

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

Prepared on behalf of the CLIVAR Pacific Panel

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Abstract

The El Niño-Southern Oscillation (ENSO) phenomenon is a naturally occurring fluctuation centred in the tropical Pacific which has impacts on ecosystems, agriculture, freshwater supplies, hurricanes and other severe weather, and the lives of millions of people around the world. Here we review recent progress on understanding the impact of increasing greenhouse gases on ENSO and the tropical Pacific more generally. Under transient global warming, the mean climate of the Pacific is likely to undergo significant changes, with a weakening of the tropical easterly trade winds, a zonally-symmetric equatorially-enhanced warming of the surface ocean and a shoaling and intensification of the subsurface thermocline. Year-to-year ENSO variability is controlled by a delicate balance of amplifying and damping feedbacks, and it is likely that one or more of the major physical processes that are responsible for determining the characteristics of ENSO will be modified by climate change. While the possibility of large changes in ENSO cannot be ruled out, research conducted to date does not yet enable us to say precisely what changes could occur. The next generation of climate models, coupled with improved observations, revised theory, and new assessment techniques which evaluate ENSO-processes, should enable climate science to provide more definitive statements in the future.

Introduction

Anthropogenic climate change is now well established as a global threat to society and the planet, and is the subject of intense international negotiations to limit its impact. One of the principal ways we are experiencing, and will continue to experience gradual anthropogenic climate change is through exacerbation of the impacts of the natural variability that occurs on top of that gradual change. One of the most important sources of natural climatic variability is the El Niño-Southern Oscillation (ENSO). On a timescale of 2-7 years, the eastern equatorial Pacific varies between anomalously cold (La Niña) and warm (El Niño) conditions. These swings in temperature are accompanied by changes to the structure of the sub-surface ocean, a strengthening and weakening of the equatorial easterly trade winds, shifts in the position of atmospheric convection and associated global teleconnections that drive changes in rainfall and weather patterns in many parts of the world.

The null hypothesis of present-day weather and climate variability continuing “as normal” on top of a gradual global mean warming of the background climate is the simplest way of considering the future of phenomena like ENSO. However, it is not clear that the climate system will evolve in such a simple manner. There will be

changes in the mean state of both the atmosphere and ocean in the tropical Pacific that could alter the amplitude, frequency, seasonal timing, or spatial patterns of ENSO. In addition, the way ENSO is communicated to remote locations outside the tropical Pacific could change even if ENSO itself does not.

In this paper we review the current state of knowledge of how the mean climate of the tropical Pacific and the ENSO cycle may be affected by global climate change. The scope of the review is restricted to changes in the physical climate system that have occurred in recent decades, and which could occur in the coming century under continuing increasing greenhouse gases (see also ref 1). We also focus, for reasons of space, on the phenomena itself, rather than on its global teleconnections and influence.

The executive summary of Chapter 10 of the IPCC AR4 (ref 2) concludes that “Multi-model averages show a weak shift towards average background conditions which may be described as ‘El Niño-like’, with sea surface temperatures in the central and east equatorial Pacific warming more than those in the west, weakened tropical circulations and an eastward shift in mean precipitation.” We discuss the use of the term El Niño-like later. Chapter 10 also concludes that “All models show continued El Niño-Southern Oscillation (ENSO) interannual variability in the future no matter what the change in average background conditions, but changes in ENSO interannual variability differ from model to model. Based on various assessments of the current multi-model data set, in which present-day El Niño events are now much better simulated than in the Third Assessment Report of the IPCC (ref 3), there is no consistent indication at this time of discernible changes in projected ENSO amplitude or frequency in the 21st century.” Have these conclusions changed in the light of recent work?

As a result of intensive research in recent decades, we have developed a good understanding of the basic physics of ENSO. The numerous properties of the climate system which are important in determining the characteristics of ENSO include: the slope, depth and intensity of the tropical Pacific thermocline; the zonal advection of heat in the upper equatorial ocean; the upwelling of cold, deep ocean waters in the east; the off-equatorial thermal structure of the ocean and the related meridional horizontal transport of heat; small-scale features such as tropical instability waves; the response of the atmospheric circulation to the distribution of sea surface temperatures (SSTs), in particular the surface wind stress response; the feedback on SST anomalies from latent and radiative heat fluxes; the statistical properties of precipitation, convective and stratiform clouds, and intraseasonal atmospheric variability; and the climatological seasonal cycle of both the atmosphere and the ocean.

While a hierarchy of mathematical models have been used to further elucidate the dynamics, energetics, linear stability and non-linearity of ENSO^{4,5}, complex Coupled Global Circulation Models (CGCMs) have become powerful tools for examining ENSO dynamics and the interactions between global warming and ENSO⁶. ENSO is now an emergent property of many CGCMs, generated spontaneously as a result of the complex and delicate interplay of thermal and dynamical components in the coupled atmosphere-ocean system. However, it still remains a major challenge to simulate ENSO with fidelity using CGCMs, because of (i) limitations in computer resources, which typically restricts climate model resolutions to fewer grid cells than

are needed to adequately resolve relevant small scale physical processes; (ii) our ability to parameterize or include some relevant physical and biological processes that are not explicitly resolved by climate models; (iii) the availability of relevant high quality observational data; and (iv) our theoretical understanding of ENSO which is constantly challenged⁷.

