Low-frequency variations of ENSO

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Clues from the past

Historical reconstructions of ENSO, like that in Figure 1, indicate that its behavior varies from decade to decade. During the 1960s and 1970s, the equatorial Pacific sea surface temperature anomaly (SSTA) variability was weak, with a biennial and westward-propagating character. The 1980s and 1990s were more active, with El Niños every five years - including two exceptional events that produced intense SSTAs in the far eastern Pacific, and a distinct eastward propagation of SSTAs as they transitioned into La Niñas. And since 1999, the SSTAs have weakened and shifted farther west.

Farther back in time, direct temperature measurements become sparse, and historical reconstructions become more sensitive to the methods used to impute missing data. This is especially true prior to 1880. For example, the exceptional El Niño of 1877-78 - whose impacts are well documented (Davis 2001; Aceituno et al. 2009) - is prominent in Figure 1, but was practically missing from the previous version of this reconstruction (Huang et al. 2015).

To augment the instrumental record, researchers have turned to paleoclimatic proxy records from corals, tree rings, lake sediments, and ice cores, which over the instrumental epoch show varying degrees of correlation with ENSO. Different proxies respond to different aspects of ENSO – but together they tell an intriguing story – that ENSO has existed in some form for over 100,000 years (Tudhope et al. 2001) and has evolved in response to changes in orbital parameters, CO2, the strength of the Atlantic Meridional Overturning Circulation, and other forcings (Liu et al. 2014, An and Choi 2014a). In particular, ENSO appears to have strengthened over the past 6,000 years, due to a gradual shift of Earth's perihelion from late September towards early January.

Proxy reconstructions also suggest that ENSO's variance has waxed and waned over the last few centuries (McGregor et al. 2013; Li et al. 2013). Figure 2 shows a multi-proxy synthesis based on 14 previous studies, which suggests that ENSO's SSTAs during 1979-2009 were significantly stronger than anytime during 1590-1880. In the broader context of the past 7,000 years, ENSO's recent variance does not appear to have been unusual (Cobb et al. 2013; Carré et al. 2014). Uncertainties remain due to the indirectness of the paleoproxy/ENSO relationship – which could evolve in time

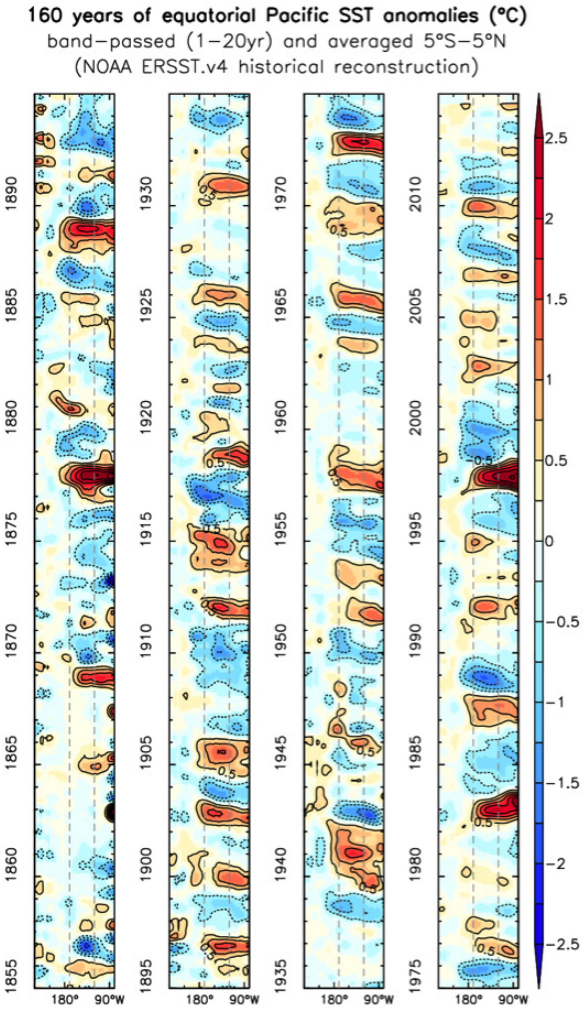

Figure 1. Longitude-time plot of equatorial Pacific ENSO SSTAs (°C, averaged 5°S-5°N) during 1855-2014 (presented as four consecutive 40-year chunks), based on the NOAA ERSST historical reconstruction version 4 (Huang et al. 2015). Contour interval is 0.5°C (zero contour omitted), and shading increments every half-contour. Gray dashed lines bracket the NINO3.4 region (170°W-120°W, 5°S-5°N). SSTAs are computed from monthly total SSTs by subtracting a 1981-2010 monthly climatology. The resulting SSTA time series is end-padded with zeros and then band-pass filtered, by first removing a convolution with a 211-month triangle, and then convolving with a 9-month triangle. The filter transmits >50% amplitude at spectral periods between 1-20yr; >90% between 2.4-12yr; and <10% outside 0.6-50yr.

