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The impact of global warming on the tropical Pacific Ocean and El Niño

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The El Niño–Southern Oscillation (ENSO) is a naturally occurring fluctuation that originates in the tropical Pacific region and affects ecosystems, agriculture, freshwater supplies, hurricanes and other severe weather events worldwide. Under the influence of global warming, the mean climate of the Pacific region will probably undergo significant changes. The tropical easterly trade winds are expected to weaken; surface ocean temperatures are expected to warm fastest near the equator and more slowly farther away; the equatorial thermocline that marks the transition between the wind-mixed upper ocean and deeper layers is expected to shoal; and the temperature gradients across the thermocline are expected to become steeper. Year-to-year ENSO variability is controlled by a delicate balance of amplifying and damping feedbacks, and one or more of the physical processes that are responsible for determining the characteristics of ENSO will probably be modified by climate change. Therefore, despite considerable progress in our understanding of the impact of climate change on many of the processes that contribute to El Niño variability, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change.

Anthropogenic climate change is now well established as a global issue of scientific and political importance. One of the principal impacts of the gradual change associated with anthropogenic climate warming comes from a shift in, or an exaggeration of, pre-existing natural variability. For example, if the average distribution of precipitation shifts to higher or lower values, this can mean that thresholds to flooding or drought are crossed more often. One of the most important sources of natural climatic variability is ENSO. On a timescale of two to seven years, the eastern equatorial Pacific climate varies between anomalously cold (La Niña) and warm (El Niño) conditions. These swings in temperature are accompanied by changes in the structure of the subsurface ocean; variability in the strength of the equatorial easterly trade winds; shifts in the position of atmospheric convection; and global teleconnection patterns associated with these changes that lead to variations in rainfall and weather patterns in many parts of the world.

In the simplest possible scenario, present-day weather and climate variability such as ENSO would continue as before, superimposed onto a gradual mean warming of the global background climate. However, it is not clear whether the climate system will evolve in such a simple manner. As the mean state of both the atmosphere and the ocean in the tropical Pacific region evolve, the amplitude, frequency, seasonal timing or spatial patterns of ENSO could be altered[1]. Furthermore, the way ENSO affects remote locations outside the tropical Pacific could change even if ENSO itself does not.

As a result of intensive research in recent decades, we have developed a good understanding of the basic physical features and processes involved in the ENSO cycle (Box 1). A hierarchy of mathematical models have been used to explain the dynamics, energetics, linear stability and nonlinearity of ENSO[2–5]. Complex coupled global circulation models (CGCMs) have become powerful tools for examining ENSO dynamics and the interactions between global warming and ENSO[6]. ENSO is now an emergent property of many CGCMs, that is, it is generated spontaneously as a result of the complex interplay of thermal and dynamic components in the coupled atmosphere–ocean system. However, it remains challenging to simulate ENSO using CGCMs, because of limitations in: (1) computer resources, which typically restrict climate model resolutions to fewer grid cells than are needed to adequately resolve relevant small-scale physical processes; (2) our ability to create parameterization schemes or include some relevant physical and biological processes that are not explicitly resolved by climate models; (3) the availability of relevant high-quality observational data; and (4) our theoretical understanding of ENSO, which evolves constantly[7]. Nevertheless, the coordination of CGCM experiments and the accessible archive of the resulting simulations[8] have led to an unprecedented level of assessment of the systematic biases in mean tropical Pacific conditions, and of the characteristics, physical processes and feedbacks underlying ENSO evolution in CGCMs[9–17].

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Box 1 | Characteristics of tropical Pacific climate and ENSO

Bjerknes feedback: A positive feedback loop that helps to control the state of the tropical Pacific, and amplifies incipient El Niño events. The easterly trade winds in the tropical Pacific induce a surface zonal current and upwelling that maintain the east–west cold–warm SST gradient. The SST gradient in turn focuses atmospheric convection toward the west and drives the Walker circulation, which enhances the trades. Changes in any one of these elements tend to be amplified by this feedback loop.