The coordination of CGCM experiments and output⁸ has 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^{9,10,11,12,13,14}. CGCMs continue to improve in terms of their ability to simulate mean climate and ENSO variability^{11,15}. In addition, the basis for the evaluation of GCMs continues to improve due to continued coordination of experiments and databases of CGCM output and the standardization of metrics and diagnostics⁶. New techniques are emerging for evaluation of ENSO in CGCMs and the real world, in which physical processes and feedbacks underlying ENSO are diagnosed separately^{10,16,17}, or are diagnosed by fitting reduced-complexity models of ENSO to the CGCM output^{4,18,19,20}. Despite their relative complexity, these tools have proven to be useful in diagnosing model fidelity and are likely to play a crucial role in forming more robust conclusions about future climate change.

Changes in Mean Climate

In order to assess and understand changes in the mean state of the tropical Pacific, we need to clarify what we mean by the mean-state, what we mean by variability, and what we mean by changes to both. There is a tendency in the literature to separate out the time-averaged seasonally-varying climate from the anomalies associated with ENSO¹⁰; considering those aspects separately as well as considering how aspects of the mean might affect the variability and how aspects of the variability might rectify the mean^{21,22}. This type of separation provides a useful way of making progress²³.

Some aspects of global climate change are robust across different CGCMs and are amenable to simple theoretical considerations. At the very basic level, all models show global surface air temperature and SST warming in response to increasing greenhouse gas concentrations. Ref 24 explores a number of robust responses in terms of the global hydrological cycle. As the global mean temperature rises, the global mean saturated water vapour pressure should also rise at a rate of approximately 7% per degree K of warming; the Clausius–Clapeyron relation being close to linear over a few degrees of temperature change. If the relative humidity remains constant, then the global mean vapour pressure should also rise at approximately 7% per degree K and this is observed in different CGCMs (figure 1a). In ref 24, the authors note that the global mean precipitation rate in CGCMs rises at a much smaller rate of only 1.2% per degree K of warming in the experiments analysed here - figure 1b. If we assume that the global mean precipitation rate is proportional to the water vapour mixing ratio multiplied by mass-mixing rate (the rate of exchange of moist boundary layer air with the dryer air above), then the slower rate of global precipitation change in comparison to the faster rate of humidity change implies that there must be a reduction in this mass mixing rate. In association with this reduction in mass flux, there should be a reduction 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.

The simplest way of describing the vertical overturning of the tropical atmosphere is in terms of the zonally symmetric Hadley Circulation and the zonally-asymmetric Pacific Walker circulation (shown schematically in figure 2). Because of the reduction in the vertical circulation expected as global temperatures rise, we also expect a reduction in the surface trade winds associated with a weaker Walker circulation (figure 1d). Refs 25, 26, 27, 28, 29 and 30 find a consistent picture of weakening trades in both observations and models as measured by the reduction in the east-west mean sea level pressure gradient across the tropical Pacific (figure 1c). In CGCMs, the weakening of the equatorial trade winds drives a reduction of equatorial oceanic circulation, including equatorial Pacific upwelling^{25,26,31}.

On interannual time scales, 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 in comparison to the west and a further weakening of the trades. This is the classical feedback described by Bjerknes. While the thermocline does, in general, tend to flatten under climate change in CGCMs, the equatorial thermocline also shoals in all projections^{26,32} and in observational reconstructions of the past 50 years^{25,33}. This is caused by a dynamical adjustment to the reduced equatorial winds²⁶ and because surface waters tend to warm at a faster rate than the deep ocean^{26,31,34}. Climate projections over the next centuries suggest that other processes may influence the distribution of SST anomalies. Despite the relatively robust observation of reducing mean sea level pressure gradient across the equatorial Pacific, trends in the observed east-west SST gradient are ambiguous^{26,30}. Detecting long-term trends in the presence of large interannual ENSO variability from datasets which, in earlier decades of the 20th century, are reconstructed from relatively sparse observations taken using different measurement techniques is a challenge. The existence of uncertainty in whether the east Pacific is warming faster than the west, or vice-versa, is an indication that the leading-order response of SSTs is not as would be expected from an extension of the Bjerknes feedback to longer time scales.

The term “El Niño-like” climate change^{2,35} becomes less useful then when describing mean tropical Pacific climate change in observations and models if a reduction in the strength of the equatorial Pacific trade winds is not accompanied with reduction in east-west gradient of SST of the magnitude expected from the normal relationship seen on interannual time scales. The multi-model ensemble mean signal of SST change averaged over the different CMIP3 models forced by increasing greenhouse gas concentrations over the next 100 years is for a more zonally-symmetric enhanced warming on the equator in comparison with the off-equatorial regions (figure 2c)^{31,36,37}. Ref 31 shows that the weaker Walker circulation leads to a reduction in the horizontal ocean heat flux divergence throughout the equatorial Pacific in CGCMs i.e. less heat transport 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 ocean vertical heat transport balances the additional warming over the cold tongue. The increased cooling tendency by vertical ocean heat transport arises from increased near-surface thermal stratification, despite a reduction in vertical velocity associated with the weakened trades. The term ‘El Niño-like’ also creates confusion in the wider community in many parts of the world where rainfall changes expected from global warming have the opposite sign to those normally associated with El Niño.