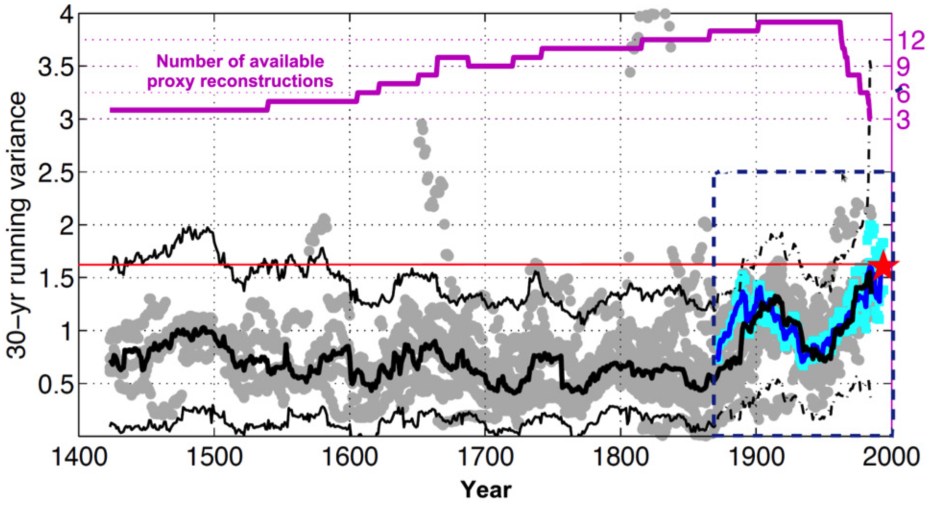

Figure 2. Proxy-reconstructed central Pacific ENSO SSTA variance over the past 600 years. Cyan squares indicate the 30-year running variance (left axis) of annual-mean (July-June) SSTAs averaged over the NINO3.4 region (170°W-120°W, 5°S-5°N), from 4 different instrumental reconstructions; blue line is their median. Magenta line indicates the number of available proxy reconstructions (right axis) based on corals, tree rings, and lake sediments. Gray dots show the 30-year running variance of the individual proxy reconstructions, each adjusted to match the instrumental variance (blue line) during 1900-1977; the thick black line is their median. Thin black lines give a proxy-based 90%-confidence band for the true running variance. Red line and star indicate the observed variance during 1979-2009. Adapted from Figure 7 of McGregor et al. (2013).

and might be poorly constrained from short instrumental records (Coats et al. 2013; Stevenson et al. 2013; Russon et al. 2015). For example, Emile-Geay et al. (2013) found that the particular choice of 20th-century instrumental dataset, used to calibrate proxy records to SSTs, exerted substantial leverage on reconstructions of the last millennium. Improved instrumental records, then, could improve understanding of ENSO not only for the instrumental era, but also farther back into the past.

An intrinsic component of ENSO modulation

General circulation model (GCM) studies have shown that multi-decadal fluctuations in ENSO behavior can occur even with no change in external forcings (Wittenberg 2009; Stevenson et al. 2012; Borlace et al. 2013). These fluctuations can then affect global climate on multi-decadal scales (Vimont 2005; DiLorenzo et al. 2010; Ogata et al. 2013). Some studies have attributed ENSO's modulation to changes in ENSO stability, driven by decadal-scale variations in the background state of the tropical Pacific and elsewhere (An & Wang 2000; Kravtsov 2012; Kang et al. 2014; Xie et al. 2014; Lübbecke and McPhaden 2014). Others have even posited a coupled feedback loop between ENSO and decadal-scale climate modes (Ogata et al. 2013; Choi et al. 2012, 2013a).