Thermocline: A region of strong vertical temperature gradient in the upper few hundred metres of the tropical Pacific Ocean. Key aspects of the equatorial thermocline are its zonal, or east–west, slope (normally the thermocline is deeper in the west than in the east); its zonal-mean depth (indicative of the heat content of the upper ocean); and its intensity (which measures the strength of the temperature contrast between the surface and deep ocean). The thermocline is dynamically active during the ENSO cycle, and is key to its evolution.

Upwelling: Upward movement of cold ocean water from depth, which in the equatorial Pacific is driven by the easterly ('from the east') trade winds. Upwelling acts to cool the surface and supply nutrients to surface ecosystems.

Surface zonal current: The mean easterly trade winds drive a surface easterly current that pushes warm surface waters into the west Pacific. When the trades weaken during El Niño, the warm west Pacific water sloshes eastward, weakening the zonal SST contrast across the Pacific and thus further weakening the trades — a positive feedback for the ENSO cycle.

Walker circulation: The zonally oriented component of the tropical Pacific atmospheric circulation. Under normal conditions, air rises in convective towers in the west Pacific, flows eastward, descends in the east Pacific, and then flows westward at the surface as the trade winds.

Delayed ocean adjustment: During El Niño, a sharpening of the poleward gradient of the tropical Pacific trade winds enhances the poleward transport of upper-ocean waters from the equator toward the subtropics. This gradually discharges the reservoir of warm surface waters from the equatorial zone, eventually resulting in a shallower thermocline, cooler upwelling, and a restored westward flow of cold east Pacific water. This slow component of the ocean adjustment helps to transition the El Niño into normal or La Niña conditions.

Atmospheric feedbacks: Variations in SSTs and atmospheric circulation drive variations in clouds and surface winds, which impact the fluxes of heat and momentum between the atmosphere and ocean. Fluxes are generally partitioned into SW and LW surface radiative fluxes, and fluxes of sensible heat and latent heat. The properties of precipitation, convection and stratiform clouds are all important in the heat balance of the mean climate and the ENSO cycle.

Intraseasonal variability: Atmospheric variability within seasons, often associated with the MJO and other organized modes of variability, can induce anomalies in surface winds in the west Pacific, which induce ocean Kelvin waves that propagate to the east and deepen the thermocline. These may either initiate or amplify the development of an El Niño event.

Small-scale features: Tropical instability waves are generated in the equatorial oceans because of a fluid dynamical instability. Although it is thought that they play a relatively minor role in ENSO dynamics, most CGCMs used for long-term climate projections do not simulate tropical instability waves well, so this is a current area of research.

Changes in mean climate

To assess and understand changes in the mean state of the tropical Pacific, we separate the time-averaged seasonally varying climate from the anomalies associated with ENSO[10]. In addition, we discuss how aspects of the mean might affect the variability, and how aspects of the variability might rectify the mean[18–20]. It is also important to distinguish between changes in ENSO while the system is adjusting to evolving boundary conditions (when, for example, the surface ocean warms at a faster rate than the deep ocean), and the state of ENSO once the system has equilibrated to a warmer climate[21,22]. Here, we generally consider the former, because transient simulations form the majority of the archive of CGCM climate change experiments: not many CGCMs have been run to climate equilibrium, despite the existence of simulations with equilibrium radiative forcing.

Some aspects of global climate change are robust across different CGCMs and are amenable to simple theoretical interpretation. At the very basic level, all models show global surface air temperature and sea surface temperature (SST) warming in response to increasing greenhouse gas concentrations. Robust responses are also evident in the global hydrological cycle[23]. As the global mean temperature rises, the global mean saturated-water vapour pressure should also rise at a rate of approximately 7% per degree Kelvin of warming, because the Clausius–Clapeyron relation is linear over a few degrees of temperature change, if the relative humidity remains constant. This effect is observed in different CGCMs (Fig. 1a). The global mean precipitation rate in CGCMs rises at a much smaller rate of only 1.2% per degree Kelvin of warming in the experiments analysed here(Fig. 1b; see also ref. 24). The slower rate of global precipitation change compared with the faster rate of humidity change implies that there must be a reduction in the rate of exchange of moist boundary-layer air with the dryer air above. In association with this reduction in mass flux, there should be a decrease in vertical motion in the main convective regions of the tropics, and this should lead to a general reduction in the strength of the atmospheric vertical overturning circulation[24].

