOF1 and EOF2 are actually modes after the trend mode are removed. In contrast, model rainfall anomalies show no such trends. Before used to identify extreme events, all EOF time series are quadratically detrended to ensure no trend is present.

Characterization of extreme La Niña events

The extreme La Niña events were diagnosed using a suite of distinctive process-based indicators, such as anomaly centre of equatorial easterly, cold, and low rainfall anomalies, which is situated at the western Pacific during extreme La Niña, as opposed to the eastern equatorial Pacific during moderate La Niña. The difference in spatial pattern is captured by different combination of two principal variability patterns. The EOF1 reflects a canonical La Niña pattern embedded in the commonly used Niño3 index, featuring cool and dry anomalies extending from the eastern equatorial Pacific to the central Pacific. The EOF2 resembles the La Niña Modoki pattern (13 Ashok), featuring a cool and dry anomalies in the central Pacific but warm and wet anomalies in the eastern equatorial Pacific. An extreme La Niña is an appropriately weighted superimposition of the two patterns, giving rise to anomaly centre in the west Pacific, whereas a moderate La Niña is an appropriately weighted difference between EOF1 and EOF2, leading to warmest anomalies in the eastern equatorial Pacific.

East-minus-west zonal SST gradient along the equator

An important feature of extreme La Niña events is an *enhanced* east-minus-west Pacific SST gradient along the equator, common to an extreme El Niño. This is because during extreme La Niña the cold anomaly centre is located in the central Pacific, where cold anomalies are colder than in the eastern Pacific. During extreme El Niño, warm anomalies are maximum in the eastern equatorial Pacific, generating an *enhanced* east-minus-west Pacific SST gradient along the equator, defined as an equatorial zonal SST anomaly gradient (Fig. 1f), defined as SST anomalies averaged over the eastern (5^{o}S-5^{o}N, 80^{o}W-90^{o}W) minus that over the central (5^{o}S-5^{o}N, 160^{o}E-210^{o}E) equatorial Pacific (Figs 1f, 4a).

Model Selection

We utilise 27 CMIP5 CGCMs (Supplementary Table 1) forced with historical anthropogenic and natural forcings, and future greenhouse gas under emission scenario of Representative Concentration Pathway (RCP) 8.5 (12Taylor), covering a 200-year period. Two features of the nonlinearity used to identify models for extreme El Niño (8Cai) are used to select models. These are the positive skewness of rainfall anomalies and ability to generate rainfall greater than 5 mm day^{-1} over the eastern equatorial Pacific. Although the majority of CGCMs generate ENSO-like variability, only a subgroup of CGCMs simulate the observed nonlinear ocean-atmosphere coupling over the eastern equatorial Pacific as depicted by the positive skewness of SST anomalies over the eastern pole during the austral summer (DJF), which is 2.7 in observations since 1979. The level of nonlinearity varies vastly among CGCMs, and we consider positive skewness of 1 as our threshold. Out of the 31 CGCMs, 17 models satisfy the rainfall skewness criterion. The selected CGCMs yield a mean skewness of 2.52, close to the observed (Extended Data Table 1).

All selected 17 CGCMs reproduce the observed extreme La Niña pattern. The same EOF analysis is carried out for each individual model using rainfall and SST anomalies referenced to the mean over the *Control* period. Prior to the analysis, data are interpolated into a common grid of 1.5 degree latitude by 1.5 degree longitude. Our EOF outputs are scaled so that the EOF time series have a standard deviation of one to facilitate an inter-model comparison and aggregation. All 17 models produce the nonlinear relationship between the two leading EOFs, indicating their ability to generate the nonlinear equatorial positive feedback associated with the extreme La Niña.

We derive changes in the occurrence of extreme La Niña events by comparing the frequency of the first 100 years (*Control* period) to that of the second 100 years (*Climate Change* period). We also test the sensitivity of our results to varying definitions (Extended Data Tables 1). In all cases, there is a statistically significant increase (near doubling) in the occurrences of extreme La Niña events from the *Control* to the *Climate Change* period.

