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Climate Change and Impacts on Variability and Interactions

ANNY CAZENAVE, GERALD MEEHL, MARISA MONTOYA,
J. R. TOGGWEILER, AND CLAUDIA WIENERS

9.1 Introduction

Climate change induced by human activity will impact the oceans in unprecedented ways. Interactions among ocean basins are also expected to change, and much effort will be required to better understand and predict these changes. This chapter starts by an overview about projected changes in processes participating in ocean interactions and mentioned in previous chapters. The overview starts with the intensity and frequency of the Pacific and Atlantic Niños. This is followed by a review of decadal climate modes in the Pacific and other basins, as well as past climate shifts in the Pacific. The following two sections discuss the ocean's thermohaline circulation, its projected changes, and its potential collapse. The last section addresses present-day and future global mean sea level rise and its geographical variations due to ocean warming and land ice loss (from glaciers, Greenland, and Antarctica).

9.2 Tropical Variability Changes with Global Warming: Pacific and Atlantic Niños under Climate Change

The Pacific and Atlantic Niños are the result of a delicate balance of positive and negative feedbacks whose strength depends on the background state. Although Paleo records suggest that at least the Pacific ENSO (El Niño/Southern Oscillation) has existed in many different past climates (Lu et al., 2018), it is quite plausible that its characteristics (amplitude, period, spatial pattern, frequency of "extreme events") may change under climate change. Lenton et al. (2008) even listed changes of ENSO as one of the potential disastrous "tipping elements" that may be activated under global warming. But can we predict how El Niño will behave in the future?

9.2.1 Observational Evidence

Zhang et al. (2008) found that the 10-year running standard deviation of Niño3 increased by 60% in 1955–2003 and suggested climate change as the cause. However, the next decade showed a relatively quiescent ENSO. Can we infer ENSO changes from observations?

Reanalysis data of tropical Pacific sea-surface temperature (SST) is available from the end of the nineteenth century, although observations were sparse before World War II. The Tropical Atmosphere Ocean (TAO) buoy array was only established in 1985–1994. This makes it difficult to define a "pre-industrial ENSO" from observations. Paleo data suggest that the ENSO amplitude has decadal and centennial variability (Lu et al., 2018). In the twentieth century, ENSO variability was comparatively strong, but there may have been earlier periods with comparable ENSO amplitudes. Thus, Paleo data gives no clear evidence for changes in ENSO amplitude caused by climate change. Wittenberg (2009) found strong decadal and centennial variability of the ENSO amplitude in the GDFL-CM2.1 model. This should further caution us against overinterpreting possible trends in the short observational record.

Not only the amplitude, but also the spatial pattern of ENSO might change. In recent decades, the Central Pacific type of El Niño has become more frequent (Ashok et al., 2007). Again, this may well be due to decadal variability rather than climate change.

9.2.2 ENSO Projections in GCMs

The most obvious approach to investigate future ENSO changes is to define measures of interest (e.g., the amplitude of the Nino3.4 index) and compare their present and future values in GCM (General Circulation Model) simulations. Note that most studies investigating ENSO changes in CMIP (Coupled Model Intercomparison Project)-ensembles use (the latter part of) the twenty-first century as "future" ENSO, i.e., a time during which at least the subsurface ocean is not equilibrated, and hence transient effects could play a role.

Both CMIP3 and CMIP5 models disagree even on the sign of the change in ENSO amplitude. Collins et al. (2010) find that of seventeen CMIP3 models, five show a significant decrease in ENSO amplitude and four a significant increase. Similarly, Stevenson (2012) finds that out of eleven CMIP5 models which have ensembles of at least three members for historical and one or more future simulations, three find a significant increase and one a significant decrease in ENSO amplitude.

What could be the cause for this disagreement? One possibility could be that potential changes in ENSO are masked by decadal and centennial variability, as suggested by Wittenberg (2009). In that case, large ensembles and/or long simulations would be needed to detect changes in ENSO. Note, however, that DiNezio et al. (2012) find that the change between preindustrial and 2xCO_2 simulations in CMIP3 for many models is larger than centennial variability in the preindustrial run, and that the model used by Wittenberg (2009) has an unusually strong centennial variability.