The mean climate of the tropical Pacific Ocean is strongly affected by this vertical atmospheric overturning circulation, which consists of the longitudinal Hadley circulation and the zonally aligned Pacific Walker circulation (shown schematically in Fig. 2). Because both aspects of the vertical circulation are expected to slow down as global temperatures rise, we also expect the surface trade winds to weaken, in association with a less vigorous Walker circulation (Fig. 1d). Weakening trade winds, as measured by the reduction in the mean sea-level pressure gradient between the eastern and western tropical Pacific (Fig. 1c), have been documented in both observations and models[24–29]. In CGCMs, this slowing down of the equatorial trade winds leads to a slower equatorial oceanic circulation, including equatorial Pacific upwelling[24,25,30].

On interannual timescales, a reduction in trade winds would lead to a flattening of the thermocline, a reduction in the upwelling of cold waters in the east, a relative warming of the east Pacific SSTs compared with the west and a further weakening of the trades. This is the classical feedback described by Bjerknes (Box 1). Although the thermocline does, in general, tend to flatten under climate change in CGCMs — that is, the east–west tilt is reduced — the equatorial thermocline also shoals (rises up) in all projections[25,31] and in observational reconstructions of the past 50 years[24,32]. This

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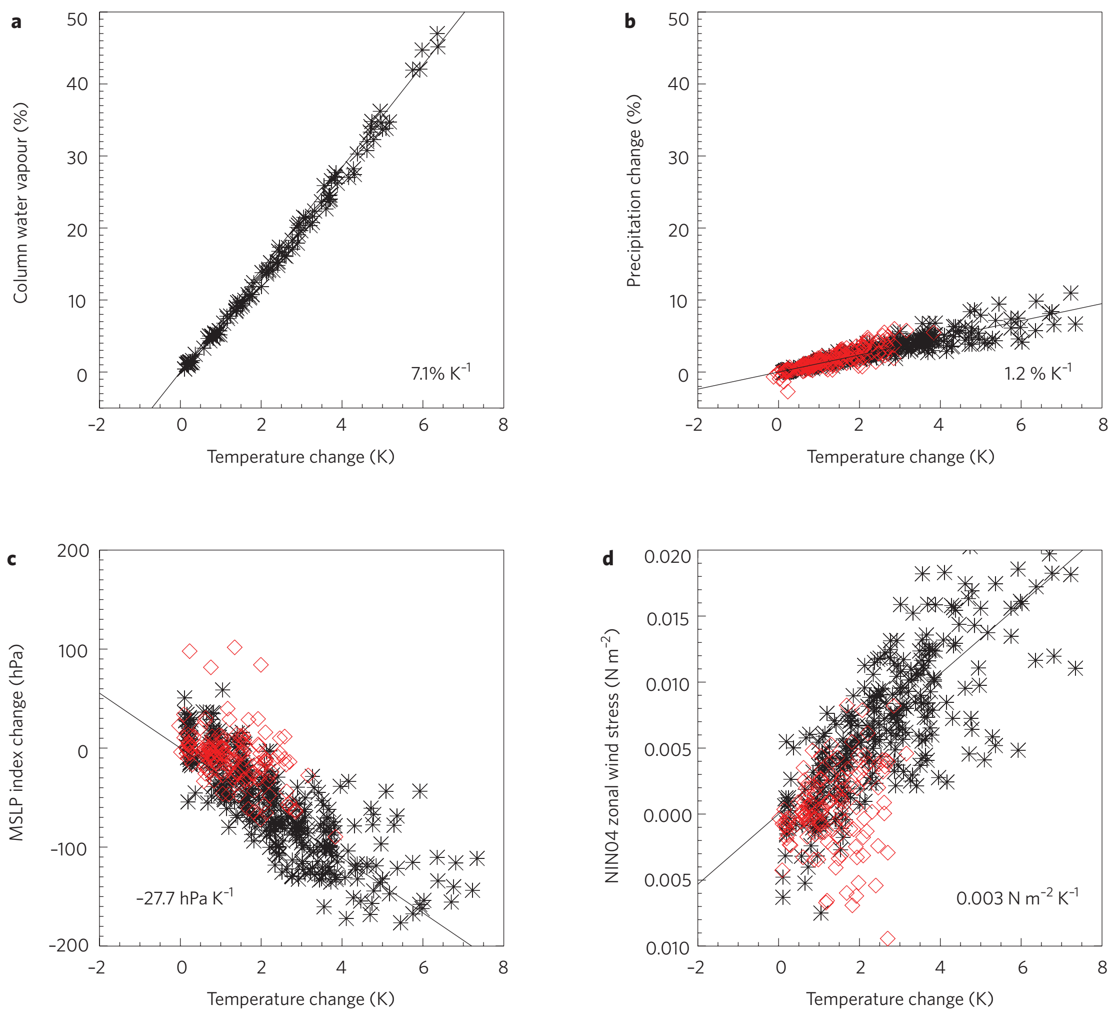