Statistical significance test

We use a bootstrap method (35Austin) to examine whether the change in frequency of the extreme La Niña events is statistically significant. The 1,700 samples from the 17 CMIP5 CGCMs in the *Control* period are re-sampled randomly to construct another 10,000 realisations of 1,700-year records. In the random re-sampling process, any extreme La Niña event is allowed to be selected again. The standard deviation of the extreme La Niña frequency using a rainfall definition in the inter-realisation is 7.7 events per 1,700 years, far smaller than the difference of 73 events per 1,700 years between the *Climate Change* and the *Control* periods (Fig. 3c, d), indicating a strong statistical significance. Using an SST definition, the inter-realisation standard deviation is 8.8 events per 1,700 years, far smaller than the difference of 42 events per 1,700 years between the *Climate Change* and the *Control* periods (Fig. 3c, d), indicating a strong statistical significance. Increasing the realisations to 20,000 or 30,000 yields essentially an identical result.

Methods References

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Extended Data legends

To be inserted.

Figures and Legends

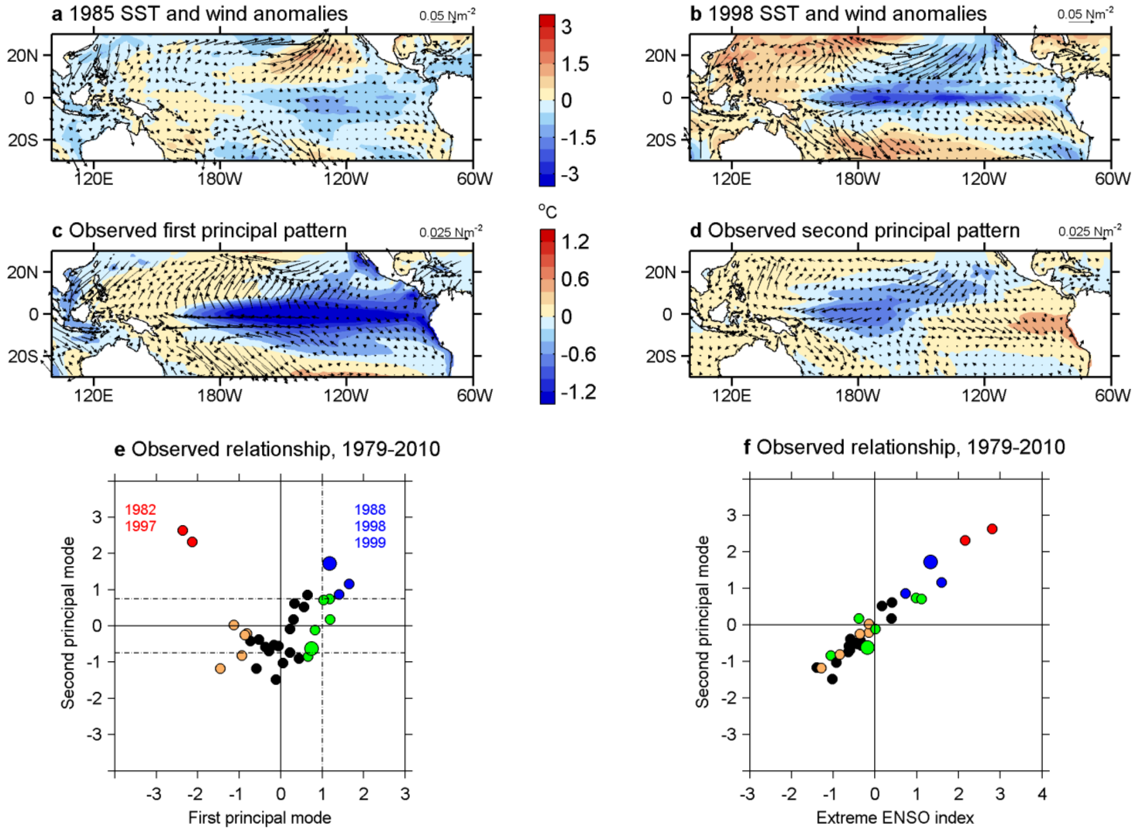