If the inter-model disagreement on ENSO change is not mainly due to long-term variability, can we then identify which models are "correct"? One way to judge model reliability is to check their ability to represent the present or the past. However, selecting only the six models judged to have the most realistic present-day ENSO does not enhance agreement on future changes (Collins et al., 2010). This is in line with Knutti et al. (2010) who find that enhanced skill to reproduce current climate variables often fails to reduce the inter-model spread in future projections. Better model performance in some simple metrics like ENSO amplitude or period does not necessarily imply a better representation of the underlying processes but may be due to error compensation: Bellenger et al. (2014) found an improvement in ENSO variability scores from CMIP3 to CMIP5, while scores quantifying underlying feedbacks improved much less. As mentioned, it may be difficult to even define "realistic" present-day or preindustrial ENSO because of the scarcity of observations.

Thus, if one attempts to select or weigh "realistic" models, it may also be worthwhile to use other metrics than those directly measuring ENSO properties, for example focusing on feedbacks underlying ENSO or the mean climate, as the background state is known to impact variability. Two systematic mean state biases in the tropical Pacific occur in many GCMs which may impact ENSO are the double ITCZ (Intertropical Convergence Zone) bias and the cold-tongue bias (Mechoso et al., 1995; Li and Xie, 2014; Ferrett et al., 2017); the former may be linked to atmospheric feedbacks in ENSO, while the latter, which involves a too large westward extend of the Pacific cold tongue, may affect the spatial pattern of ENSO. As a caveat, Latif et al. (2001) already pointed out that a more realistic background state not necessarily leads to a more realistic ENSO variability.

A step back from selecting "realistic" models to predict future changes could be a reverse approach, namely searching for common features among models (or even ensemble members) showing increasing or decreasing ENSO amplitudes. One such attempt by Ham and Kug (2016) finds a correlation between Niño3 amplitude change and a tripole pattern of present-day precipitation, whereas Zheng et al. (2016) link ENSO amplitude increase to higher mean SSTs in the east (leading to stronger SST-wind coupling through enhanced convection). While such approaches can potentially enhance our understanding of relevant mechanisms in GCMs, statistical relationships should be backed up by physical insight to reduce the risk of hunting spurious correlations.

Although no robust change of the ENSO-related SST variability has been found, changes in precipitation and teleconnections may still be detected. Cai et al. (2014) define "extreme El Niño" as events where the precipitation over Niño3 in December–February exceeds 5mm/day and find a doubling in frequency for such events between 1891–1990 and 1991–2090. The reason is that under global warming, even moderate warm SST anomalies lead to absolute SST values above 28°C (the threshold for deep convection) over Niño3. Changes in deep convection in turn influence atmospheric teleconnections and the likelihood of subsequent extrema La Niña.

9.2.3 Mechanism-Based Understanding of ENSO Change

While CMIP projections greatly disagree on future ENSO behavior, the agreement for the background state is closer. Global warming affects the surface ocean more quickly than deeper layers (a transient effect), leading to increased stratification, a shallower mixed layer and a sharper thermocline. The region with SSTs above 28ºC expands eastwards, leading to a larger area suitable for deep atmospheric convection. Apart from these regions, convection is expected to decrease because of the generally more stable atmospheric stratification (Philip and Oldenburg, 2006).

The tropical atmospheric circulation is expected to weaken: It has been argued that while the boundary layer moisture increases under global warming by 7%/K (following Clausius–Clapeyron), the evaporation rate increases only by 2%/K. This implies an increase in residence time of the moisture, which must be linked to a decrease in vertical motion (Held and Soden, 2006). This weakens the Hadley and Walker circulations and thus the equatorial easterlies. In the Ocean, equatorial divergence and upwelling is therefore predicted to decrease, leading to enhanced heating along the equator. In the last 3 decades, the Walker circulation actually strengthened, possibly due to interannual-interdecadal Pacific variability or influence from neighboring oceans (Cai et al., 2015b).