It is easily demonstrated that spontaneous multidecadal modulation can arise even from an unforced, purely memoryless process with an interannual time scale (Wittenberg 2009). Stripped-down models of ENSO, which explicitly omit interactions with external decadal modes, have also displayed intrinsic modulation that resembles observations in many respects (Cane et al. 1995; Timmermann et al. 2003; Newman et al. 2011a,b; Choi et al. 2013b). Wittenberg et al. (2014) recently showed that epochs of extreme ENSO behavior in a GCM control run could be completely disrupted by a tiny perturbation – suggesting that the intrinsic component of ENSO modulation, despite any influence it might feel from interaction with the decadal background state, is essentially chaotic and unpredictable. It remains an open question whether the ENSO modulation in models is inherently more or less predictable than in the real world (Karamperidou et al. 2014; Eade et al. 2014).

Impacts of increasing CO_2

Numerous studies have demonstrated that both natural and anthropogenic forcings can alter ENSO, in a manner detectable with sufficiently long records or large ensembles (Cane 2005; Vecchi and Wittenberg 2010; Collins et al. 2010; Li et al. 2013). But nature will provide just one realization of ENSO over the coming decades. So what will be the dominant drivers of near-term changes in ENSO behavior, and how long must we wait to detect anthropogenic impacts?

Figure 3 (next page) shows that the answer may depend on the variable and location of interest. In panel (a) for the western equatorial Pacific, each blue dot corresponds to a single 30-year chunk from a preindustrial (1860) control run of a coupled GCM. The vertical axis is the mean SST in that 30-year chunk relative to the longer-term mean of the 1860 run, while the horizontal axis is the percent amplification of ENSO SSTAs in that chunk relative to the long-term average amplitude. The horizontal spread of the blue dots represents the unforced, intrinsic modulation of ENSO amplitude among the 30-year chunks - which spans roughly a factor of two. The western equatorial Pacific cools slightly during intrinsically-generated, active-ENSO epochs, and the linearity of this relationship suggests that much of the multidecadal variability in this region is linked to ENSO modulation.