Figure 1 | Comparison of a moderate and extreme La Niña and identification of extreme La Niña events. a, b, December to February (DJF) average SST anomalies (shading, ^{o}C) and wind stress (vectors, scale shown in the top right corner for each panel) anomalies associated with a moderate (1985) and extreme (1998) extreme La Niña. **c, d,** Principal variability patterns of SST obtained by applying EOF analysis to a satellite-era SST anomalies (see Methods), in the equatorial region (15^{o}S-15^{o}N, 140^{o}E-280^{o}E). The associated SST anomalies outside the domain and wind stress vectors from reanalysis data (see Methods) are presented as linear regression onto the EOF time series. **e,** Relationship between the two principal component time series. An extreme La Niña event (**blue** dots, **big blue 1998**) is defined as when the first principal component is greater than 1.0 standard deviation (s.d.), and the second principal component is greater than 0.75 s.d. An extreme El Niño event (**red** dots) is defined as when amplitude of the first principal component is greater than 1.0 standard deviation (s.d.), and the second principal component is greater than 0.75 s.d. **Orange** dots indicate **weak El Niño**, and **green** dots, **weak La Niña (big green, 1985)** defined as when quadratically detrended Niño3 is greater than 0.75 s.d. in amplitude. **f,** Relationship between the second principal component time series and a time series of an equatorial east-minus-west anomalous SST gradient, referred as an Amplifier index, defined as an average over the east (5°S-5°N, 80°W-90°W) minus that over the central Pacific (5°S-5°N, 160°E-210°E).