Figure 1 | Changes in global and tropical Pacific mean climate from complex climate models as a function of the global mean temperature change. Red diamonds are values derived from the CMIP3 multi-model database[8], black asterisks are values derived from perturbed physics ensembles with the HadCM3 model[73]. **a**, Percentage change in global mean column integrated water vapour. **b**, Percentage global precipitation change. **c**, Change in the mean sea-level-pressure (MSLP) gradient in hPa across the tropical Pacific basin[24]. **d**, Changes in the mean wind stress averaged in the NINO4 region in the central Pacific. Positive values indicate a reduction in the strength of the easterly trade winds.

is caused by a dynamical adjustment to the reduced equatorial winds[25] and by the tendency of surface waters to warm at a faster rate than the deep ocean[25,30,33]. Hence the Bjerknes feedback does not operate on climate change timescales[24] and other processes may influence the distribution of SST anomalies[30,35–37]. Despite the relatively robust observation of a reduction in the mean sea-level pressure gradient across the equatorial Pacific[24,26–28,39], trends in the observed east–west SST gradient are ambiguous[25,28,29].

Averaged results from the different Coupled Model Intercomparison Project (CMIP3) models, forced by increasing greenhouse gas concentrations over the next 100 years, show that SSTs rise faster along the equator than in the off-equatorial regions[32,36,38] (Fig. 2). The CGCMs show that this is because the weaker Walker circulation leads to a slowing of the horizontal ocean circulation and reduced heat-flux divergence throughout the equatorial Pacific[25,30], that is, less heat is transported away from the equator. In the west, cloud-cover feedbacks and evaporation balance the additional dynamical heating as well as the greenhouse-gas-related radiative heating. In the east, increased cooling by vertical heat transport within the ocean balances the additional warming over the cold tongue. The increased cooling tendency arises from increased near-surface thermal stratification, despite a reduction in vertical velocity associated with the weakened trades[31].

Because a reduction in the strength of the equatorial Pacific trade winds is not necessarily accompanied by a reduction in the magnitude of the east–west gradient of SST — as would be expected from the typical relationship seen on interannual timescales — the term ‘El Niño-like’ climate change[35] is of limited use when describing mean tropical Pacific climate change in observations and models. It also creates confusion in many parts of the world where rainfall changes expected as a result of global warming are different to those normally associated with El Niño[25,34].