The above description of mean changes represents a consistent story of how the mean climate of the tropical Pacific might change under enhanced levels of greenhouse gases. It shows how progress in climate change research can be made even when presented with such a complex system with many interacting physical processes. Nevertheless, there are complications to that story. CGCMs have common spatial biases such as extensive cold tongues and “double ITCZs”³⁹. In some climate models the existing biases in the eastern equatorial Pacific cold tongue region are comparable in magnitude with the projected anthropogenic climate change signal in these areas. In addition there are aspects of the present day global circulation which are either not simulated well by CGCMs or are not even represented at all. Organised intraseasonal variability in the form of the Madden Julian Oscillation (MJO^{40,41}) is present in some CGCMs, albeit with characteristics which are not identical to that seen in the observations, but absent in others. The current rate of increase of spatial resolution of the majority of CGCMs means that the spontaneous simulation of tropical cyclones and typhoons is still some way off. Might these phenomena affect the details of mean changes in climate? Currently we do not know, nevertheless 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.

The response of ENSO to external forcing

One way of examining the sensitivity of ENSO to climate change is to study the past history of ENSO using proxy-based climate reconstructions^{42,43,44}. CGCM studies of the mid-Holocene (6,000 years ago) and the Last Glacial Maximum (21,000 years ago) provide insight into ENSO dynamics^{45,46,47,48} as do studies which examine the last millennium^{49,50}. However there is no direct paleo-analogue of the rapid greenhouse-gas induced climate change we are experiencing now.

First, a word of caution. Detecting externally forced changes in the characteristics of ENSO, using either observational data or climate change simulations conducted with CGCMs, is confounded by large natural variations in ENSO behavior, which can occur on multi-decadal and centennial time scales even in the absence of external forcing^{52,53,54}. While 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, this is obviously not possible in the real world where naturally occurring variability might also be masking changes driven by global warming.

ENSO processes and feedbacks may be impacted by greenhouse-gas induced changes in mean climate or by direct changes to some of those physical feedbacks and this may, in turn, lead to changes in the characteristic amplitude or frequency of ENSO events. As illustrated by figure 3, some CGCMs show an increase in the amplitude of ENSO variability in the future, some show a decrease, some show no statistically significant changes. The figure is based on just one of many studies that have come to the same conclusions^{9,10,55,56,57,58,59,60}. Based on the assessment of the current generation of CGCMs, it is safe to agree with the IPCC statement reproduced above that there is no consistent picture of changes in ENSO amplitude or frequency in the

future. However, by assessing individual feedback processes¹⁹ separately in CGCMs it is possible to shed some light on how ENSO might be impacted by climate change.

Mean upwelling and advection: Both the mean upwelling of cold water in the eastern equatorial Pacific and the mean subsurface advection act as a negative feedback in the ENSO cycle, damping positive SST anomalies in the east and re-establishing the climatological temperature gradients in the horizontal and the vertical. Mean upwelling and mean advection in CGCMs is reduced under climate change due to the general weakening of the equatorial trade winds²⁶. This would lead to a tendency for enhanced ENSO activity.

Thermocline feedback: Changes to the eastern equatorial Pacific thermocline depth can impact the character of El Niño: a flattening of the equatorial thermocline on interannual time scales 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 increase¹⁸. In CGCM projections, changes in mean depth of the thermocline in the East Pacific are damped by compensation between a shoaling of the equatorial thermocline and a reduction of the equatorial thermocline slope^{25,26}, the former driving a deepening the latter a shoaling. Changes in thermocline feedbacks would 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 time scales leads to positive SST anomalies as less cold water is pumped upward from below the surface of the ocean. This effect could increase under climate change because of the reduced mixed layer depth which arises as a result of the reduced mean trade wind strength, and reduced thermal stratification^{18,34}. 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 largest¹⁸ i.e. 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 (figure 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 changes³², favouring a more central Pacific or “Modoki” mode.

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^{16,18}. This would therefore tend to act 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 convective⁶¹) remain a large uncertainty in CGCMs^{16,62}, likely driving a large fraction of ENSO errors in control climate in present-day CGCMs¹⁶.