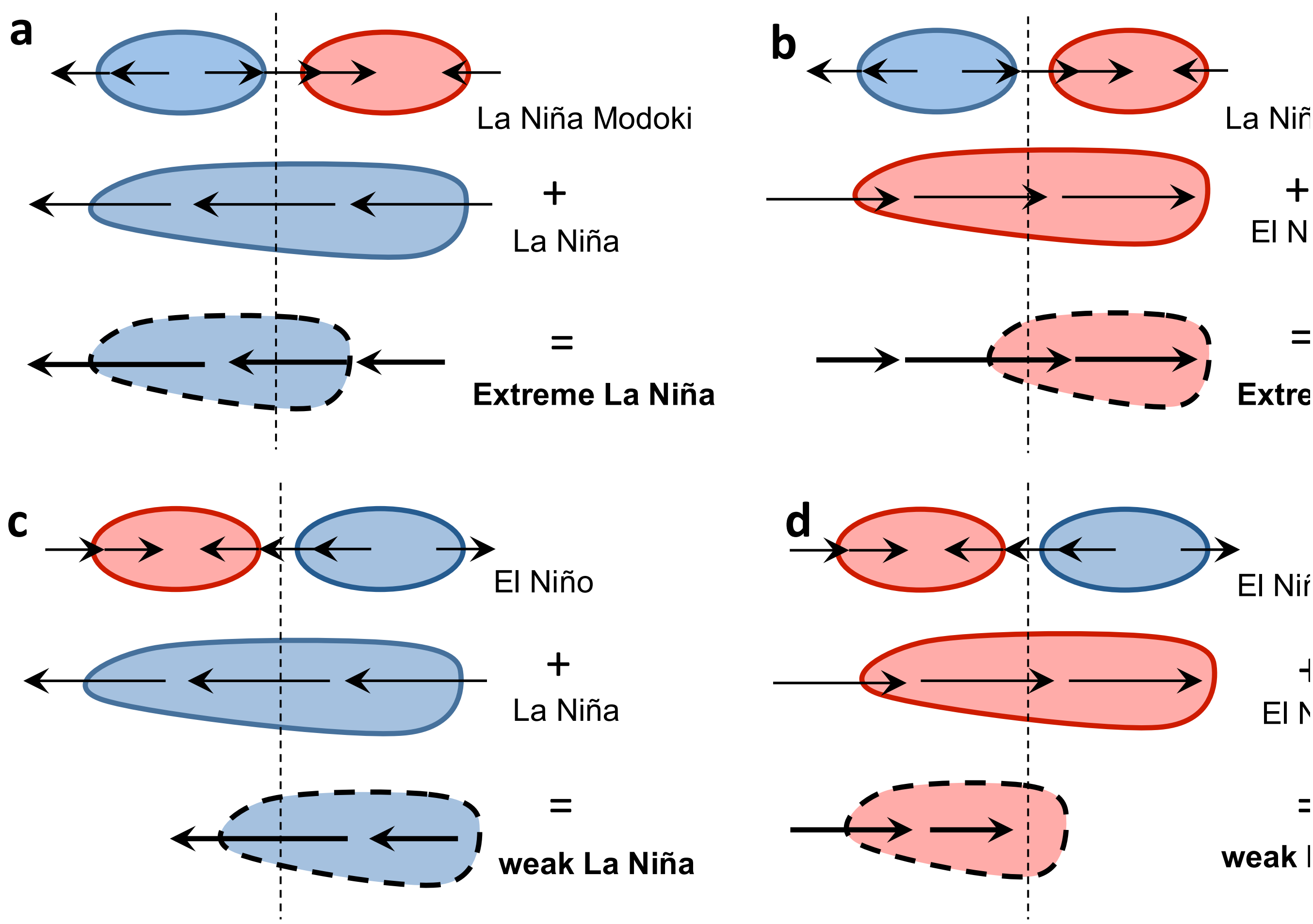

Figure 2 | Schematic diagram of the ENSO Modoki effect on ENSO. The effect can be discerned by superimposing SST and wind anomalies associated with ENSO Modoki onto those of canonical ENSO. **Red** and **blue** patterns correspond with **warm** and **cold** anomalies, respectively, and arrows of different sizes denote anomalous wind anomalies of relative strengths. Superimposing La Niña Modoki SST anomalies onto either canonical La Niña (**a**) or El Niño (**b**) anomalies yield either extreme La Niña events characterized by large cool anomalies in the central Pacific (**a**), or extreme El Niño events characterised by strong SST anomalies in the eastern Pacific (**b**). In contrast, superimposing El Niño Modoki SST anomalies result in either a weak La Niña (**c**) or a weak El Niño (**d**) event.