The changes outlined above are physically consistent, and describe our understanding of expected variations in the mean climate of the tropical Pacific region under enhanced levels of atmospheric greenhouse gases. Nevertheless, there are further complications. CGCMs have common spatial biases such as cold tongues that extend too far west and unrealistic patterns of tropical precipitation (e.g. ‘double InterTropical Convergence Zones’[39]). In some climate models the existing biases in the cold tongue region of the eastern equatorial Pacific are comparable in magnitude to the projected anthropogenic climate change signal. Moreover, there are aspects of the present global circulation that are either not simulated well by CGCMs, or are not represented at all. For example, organized intraseasonal variability in the form of the Madden–Julian Oscillation (MJO)[40,41] is absent in some CGCMs,

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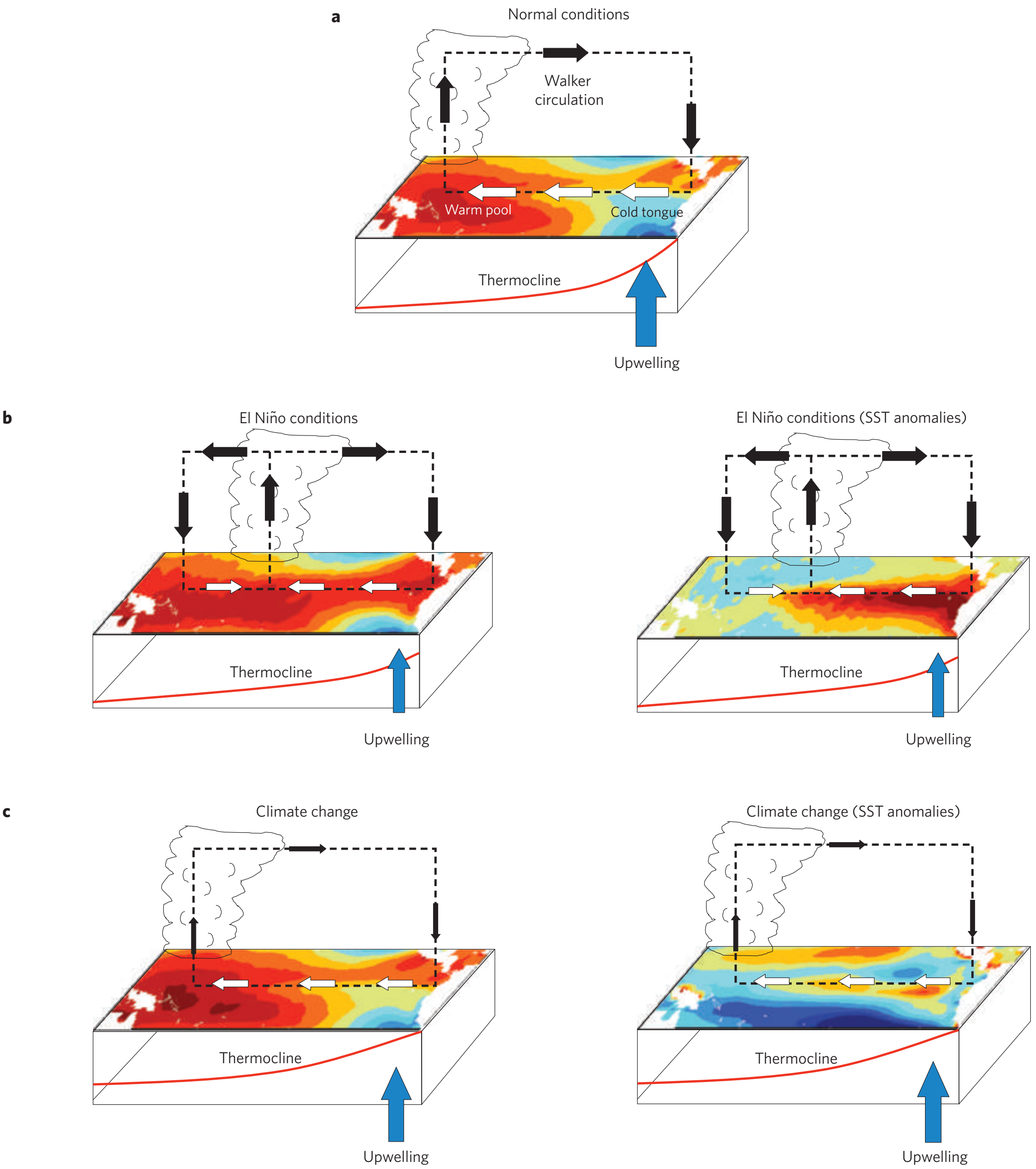