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^{63,64,65,66}. 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 thus an important factor for potential intensification of the El Niño activity³⁷. However, it should be noted that the simulation of 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 events. A sharp salinity front is observed at the eastern edge of the warm pool and this could be important in ocean-atmosphere interactions⁶⁸. The front has the potential to intensify as precipitation goes up in a warmer world. A non-local response of freshwater flux to SST anomaly associated with ENSO could in turn intensify ENSO by influencing the mixed layer depth and upper ocean stability⁶⁹. Tropical Instability Waves (TIWs^{70,71}) transport heat meridionally and are impacted by ENSO³⁴, although the ability of CGCMs to simulate such waves can be limited by resolution and by 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 then we expect that climate change is likely to have a significant impact on the processes and feedbacks which determine ENSO characteristics. A weakening of the mean upwelling and zonal advection and 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. Negatively 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.

The future of ENSO thus depends on changes in the delicate balance between those positive and negative feedbacks that are set to be modified by climate change¹⁸. In some models, the enhancing feedbacks win out, in other models the damping feedbacks win out. What is perhaps unlikely in the real world is that there will be an exact cancellation of these feedback changes.

Summary and Future Research

There is no doubt that the mean climate of the tropical Pacific will change in the coming century if greenhouse gases continue to rise unchecked. The trade winds will weaken, the pattern of SSTs 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 but with a delicate balance between amplifying and damping processes meaning that it is not clear at this stage whether ENSO variability

will go up or down or be unchanged if there is a fortuitous counterbalancing 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 which is completely consistent with our understanding and statistically consistent with what we observe in the real world. Models of such quality may be some years off and hence there is a need to be able 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. The existence of efforts to coordinate model experiments, output and metrics will contribute greatly to this endeavour.

Much of the research on how the tropical Pacific will change as a consequence of global warming has focussed on long term changes at relatively high levels of radiative forcing. There is a natural tendency for researchers to do this in order to maximise signal-to-noise. Also the policy-drive for information about climate change has come from the point of view of mitigation. Could ENSO change irreversibly if we do not limit our emissions of greenhouse gases?

Now the policy-drive is much more subtle. The scientific case for limiting emissions is strong, although, of course, there is considerable political progress still to be made. Perhaps of more relevance is the adaptation-driven question of what might ENSO be like in the next 10, 20 or 30 years? Might we see two decades with relatively few ENSO events? Is it possible that there could be a highly active phase of ENSO coming? Such questions involve not only the potential impact of increasing greenhouse gases on ENSO, but also the natural interannual-decadal variability of the phenomena and potentially even the impact of (unpredictable) natural forcing agents like solar variability and volcanic eruptions.

References

1. Vecchi, G. A., and A. T. Wittenberg, 2009: El Niño and our future climate: Where do we stand? Submitted to Wiley Interdisciplinary Reviews: Climate Change.
2. Solomon, S. et al. IPCC 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 996pp.
3. Houghton J. et al. IPCC 2003: Climate Change 2003: The Physical Science Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
4. Fedorov, A. V. 2007: Estimating net energy dissipation rates in the tropical ocean: diabatic effects on ENSO dynamics. *J. Climate*. 20, 1099–1108.

5. Roberts, W.G.H. and D.S. Battisti 2009: A new tool for evaluating the physics of coupled atmosphere-ocean variability in nature and in General Circulation Models. Submitted, Climate Dynamics.
6. Guilyardi, E, Wittenberg, A, Fedorov, A, Collins, M, Wang, C, Capotondi, A, van Oldenborgh, GJ., 2009a: Understanding El Niño in Ocean-Atmosphere General Circulation Models: progress and challenges. *Bulletin of the American Meteorological Society*, 90, 325–340.
7. McPhaden M.J., Zhang X.B. Asymmetry in zonal phase propagation of ENSO sea surface temperature anomalies, 2009: *Geophys. Res. Letts.* 36 Article Number: L13703.
8. Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J. and Taylor, K.E., 2007: The WCRP CMIP3 Multimodel Dataset: A new era in climate change research. *Bulletin of the American Meteorological Society*, 88, 9, 1383-1394.
9. van Oldenborgh, G. J., S. Philip, and M. Collins, 2005: El Niño in a changing climate: a multi-model study. *Ocean Science*, 2, 267-298.
10. Guilyardi E. (2006): El Niño- mean state - seasonal cycle interactions in a multi-model ensemble. *Clim. Dyn.*, 26:329-348, DOI: 10.1007/s00382-005-0084-6.
11. AchutaRao, K. and Sperber, K., 2006: ENSO simulations in coupled ocean-atmosphere models: are the current models better? *Climate Dynamics*, 27, 1-15.
12. Merryfield, W.J., 2006: Changes to ENSO under CO2 Doubling in a Multimodel Ensemble. *J. Climate.*, 19, 4009-4027.
13. Capotondi, A., A. Wittenberg, S. Masina, 2006: Spatial and temporal structure of Tropical Pacific interannual variability in 20th Century coupled simulations. *Ocean Modelling*, 15, 274-298.
14. Lengaigne, M. and G.A. Vecchi, 2009: Contrasting the termination of moderate and extreme El Niño events in Coupled General Circulation Models. *Climate Dynamics*, doi: 10.1007/s00382-009-0562-3.
15. Reichler T. and Kim, J. 2008: How well do climate models simulate today's climate? *Bull. Am. Meteorol. Soc.*, 89, 3, 303-311.
16. Lloyd J., E. Guilyardi, H. Weller, J. Slingo (2009). The role of atmosphere feedbacks during ENSO in the CMIP3 models. *Atmos. Sci. Lett.*, in press
17. Kim, S. et al. Manuscript submitted to *J. Clim.*