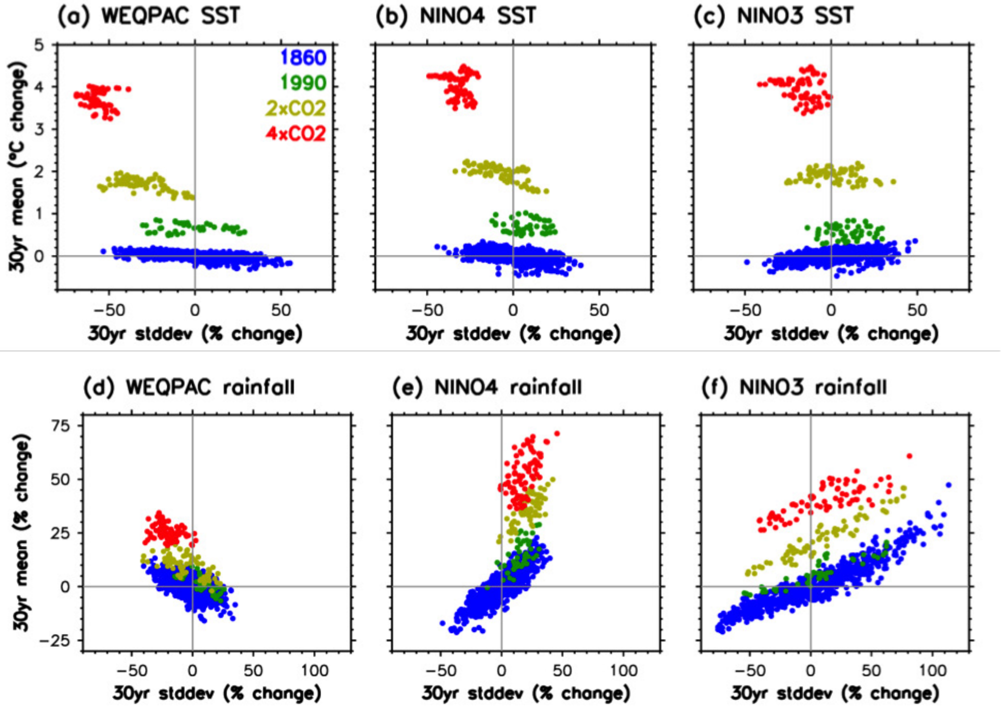

Figure 3. Scatterplots of local climate change versus local ENSO amplification, for equatorial Pacific SST and rainfall simulated by the GFDL CM2.1 global coupled GCM. Panel titles indicate averaging regions: WEQPAC (120°E-160°E, 5°S-5°N), NINO4 (160°E-150°W, 5°S-5°N), and NINO3 (150°W-90°W, 5°S-5°N). Dots indicate statistics for sliding 30-year windows sampled at 5-year intervals. Blue dots are from a 4000-year control run with solar irradiance, land cover, and atmospheric composition held fixed at pre-industrial (1860) values, and CO_2 at 286 ppmv. Green dots are from a 300-year control run with modern (1990) forcings, and CO_2 at 353 ppmv. Yellow (red) dots are from the last 400 years of a 600-year run in which all forcings are as in the pre-industrial run, except for CO_2 which increases 1% per year until doubling (quadrupling), after which CO_2 is held fixed at 572 (1144) ppmv. Abscissa indicates the percent departure of local ENSO amplitude (30-year standard deviation of running annual means) from the pre-industrial 4000-year mean amplitude. Ordinate indicates the departure of the local 30-year mean climate from the pre-industrial 4000-year mean, expressed as (a,b,c) °C of SST, or (d,e,f) percent of rainfall.

As CO_2 increases to 1990 conditions (green), then doubles (yellow) or quadruples (red) relative to 1860, the west Pacific SSTs in this model warm to previously unprecedented levels on the vertical axis - far outside the range of intrinsic variations (blue). The mean warming at this location could thus easily be detected within just 30 years, against the backdrop of intrinsic (mostly ENSO-driven) multidecadal variability in the 1860 run. Also as CO_2 increases, the ENSO SSTAs weaken (shift to the left). Given the horizontal overlap between the yellow and blue dots, the weaker ENSO at doubled CO_2 could take many decades to detect against the backdrop of ENSO modulation; but eventually the reduction in active-ENSO epochs, and the decreased interdecadal modulation (horizontal spread) of ENSO amplitude, would become obvious. At quadrupled CO_2, these ENSO changes might well be detected with just 30 years of data.

The eastern equatorial Pacific (Figure 3c) tells a different story. The blue dots indicate that east Pacific mean SSTs tend to *warm* slightly during active-ENSO epochs, the opposite of the western Pacific. This is consistent with recent studies (Ogata et al. 2013; Sun et al. 2014; An and Choi 2014b). Then as CO_2 increases, ENSO SSTAs at first strengthen up to present-day values of CO_2, then weaken at even higher CO_2. This suggests that there might be an "optimal climate" for ENSO SSTAs in the eastern/central Pacific - perhaps around present-day values of CO_2. If so, then the future of ENSO would depend not only on spatial location, but also on how close the tropical Pacific was to that climate optimum, and which side it was currently on. Taking Figure 2 at face value, one might be tempted to suggest that the increased activity during 1979-2009 evidenced an anthropogenic boost in ENSO; but Figure 3c cautions that many decades might be needed to reliably detect such a signal in the east Pacific, and that ENSO's fortunes could even reverse at still higher CO_2.

The story is even more interesting for rainfall. Looking in the central and eastern Pacific (Figure 3e,f) at the blue dots, we see that strong-ENSO epochs are associated with much wetter mean conditions (Watanabe and Wittenberg 2012; Watanabe et al. 2012). The tight relationship again suggests that most of the intrinsic decadal-scale variability in those regions could arise from chaotic ENSO modulation. The relationship also holds at higher values of CO_2, though at a much warmer and wetter level. The opposite holds in the west Pacific (Figure 3d), with drier mean conditions during active-ENSO epochs.

In the eastern equatorial Pacific (Figure 3f), the CO_2-induced changes in time-mean rainfall along the vertical axis would be obscured in short records, due to the (largely ENSO-driven) intrinsic multidecadal variations in rainfall, which causes overlap of the red and blue dots in the vertical. Similarly, changes in the amplitude of ENSO rainfall anomalies might take centuries to detect, though the decrease in amplitude modulation would eventually become apparent. But note that the yellow and red dots *do not* overlap the blue in two dimensions - thus for a *known* ENSO amplitude in a single 30-year record, it would actually be quite easy to detect a CO_2-induced enhancement of mean rainfall.