Figure 2 | Idealized schematic showing atmospheric and oceanic conditions of the tropical Pacific region and their interactions during normal conditions, El Niño conditions, and in a warmer world. a, Mean climate conditions in the tropical Pacific, indicating SSTs, surface wind stress and associated Walker circulation, the mean position of convection, and the mean upwelling and position of the thermocline. **b**, Typical conditions during an El Niño event. SSTs are anomalously warm in the east; convection moves into the central Pacific; the trade winds weaken in the east and the Walker circulation is disrupted; the thermocline flattens and the upwelling is reduced. **c**, The likely mean conditions under climate change derived from observations, theory and CGCMs. The trade winds weaken; the thermocline flattens and shoals; the upwelling is reduced although the mean vertical temperature gradient is increased; and SSTs (shown as anomalies with respect to the mean tropical-wide warming) increase more on the equator than off. Diagrams with absolute SST fields are shown on the left, diagrams with SST anomalies are shown on the right. For the climate change fields, anomalies are expressed with respect to the basin average temperature change so that blue colours indicate a warming smaller than the basin mean, not a cooling.

and where it is present, the characteristics do not fully resemble observations. If the spatial resolution of most CGCMs continues to increase as slowly as it has done in the past, simulation of tropical cyclones and typhoons as an emergent property is still some way off. Whether these phenomena affect the details of mean changes in climate we do not know. But we can hypothesize that it is not necessarily essential to be able to simulate all these aspects of climate with absolute fidelity before we can extract useful information from CGCMs about the details of climate change. This hypothesis is continually tested as we improve our observations, understanding and representation of the climate system.

The response of ENSO to external forcing

The sensitivity of ENSO to climate change can be studied by investigating the past history of ENSO using proxy-based climate reconstructions[42–44]. CGCM studies of the mid-Holocene (6,000 years ago) and the Last Glacial Maximum (21,000 years ago) provide insight into ENSO dynamics[45–48], as do studies that examine the

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past millennium[49,50]. However, there is no direct palaeo-analogue of the rapid greenhouse-gas-induced climate change that we are currently experiencing.

Detecting externally forced changes in the characteristics of ENSO using observational and climate change simulations is difficult because of the large intrinsic variations in ENSO behaviour, which can occur on multidecadal and centennial timescales, even in the absence of external changes[52–54]. This problem can be partially overcome in CGCMs by performing multiple runs with the same model and measuring forced changes against natural variability from long, unforced control experiments. However, in the real world this is not possible, and naturally occurring variability could be masking changes driven by global warming.

ENSO processes and feedbacks may be affected by greenhouse-gas-induced changes in mean climate or by direct changes to some of those physical feedbacks and this could, in turn, lead to changes in the characteristic amplitude or frequency of ENSO events. As illustrated in Fig. 3, some CGCMs show an increase in the amplitude of ENSO variability in the future, others show a decrease, and some show no statistically significant changes. Figure 3 is based on just one of many studies that have come to the same conclusions[9,10,55–60]. Based on the assessment of the current generation of CGCMs, there is no consistent picture of changes in ENSO amplitude or frequency in the future. However, by assessing individual feedback processes[16] separately in CGCMs, we can shed some light on how ENSO might be affected by climate change:

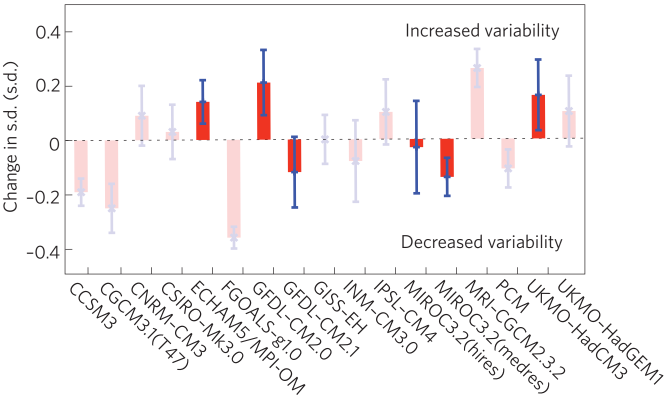

Figure 3 | Projected changes in the amplitude of ENSO variability, as a response to global warming, from the CMIP3 models[8,9]. The measure is derived from the interannual standard deviation (s.d.) of a mean sea-level-pressure index, which is related to the strength of the Southern Oscillation variations. Positive changes indicate a strengthening of ENSO, and negative changes indicate a weakening. Statistical significance is assessed by the size of the blue bars, and the bars indicated in bold colours are from those CMIP3 CGCMs that are judged to have the best simulation of present-day ENSO characteristics and feedbacks.

Mean upwelling and advection. Both the mean upwelling of cold water in the eastern equatorial Pacific and the mean subsurface advection act to strengthen the climatological temperature gradients in the horizontal and the vertical. If a positive thermal anomaly occurs in the east Pacific, then these processes damp that anomaly. Mean upwelling and mean advection in CGCMs are reduced under climate change due to the general weakening of the equatorial trade winds[25]. This would lead to a tendency for enhanced ENSO activity.

Thermocline feedback. Changes to the eastern equatorial Pacific thermocline depth can affect the character of El Niño. A flattening of the equatorial thermocline on interannual timescales leads to a positive SST anomaly in the east Pacific. As the climatological thermocline shoals in CGCMs under greenhouse warming, the SST response to an anomaly in thermocline depth should increase[15]. In CGCM projections, changes in the mean depth of the thermocline in the east Pacific are affected by two compensating processes; thermocline shoaling or rising up tends to reduce the depth in the east, but a reduction of the equatorial thermocline slope tends to deepen it[24,25]. These changes could be expected to enhance the amplitude of ENSO events under climate change.

SST/wind stress (Ekman) feedback. A weakening of the wind stress during El Niño events on interannual timescales leads to positive SST anomalies as less cold water is pumped upwards from below the surface of the ocean. Those positive SST anomalies further weaken the wind stress. This effect could increase under climate change because of the reduced mixed-layer depth that arises as a result of the reduced mean trade wind strength, and increased thermal stratification[15,33]. Wind stress anomalies could become more effective at exciting SST anomalies; in addition, the wind stress response to SST anomalies can become stronger in regions where SST increases are largest[15], that is, on the equator. Both effects would tend to amplify ENSO.

Surface zonal advective feedback. This is a positive feedback in the ENSO cycle. The anomalous zonal advection of the mean SST gradient amplifies El Niño events during their growth phase. As there is little change in the mean zonal SST gradient in CGCMs (Fig. 2c), it is unlikely that this feedback would change significantly under climate change. However, it might be important if the relative frequency of occurrence of different types of ENSO modes changes[31]. The zonal advective feedback is more prominent in central Pacific El Niño, or 'Modoki', variability in which SST anomalies occur principally in the central Pacific without the warm anomalies in the east.

Atmospheric damping. The atmospheric damping of SST anomalies is generally partitioned into components associated with sensible and latent heat fluxes, and surface short wave (SW) and long wave (LW) fluxes. In general we expect that SST anomaly damping through surface fluxes will increase because of increased climatological SSTs[15,17]. This increase would therefore tend to reduce ENSO variability. Surface flux damping might also change because of mean cloud changes brought about by weakening of Walker circulation and/or changes in cloud properties. Cloud feedbacks and their link to the two large-scale circulation regimes that operate in the east Pacific (subsidence and convective[61]) remain a large uncertainty in CGCMs[17,62], probably driving a large fraction of the ENSO errors in the control climate conditions of present-day CGCMs[17].