18. Philip, S.Y. and G.J. van Oldenborgh, 2006: Shifts in ENSO coupling processes under global warming, *Geophys. Res. Letts.*, 33, L11704, doi:10.1029/2006GL026196.
19. Jin F.-F., S. T. Kim and L. Bejarano, 2006: A coupled-stability index for ENSO. *Geophys. Res. Let.* 33. L23708.
20. Dewitte B., C. Cibot, C. Périgaud, S.-I. An and L. Terray 2007: Interaction between near-annual and ENSO modes in a CGCM simulation: role of equatorial background mean state. *J. Climate*, 20:1035-1052.
21. Jin, F.-F., S.-I. An, A. Timmermann, and J. Zhao, 2003: Strong El Nino events and nonlinear dynamical heating. *Geophys. Let. Lett.*, 30, 1120, doi:10.1029/2002GL016356.
22. An, S. -I., 2009: A review of interdecadal changes in the nonlinearity of the El Nino-Southern Oscillation, *Theor. Appl. Climatol.*, 97, 29-40.
23. Pezzulli, S.; Stephenson, D. & Hannachi, A. , 2005: The Variability of Seasonality. *J. Climate*, 18, 71-88.
24. Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Climate*, 19, 5686–5699.
25. Vecchi, G. A., A. T. Wittenberg, and A. Rosati, 2006: Reassessing the role of stochastic forcing in the 1997-8 El Niño. *Geophys. Res. Lett.*, 33, L01706. doi:10.1029/2005GL024738.
26. Vecchi, G.A., and B.J. Soden, 2007: Global Warming and the Weakening of the Tropical Circulation. *J. Clim.*, 20(17), 4316-4340.
27. Power, S.B., and I.N. Smith, 2007: Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophys. Res. Lett.*, 34, L18702, DOI 10.1029/2007GL030854.
28. Zhang, M., and H. Song, 2006: Evidence of deceleration of atmospheric vertical overturning circulation over the tropical Pacific, *Geophys. Res. Lett.*, 33, L12701, DOI10.1029/2006GL025942.
29. Bunge, L., and A.J. Clarke, 2009: A Verified Estimation of the El Niño Index Niño-3.4 since 1877. *J. Climate*, 22, 3979–3992.
30. Karnauskas, K.B., R. Seager, A. Kaplan, Y. Kushnir, and M.A. Cane, 2009: Observed Strengthening of the Zonal Sea Surface Temperature Gradient across the Equatorial Pacific Ocean. *J. Climate*, 22, 4316–4321.
31. DiNezio, P.N., A.C. Clement, G.A. Vecchi, B.J. Soden, B.P. Kirtman, S.-K. Lee, 2009: Climate Response of the Equatorial Pacific to Global Warming. *J. Climate*, in press DOI10.1175/2009JCLI2982.1.

32. Yeh S-W, Kug J-S, Dewitte, B, Kwon, M-H, Kirtman, BP, Jin F-F, 2009 El Nino in a changing climate. *Nature* 461, 511-514.
33. Zhang Q., Y. Guan, and H. Yang, 2008: ENSO amplitude change in observation and coupled models, *Adv. Atmos. Sci.*, 25, 361–366.
34. An, S.-I., 2008: Interannual variations of the tropical ocean instability wave and ENSO. *J. Clim.*, 21, 3680-3686.
35. Collins, M. et al. 2005: El Nino- Or La Nina-Like Climate Change? *Climate Dynamics*, 24 (1): 89-104.
36. Liu, Z., S. Vavrus, F. He, N. Wen, and Y. Zhong, 2005: Rethinking Tropical Ocean Response to Global Warming: The Enhanced Equatorial Warming. *J. Climate*, 18, 4684–4700.
37. Gastineau, G., Li, L. And Le Treut, H. 2009: The Hadley and Walker circulation changes in global warming conditions described by idealised atmospheric simulations. *J. Clim.*, 22, 3993-4013.
38. Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2009: Global warming pattern formation: Sea surface temperature and rainfall. *J. Climate*, accepted September 2009.
39. Lin, J-L, 2007: The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean–atmosphere feedback analysis. *J. Climate*, 20, 18, 4497–4525.
40. Inness, P.M. and J.M. Slingo, 2003. Simulation of the Madden-Julian Oscillation in a coupled general circulation model I: Comparison with observations and an atmosphere-only GCM. *J. Climate*, 16, 3, 345-364.
41. Lin, J.L., G.N. Kiladis, B.E. Mapes, K.M. Weickmann, K.R. Sperber, W.Y. Lin, M. Wheeler, S.D. Schubert, A. Del Genio, L.J. Donner, S. Emori, J.-F. Gueremy, F. Hourdin, P.J. Rasch, E. Roeckner, and J.F. Scinocca, 2006: Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals. *J. Climate*, 19, 2665-2690.
42. Cobb, K., C. D. Charles, H. Cheng, and R. L. Edwards, 2003: El Niño-Southern Oscillation and tropical Pacific climate during the last millenium. *Nature*, 424, 271–276.
43. Tudhope, A.W. and Coauthors, 2001: Variability in the El Niño-Southern Oscillation Through a Glacial-Interglacial Cycle. *Science*, 291, 1511–1517, DOI: 10.1126/science.1057969.
44. D’Arrigo, R., E. Cook, R. Wilson, R. Allan, and M. Mann, 2005: On the variability of ENSO over the past six centuries. *Geophys. Res. Lett.*, 32, L03711, doi:10. 1029/2004GL02205.
45. Rosenthal, Y. and A.J. Broccoli, 2004: In Search of Paleo-ENSO. *Science*,