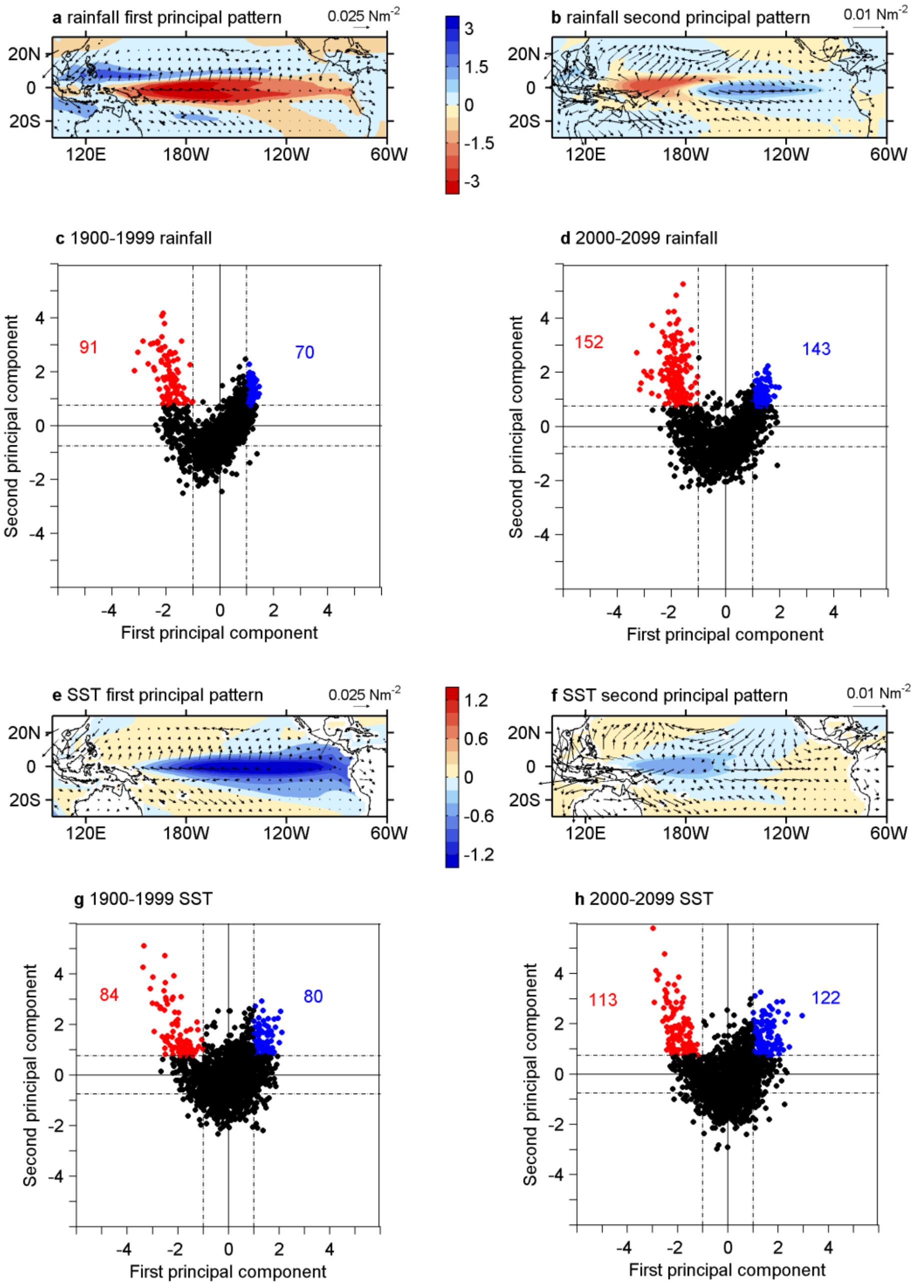

Figure 3 | Multi-model ensemble average of the principal variability patterns of austral summer season and their nonlinear relationship. **a, b,** First and second principal variability patterns of SST anomalies referenced to the *Control* period (1900-1999), obtained by applying an EOF analysis to rainfall anomalies in the equatorial region (5°S-5°N, 140°E-280°E). Note the different vector scales in **a** and **b**. Trends in the associated time series are removed quadratically. The associated pattern and wind stress vectors beyond the domain are obtained by a linear regression onto the detrended principal component. Colour scale indicates SST in °C per one s.d. change; blue or red contours indicate cold or warm rainfall. **c, d,** A nonlinear relationship between the first and second principal component for the *Control* (1900-1999) and *Climate Change* (2000-2099) periods. An extreme La Niña event (**red** dots) is defined as when the first principal component is greater than 1 and when the second principal component is greater than 0.75 s.d.. An extreme El Niño event (**red** dots) is defined as when amplitude of the first principal component is greater than 1, and when the second principal component is greater than 0.75 s.d.. Number of extreme El Niño and La Niña years is indicated.