Farther west (Figure 3d,e), increased CO_2 in this simulation boosts the time-mean rainfall to unprecedented levels along the vertical axis. At the same time, the ENSO rainfall variability shifts eastward along the equator, with less variance in the west and more in the central Pacific. For the central equatorial Pacific then, increased CO_2 could *enhance* ENSO rainfall variability, despite *weakened* SSTAs (rightward shift of red dots in Figure 3e, leftward shift of red dots in Figure 3b). Most model studies suggest that in the Pacific of the future, the time-mean warming at the equator will exceed that off-equator (Liu et al. 2005; Xie et al. 2010). This could make near-equatorial rainfall more sensitive to equatorial SSTAs, especially in the central Pacific; indeed this appears to be a robust response among most climate models (Power et al. 2013; Cai et al. 2014; Watanabe et al. 2014).

Thus changes in ENSO may vary regionally, and affect different stakeholders in different ways. For a given level of CO_2, some regions could see robust increases or decreases in variability of SST or rainfall within only a few decades, while other regions might not detect ENSO changes for much longer. However, it is clear from Figure 3 that at each location, changes in CO_2 greatly alter the *likelihood* of hitherto "extreme" epochs (the fringes of the blue dots). Thus for these regions we would expect not only unprecedented increases in the *mean* SST and rainfall, but also big changes in the likelihood of epochs of strong and weak ENSO variability.

Results from CMIP projections

The Coupled Model Intercomparison Project phases 3 and 5 (CMIP3, CMIP5) tell a rather murky story about the future of ENSO - with projections ranging from strengthening, to weakening, to a change in spatial pattern, to no significant change (Vecchi and Wittenberg 2010; Collins et al. 2010; Stevenson et al. 2012; Watanabe et al. 2012; Guilyardi et al. 2012; Taschetto et al. 2014; Capotondi et al. 2015). Models at least project that ENSO will neither vanish nor explode over the coming century, with the IPCC Fifth Assessment concluding that *"there is high confidence that ENSO very likely remains as the dominant mode of interannual variability in the future… However, natural modulations of the variance and spatial pattern of ENSO are so large in models that confidence in any specific projected change in its variability in the 21st century remains low"* (Christensen et al. 2013).

Based on an analysis of CMIP3 projections, DiNezio et al. (2012) found that a competition of changes in ocean-atmosphere feedbacks tempers ENSO's response to anthropogenic forcings. A projected future weakening of the Pacific Walker Circulation (Vecchi et al. 2006) would tend to weaken equatorial oceanic upwelling – attenuating ENSO by weakening the influence of thermocline depth fluctuations on SSTs. On the other hand, CO_2-induced intensification of oceanic thermal stratification would boost subsurface zonal and vertical temperature contrasts along the equator – amplifying ENSO by strengthening the influence of zonal and vertical current fluctuations on SST. Given this competition, it is perhaps not surprising that models – which exhibit a wide range of strengths for these competing processes – also exhibit a wide range of ENSO responses to increasing CO_2.

Challenges and opportunities

The models used to project low-frequency variations in ENSO have known biases (see article by Capotondi et al., this issue). A model with the wrong level of intrinsic variability, incorrect forcings, or wrong sensitivity to forcings, might well produce a biased projection of ENSO. The projected eastward/equatorward shift of future ENSO rainfall variability (Figure 3d,e), for example, depends on SSTs in the equatorial/eastern Pacific warming faster than the off-equatorial/western Pacific (Grose et al. 2014). But a debate continues on whether that will be the case in the real world (Tokinaga et al. 2012; Newman 2013; DiNezio et al. 2013; Yang et al. 2014; Carilli et al. 2014; Sandeep et al. 2014; Bayr et al. 2014; Kociuba and Power 2015). Improved models, and better understanding of how to extrapolate from biased models to real-world sensitivities, are both greatly needed.

A major challenge for improving climate models is that the complex interplay of ENSO feedbacks – involving surface air-sea fluxes, atmospheric convective and cloud feedbacks, and three-dimensional oceanic advection and mixing - is not well constrained from the available instrumental record, in part because that record is short, and ENSO and its feedbacks are interdecadally modulated (Wittenberg 2009; Russell and Gnanadesikan 2014). Advances in data assimilation (Rosati et al., this issue) offer potential improvements in this regard. Going forward, there will be a continuing need for sustained tropical Pacific observing systems, as well as improved instrumental and paleo reconstructions of the past, to advance understanding, improve models, and enable clearer projections of ENSO's future.

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