304, 219-221.

46. Brown, J, Collins, M, Tudhope, AW and Toniazzo, T. 2008: Modelling mid-Holocene tropical climate and ENSO variability: Towards constraining predictions of future climate change with palaeo-data. *Climate Dynamics*, 30, 19-36.
47. Timmermann, A., and S. Lorenz, S.I. An, A. Clement, S.-P. Xie, 2007: , The effect of orbital forcing on the mean climate and variability of the tropical Pacific, *J. Climate*, 20, 4147-4159.
48. Otto-Bliesner et al (2009) *Clim. Dyn.*, 32(6), 799-815. DOI10.1007/s00382-008-0509-0.
49. Crowley, T., 2000: Causes of climate change over the past 1000 years. *Science*, 289, 270–277.
50. Mann, M., M. Cane, S. Zebiak, and A. Clement, 2005: Volcanic and Solar Forcing of the Tropical Pacific over the Past 1000 Years. *J. Climate*, 417–456.
51. Emile-Geay, J., R. Seager, M. Cane, E. Cook, and G. Haug, 2006: The volcanic eruption of 1258 A.D. and the subsequent ENSO event. *Geophys. Res. Lett.*
52. Wittenberg, A. T., 2009: Are historical records sufficient to constrain ENSO simulations? *Geophys. Res. Lett.*, 36, L12702. doi:10.1029/2009GL038710.
53. Power, S., M. Haylock, R. Colman, and X. Wang, 2006: The predictability of interdecadal changes in ENSO and ENSO teleconnections. *J. Climate*, 8, 2161-2180.
54. Power, S.B., and R. Colman, 2006: Multi-year predictability in a coupled general circulation model. *Climate Dynamics*, 26, 247-272.
55. Zelle H, Van Oldenborgh GJ, Burgers G, et al., 2005: El Nino and Greenhouse warming: Results from ensemble simulations with the NCAR CCSM. *J. Clim.*, 18(22) , 4669-4683.
56. Meehl, G.A., H. Teng, and G. Branstator, 2006: Future changes of El Niño in two global coupled climate models. *Clim. Dyn.*, 26, 549-566. DOI 10.1007/s00382-005-0098-0.
57. Yeh SW, Park YG, Kirtman BP, 2006: ENSO amplitude changes in climate change commitment to atmospheric CO2 doubling. *Geophys., Res. Letts.*, 33(13) Article Number: L13711.
58. Yeh, S. W. and Kirtman, B. P. 2007: ENSO Amplitude Changes due to Climate Change Projections in Different Coupled Models. *J. Climate* 20, 203-217.

59. Cherchi, A., S. Masina, A. Navarra, 2008: Impact of extreme CO2 levels on tropical climate: a CGCM study. *Clim. Dyn.*, 31, 743-758. DOI 10.1007/s00382-008-0414-6.
60. Park W, Keenlyside N, Latif M, et al. 2009 : Tropical Pacific Climate and Its Response to Global Warming in the Kiel Climate Model. *J. Clim.* 22(1) 71-92.
61. Guilyardi E., P. Braconnot, F.-F. Jin, S. T. Kim, M. Kolasinski, T. Li and I. Musat , 2009: Atmosphere feedbacks during ENSO in a coupled GCM with a modified atmospheric convection scheme. *J. Clim.*, in press.
62. Bony, S. and Dufresne, J. L. 2005: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.* 32, 20806.
63. Lengaigne, M.; Guilyardi, E.; J.P. Boulanger, J. P.; Menkes, C.;P. Delecluse, P.; Inness, P.; Cole, C. Menkes et J. & Slingo, J. , 2004: Triggering of El Nino by westerly wind events. *Clim. Dyn.*, 23, 601-620.
64. Vecchi, G.A., B.J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006.b: Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, 441, 73–76.
65. Gebbie, G., I. Eisenman, A. Wittenberg, and E. Tziperman, 2007: Modulation of westerly wind bursts by sea surface temperature: A semistochastic feedback for ENSO. *J. Atmos. Sci.*, 64, 3281-3295.
66. Zavala-Garay, J., C. Zhang, A. M. Moore, A. T. Wittenberg, M. J. Harrison, A. Rosati, J. Vialard, and R. Kleeman, 2008: *J. Climate*, 21, 3704-3721. doi:10.1175/2007JCLI1188.1
67. Jin et al. 2009: In prep.
68. Maes, C., Picaut, J. and Belamari, S., 2002: Salinity barrier layer and onset of El Nino in a Pacific coupled model, *Geophys. Res. Letts.* 10.1029/2002GL06029.
69. Zhang, R.-H., and A. J. Busalacchi, 2009: Freshwater Flux (FWF)-Induced Oceanic Feedback in a Hybrid Coupled Model of the Tropical Pacific. *J. Climate*, 22(4), 853-879.
70. Yu, JY, WT Liu, 2003: A linear relationship between ENSO intensity and tropical instability wave activity in the eastern Pacific Ocean, *Geophys. Res. Letts.* 30, 14, 1735.
71. Seo, H., Jochum, M., Murtugudde, R., Miller, A.J. and Roads, J. O. 2007: Feedback of tropical instability-wave-induced atmospheric variability onto the ocean. *J. Climate*, 20, 5842-5855.