A weakening Walker circulation contributes toward reducing the zonal SST gradient: Weakening upwelling and westward currents should reduce East Pacific cooling and lead to a flatter thermocline (less zonal tilt). However, the thermocline is also predicted to shoal (decreasing depth). While shoaling and flattening combine in the West Pacific to reduce thermocline depth, they counteract in the East, where thermocline depth is most relevant for ENSO. In addition, the effect of reduced upwelling could be balanced by stronger stratification which makes the “remaining” upwelling more effective (Seager and Murtugudde, 1997). Cloud-Albedo feedback (ocean warming causing cloud formation and hence shading) might be strongest in the West, contributing to a reduced SST gradient (Meehl and Washington, 1996). Most models predict a reduced SST gradient.

The changes described in the background state can affect the ENSO amplitude. In the following, (+) and (−) denote feedbacks which enhance or reduce ENSO, respectively, under climate change.

Thermocline and Upwelling Feedback. Background upwelling in the Pacific leads to surface cooling, especially when the vertical temperature gradient is high, i.e., during El Niño. Due to this asymmetry, weaker background upwelling reduces ENSO damping (+). On the other hand, reduced upwelling also decreases the effect of thermocline depth variations on the SST (−). At least in the Zebiak–Cane (ZC) model, the latter effect is dominant (−) (Wieners et al., 2017). Similarly, an increased mean thermocline depth in the East Pacific would reduce the effect of upwelling anomalies on the SST (reducing ENSO) but also the vertical temperature gradient, especially during El Niño. However, as explained, it is unclear whether the thermocline will deepen or shoal in the East Pacific. A sharpening of the thermocline can enhance the effect of upwelling variability on the SST (+).

Wind Response. SST anomalies induce diabatic heating by triggering convection and thus latent heat release, which will cause high-level divergence and surface convergence (Gill, 1980). This response is strongest in regions with high background SSTs, where convection is easily triggered. Hence the SST-wind coupling is expected to increase over the equatorial Pacific(+), while on the other hand, a more stable overall stratification of the atmosphere might suppress convection and counter the SST effect (−) (Philip and Oldenburg, 2006).

Other Processes. Additional processes that may alter ENSO properties include changes in radiative damping (e.g., due to changes in cloud cover; sign currently uncertain) and reduced mixed-layer depth reducing thermal inertia (+). The sharper thermocline may affect the phase speed of Kelvin and Rossby waves. Finally, intraseasonal variability such as the Madden–Julian Oscillation, which can trigger ENSO events, may change their characteristics (sign unknown).

Many processes with opposing signs can affect the amplitude and other characteristics of ENSO under global warming, and the disagreement among CMIP models likely arises because each model has a slightly different balance between competing effects. Investigating the relative importance of the effects is still a difficult task.

9.2.4 The Atlantic Niño

Changes of the Atlantic Niño under global warming are hardly studied. The Atlantic Niño follows similar dynamics to its Pacific counterpart but is more damped and therefore more dependent on external forcings (e.g., from the Pacific ENSO). Projecting changes in the Atlantic Niño may therefore be even more difficult than for the Pacific, because the change in external forcings may play a more important role. In addition, severe model biases are present in the tropical Atlantic, with little improvement from CMIP3 to CMIP5, and models generally perform poorly in representing the Atlantic Niño (Richter et al., 2014), giving little confidence in future projections. However, as in the Pacific case, even if the oceanic characteristics of the Atlantic Niño remain unchanged, its impact on atmospheric teleconnections might increase (Mohino and Losada, 2015).