Atmospheric variability. Westerly wind variability in the west Pacific, often associated with coherent intraseasonal variability and the MJO, has been shown to be important in triggering and amplifying El Niño events[63–66]. Thermocline anomalies excited in the west can propagate to the east, where they are amplified. Climate change simulations in several CGCMs project a future enhancement of the intraseasonal variability in the equatorial Pacific in response to greenhouse gas increase, and this is an important factor for potential intensification of the El Niño activity[38]. However, it should be noted that the simulation of the MJO and related activity is perhaps one of the major weaknesses of current CGCMs, but is an area in which there is considerable potential for improvement.

Other processes and feedbacks. Other processes have been shown to play a role in determining the precise characteristics of ENSO

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events. A sharp salinity front is observed at the eastern edge of the warm pool and this could be important in ocean–atmosphere interactions[67]. The front has the potential to intensify as precipitation increases in a warmer world. A non-local response of freshwater flux to the SST anomalies associated with ENSO could in turn intensify ENSO variability by influencing the mixed-layer depth and upper-ocean stability[68]. Tropical instability waves (TIWs[69,70]) transport heat meridionally and are impacted by ENSO[33], although the ability of CGCMs to simulate such waves can be limited by resolution and physical parameterizations. There are indications that TIWs impact the atmosphere above them[71,72], and it is possible that high atmospheric resolution is required to adequately simulate the full impact of TIWs.

In conclusion, we expect that climate change will probably have a significant impact on the processes and feedbacks that determine ENSO characteristics. A weakening of the mean upwelling and zonal advection, an enhancement of the SST response to thermocline anomalies, and the SST response to wind stress anomalies are all expected to increase the tendency for larger ENSO events. Atmospheric-damping feedbacks are also expected to be enhanced and thus have a tendency to reduce ENSO variability. For other feedbacks, either there is expected to be little overall change, or we do not currently have the evidence to suggest that they will change significantly.

Uncertain outcome

There is no doubt that the mean climate of the tropical Pacific region will continue to change in the coming century as a result of past and future projected emissions of greenhouse gases. The trade winds will weaken, the pattern of SST change is likely to have a zonally symmetric character with maximum warming on the equator, and the thermocline is likely to shoal and flatten. The physical feedbacks that control the characteristics of ENSO are likely to be affected by these changes. However, because the expected changes in the amplifying and damping processes could partly cancel each other out, it is not clear at this stage which way ENSO variability will tip. As far as we know, it could intensify, weaken, or even undergo little change depending on the balance of changes in the underlying processes.

With a sustained community effort, CGCMs, observational records and theoretical understanding should continue to improve in coming years. Perhaps the ultimate challenge is to produce a reliable projection model for ENSO that is consistent with our understanding, as well as being consistent with what we observe in the real world. The development of models of such quality may be some years off. In the meantime, we need to combine all the sources of information that we have — models, analysis techniques, observations and theory — to make some rational and robust statements about the impact of climate change on ENSO for international assessments. Existing efforts to coordinate model experiments, output and metrics will contribute greatly to this endeavour.

Much of the climate change research for the tropical Pacific has focused on long-term changes, both in order to maximize signal-to-noise and because policymakers were looking at mitigation, asking whether ENSO could change irreversibly if we do not limit our emissions of greenhouse gases. Now, as the scientific case for limiting emissions is much stronger, adaptation-driven questions on the likely nature of ENSO in 10 to 30 years have come into focus. Can we predict the level of ENSO activity for the coming decades, even though we accept that we cannot produce decadal predictions of the exact timing of events[53]? Such questions involve not only the potential impact of increasing greenhouse gases on ENSO, but also an understanding of the natural interannual–decadal variability of the phenomenon, and possibly the impact of predictable and unpredictable natural forcing agents such as solar variability and volcanic eruptions.

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Additional information

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