72. Roberts, M.J., A. Clayton, M.E. Demory, J. Donners, P.L. Vidale, W. Norton, L. Shaffrey, D.P. Stevens, I. Stevens, R.A. Wood, and J. Slingo, 2009: Impact of Resolution on the Tropical Pacific Circulation in a Matrix of Coupled Models. *J. Climate*, 22, 2541–2556.
73. Collins, M, Booth, BBB, Bhaskaran, B, Harris, G, Murphy, JM, Sexton, DMH, Webb, MJ. A comparison of perturbed physics and multi-model ensembles: Model errors, feedbacks and forcings. *Climate Dynamics*, submitted.

Figures

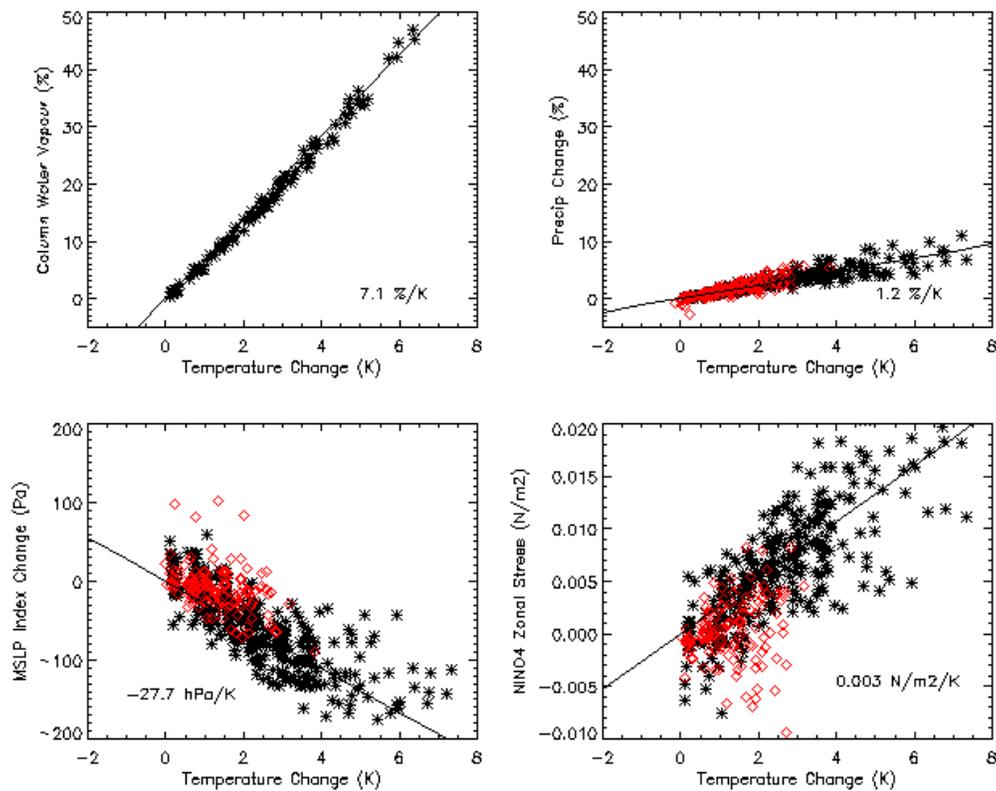
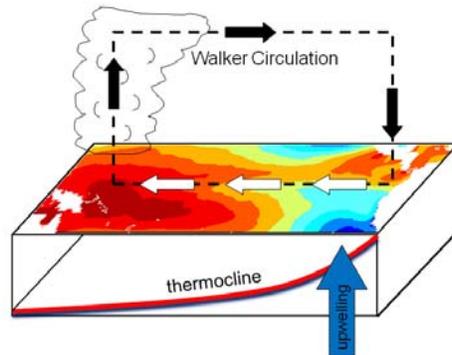
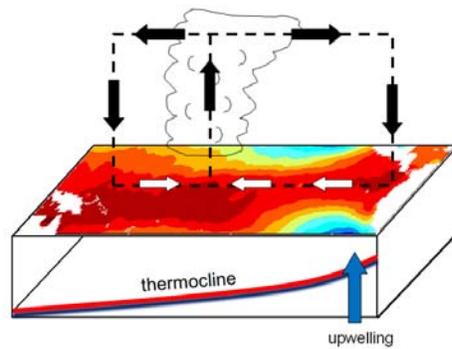