9.2.5 Ongoing and Future Research

One obvious, but hard to achieve, task would be to reduce model biases such as the double ITCZ and cold tongue biases. An alternative approach could be to better understand how the strength of feedbacks depend on the background state. A first step would be to systematically analyze existing model output using the Bjerknes index or more sophisticated heat budget analysis tools (Graham et al., 2014) to quantify the relative importance of feedbacks in various models (as Wang et al., 2019 do for the Representative Concentration Pathway [RCP] 8.5 scenario in the Community Earth System Model [CESM]). As a next step, expanding work like Zheng et al. (2016) and Ham and Kug (2016), the strengths of these feedbacks should be statistically linked to properties of the background state (see also Kim et al., 2014 and Bayr et al., 2018 for present-day simulations in CMIP5). This could lead to statements like “models with a strong vertical stratification typically have a strong upwelling feedback”. Comparison can be carried out among different projections (e.g., preindustrial vs RCP scenarios), different models and even different ensemble members, in case the model shows strong interdecadal or centennial variability. However, care should be taken not to confuse equilibrium changes and transient ones (in particular, strong surface heating). As a third step, dedicated model experiments with perturbed background states could be performed, possibly in an ocean-only or atmosphere-only setting. For example, the SST could be artificially increased by a fixed amount in the equatorial Pacific to investigate the changes in the wind-SST-coupling strength due to changing convection characteristics, or the mean zonal wind stress could be reduced to mimic a weakening

Walker and Hadley circulation. Seeing that GCMs agree better on the mean climate change than on ENSO changes, a sound knowledge of how various feedbacks depend on the background climate might provide an indirect approach to predicting the future of ENSO, although quantifying the relative importance of competing feedback mechanisms remains a daunting task.

9.3 Climate Shifts in the Pacific and Global Influences

9.3.1 Pacific Decadal Variability

ENSO-like decadal-timescale variability in the Pacific distinct from interannual ENSO variability was identified by Zhang et al (1997) using an Empirical Orthogonal Function (EOF) analysis. Their phrase "ENSO-like" referred to a pattern where the tropical Pacific SST anomalies are opposite in sign to those in the northwest and southwest Pacific. The ENSO interannual pattern in that paper was more confined to the near-equatorial region, while the decadal pattern was spread poleward in the Pacific tropics to nearly the subtropics with largest values in the central equatorial Pacific, with same-sign anomalies extending across the tropical Pacific and opposite-sign anomalies in the northwest and southwest (Figure 9.1a and b).

A number of subsequent studies looked at different aspects of this Pacific decadal variability. In one, EOFs were calculated for the Pacific north of 20°N and the resulting pattern was dubbed the "Pacific Decadal Oscillation" (PDO, Mantua et al., 1997; Mantua and Hare, 2002; Newman et al., 2016). Even though the EOF calculation used only northern Pacific SSTs, the projection of the PC (principal component) time series back onto the entire Pacific basin showed nearly the same ENSO-like Pacific decadal variability pattern as that in Zhang et al. (1997). Calculating EOFs using SSTs for the entire Pacific basin, Folland et al. (1999) and Power et al. (1999) also found an ENSO-like Pacific decadal variability pattern that they dubbed the "Interdecadal Pacific Oscillation" (IPO). The basin-wide patterns of the PDO and IPO, and their PC time series, are comparable (+0.88 correlation), but differ considerably from decadal variability in the Indian Ocean (Han et al., 2014) (Figure 9.1e). Therefore, in the subsequent literature the IPO and PDO have been used interchangeably. More recent efforts have attempted to revise the terminology and refer to decadal variability in the Pacific region more generically as "Pacific Decadal Variability" (PDV) which would include both IPO and PDO (Cassou et al., 2018). Thus, the literature contains references to IPO, PDO and PDV, but all are referring to the same phenomenon: decadal-timescale variability with an SST anomaly pattern that resembles ENSO but with tropical Pacific SST anomalies that extend to nearly the subtropics and across the basin, with largest values in the central equatorial Pacific and opposite sign anomalies to the northwest and southwest. The IPO positive phase is when tropical Pacific SSTs are somewhat above normal, and vice versa for the IPO negative phase (Figure 9.1a and b).

Long control runs with Earth System Models show this decadal pattern as the first EOF of low-pass filtered SSTs (e.g., Henley et al., 2015) (Figure 9.1c and d). Since only internal