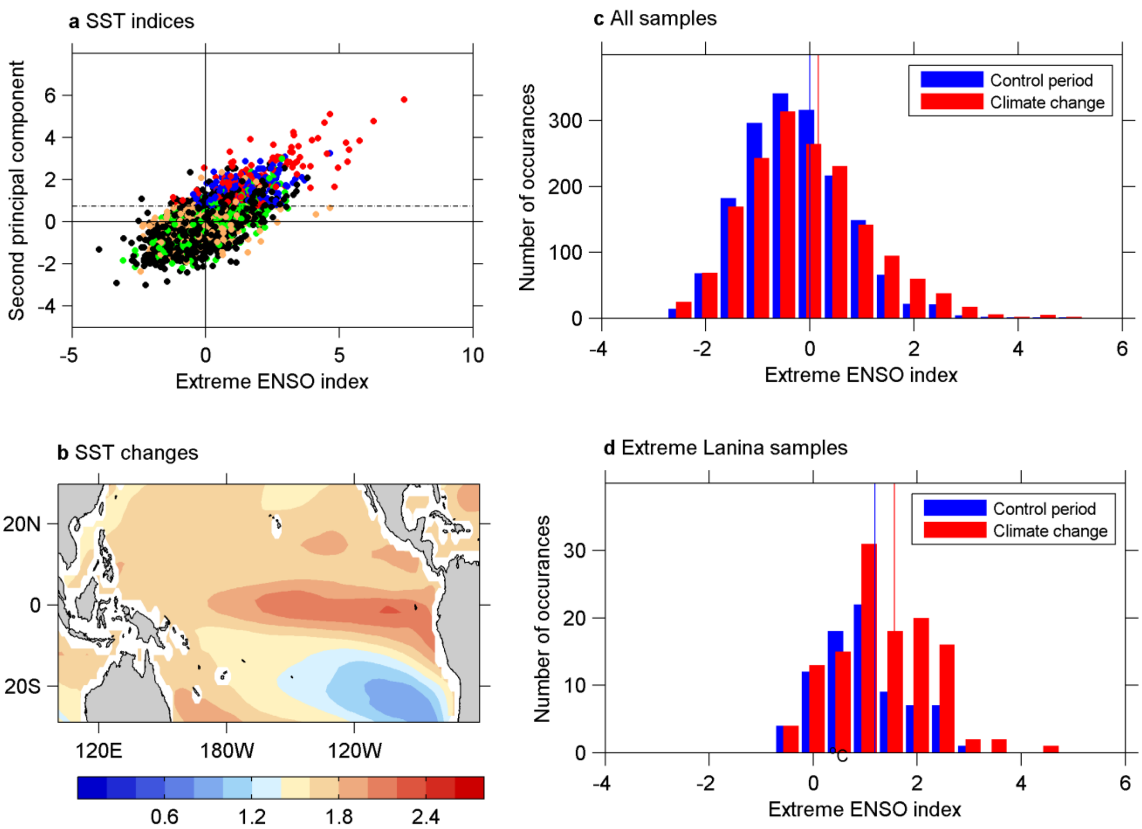

Figure 4 | Multi-model statistics associated with the increase in frequency of extreme La Niña events. **a,** Relationship between principal component of the second SST variability pattern and time series of ENSO extreme Amplifier, defined as an average over the east (5^{o}S-5^{o}N, 80^{o}W-90^{o}W) minus that over the central Pacific (5^{o}S-5^{o}N, 160^{o}E-210^{o}E). **b,** Multi-model ensemble average of SST changes (in ^{o}C) between the average over the *Climate Change* and the *Control* period. **c**, **d**, Multi-model ensemble histogram of ENSO raw Amplifier index but normalised by the standard deviation of the *Control* period for all samples and for extreme La Niña samples only, respectively. Values are separated into 0.5 bins centred at the tick point for the *Control* (**blue**) and *Climate Change* (**red**) period. The multi-model median for the *Control* (dashed **blue** line) and the *Climate Change* (dashed **red** line) periods are indicated. An extreme La Niña event (**blue** dots) is defined as when the first principal component is greater than 1.0 standard deviation (s.d.), and the second principal component is greater than 0.75 s.d. An extreme El Niño event (**red** dots) is defined as when amplitude of the first principal component is greater than 1.0 standard deviation (s.d.), and the second principal component is greater than 0.75 s.d. **Orange** dots indicate **weak El Niño**, and **green** dots, **weak La Niña** defined as when quadratically detrended Niño3 is greater than 0.75 s.d. in amplitude.