Figure 1: Changes in global and tropical Pacific mean climate from complex climate models as a function of the global mean temperature change. Red diamonds are values derived from the CMIP3 multi-model data base⁸, black asterisks are values derived from perturbed physics ensembles with the HadCM3 model⁷³. (a) Percentage changes in global mean column integrated water vapour vs. global mean warming. (b) Percentage global precipitation change vs. global mean temperature change. (c) Change in the mean-sea-level-pressure gradient in hPa across the tropical Pacific basin²⁵ vs. global mean-temperature change. (d) Changes in the mean wind stress averaged in the NINO4 region in the central Pacific vs. global mean temperature change.

Normal Conditions



El Niño Conditions



Climate Change

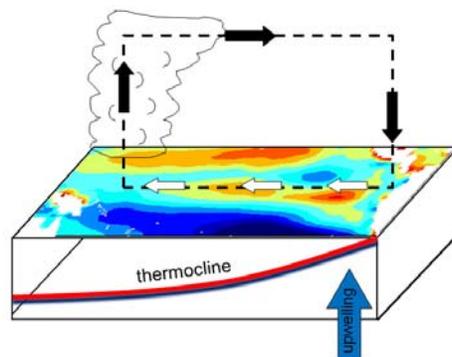


Figure 2: Schematic figures indicating (a) mean climate conditions in the tropical Pacific; SSTs, surface wind stress and associated Walker circulation, the mean position of convection and the mean upwelling and position of the thermocline. (b) Typical conditions during a El Niño event, SSTs are anomalously 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) likely mean conditions under climate change derived from observations, understanding and CGCMs. The trade winds weaken, the thermocline flattens and

shoals, the upwelling is reduced although the mean vertical temperature gradient is increase and SSTs (shown as anomalies with respect to the mean tropical-wide warming) warm more on the equator than off.

Changes in ENSO variability 2050-2100 in CMIP3 A1B experiments

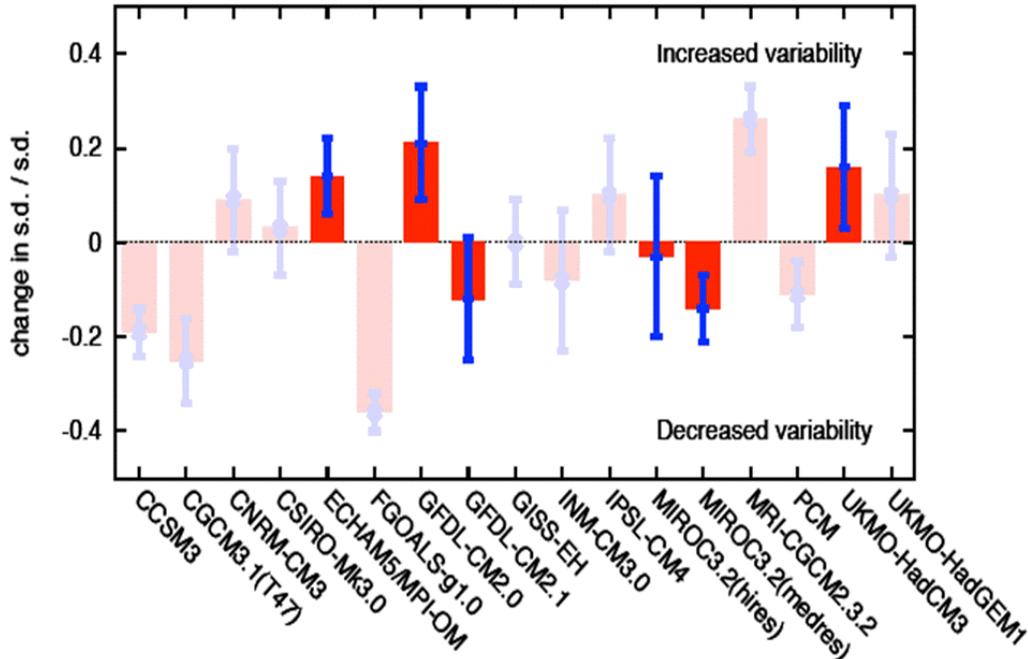


Figure 3. Changes in the amplitude of ENSO variability from the CMIP3 models⁸. The measure is derived from the interannual standard deviation of a mean sea level pressure index which is related to the strength of the Southern Oscillation variations. Positive changes indicate a strengthening of ENSO and negatives changes a weakening. Statistical significance is assessed by the size of the blue bars and the bars indicated in the bold colours are from those CMIP3 CGCMs which are adjudged to have the best simulation of present-day ENSO characteristics and feedbacks.