Can the response to global warming be La Niña-like?

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Abstract

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The majority of the models that participated in the Coupled Model Intercomparison Project Phase 5 global warming experiments warm faster in the eastern equatorial Pacific Ocean than in the west. GFDL-ESM2M is an exception among the state-of-the-art global climate models in that the equatorial Pacific sea surface temperature (SST) in the west warms faster than in the east, and the Walker circulation strengthens in response to warming. This dissertation shows that this “La Niña-like” response simulated by GFDL-ESM2M could be a physically consistent response to warming, and that the forced response may be detectable during this century.

To highlight the uniqueness of GFDL-ESM2M, two other models are also examined: GFDL-ESM2G, which differs from GFDL-ESM2M only in the oceanic components, warms without a clear change in the zonal SST gradient in the tropical Pacific; HadGEM2-CC exhibits a warming pattern that resembles the multi-model mean, with more warming in the eastern than western Pacific. A fundamental observed constraint between the amplitude of the El Niño Southern Oscillation (ENSO) and the mean-state zonal SST gradient is reproduced well by GFDL-ESM2M, but not by the other two models, which display substantially weaker ENSO nonlinearity than is observed. Under this constraint, the weakening nonlinear ENSO amplitude in GFDL-ESM2M rectifies the mean state to be La Niña-like. GFDL-ESM2M exhibits more realistic equatorial thermal stratification than GFDL-ESM2G, which
appears to be the most important difference for the ENSO nonlinearity and the warming response. On longer time scales, the weaker polar amplification in GFDL-ESM2M may also explain the origin of the colder equatorial upwelling water, which could in turn weaken the ENSO amplitude.

Using an idealized model, we further explore the cause of this exceptional response and propose a new mechanism, the Nonlinear ENSO Warming Suppression (NEWS), where the transient heating rate difference between the atmospheric and oceanic reservoirs annihilates extreme El Niños, causing a suppression of mean-state warming in the east. Heat budget analyses of GFDL-ESM2M robustly show that nonlinear dynamical heating, which is necessary for extremely warm El Niños, becomes negligible under warming. An idealized nonlinear recharge oscillator model suggests that, if the temperature difference between the atmospheric and oceanic reservoirs becomes larger than some threshold value, the upwelling becomes too efficient for ENSO to retain its nonlinearity. Therefore, extreme El Niños dissipate but La Niñas remain almost unchanged, causing a La Niña-like mean-state warming. NEWS is consistent with observations and GFDL-ESM2M but not with the majority of state-of-the-art models, which lack realistic ENSO nonlinearity. NEWS and its opposite response to atmospheric cooling, the Nonlinear ENSO Cooling Suppression (NECS), might contribute to the Pacific multi-decadal natural variability and global warming hiatuses.

Then, to explore necessary conditions of NEWS, the ENSO amplitude response to global warming is examined in two global climate models with realistic nonlinearity of the El Niño Southern Oscillation (ENSO). GFDL-ESM2M and MIROC5 are the two models that exhibit realistic ENSO nonlinearity. With quadrupled atmospheric carbon dioxide, the ENSO amplitude of GFDL-ESM2M decreases by about 40%, whereas that of MIROC5 remains almost constant. Because GFDL-ESM2M exhibits stronger climatological thermal stratification than MIROC5, greenhouse gas forcing increases the upper ocean stability and causes the thermocline to be less sensitive to wind perturbations. The stiffer thermocline inhibits
the large, nonlinear variations of subsurface temperature anomalies so that the ENSO amplitude substantially weakens. Idealized nonlinear recharge oscillator model experiments further support climatological thermal stratification as a determinant of the warming response. Observations exhibit stronger thermal stratification than both models, so the real world may terminate strong, nonlinear El Niños sooner than model-based projections. Based on the NEWS mechanism, this physical explanation for the termination of extreme El Niños supports the notion that the response to global warming could be La Niña-like.
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DEDICATION

to my beloved wife, my dear son,
and my esteemed parents.

Rikako Kohyama
Taku Kohyama
Kazunori Kohyama
Hiromi Kohyama
Chapter 1

INTRODUCTION

The tropical Pacific Ocean has profound impacts on the global climate system, and the response of this region to anthropogenic greenhouse gas forcing has been a controversial research topic since the late 20th century [e.g., Knutson and Manabe, 1995; Cane et al., 1997; Collins et al., 2005; DiNezio et al., 2009; Collins et al., 2010; Xie et al., 2010]. The recent multi-decadal trends of the zonal sea surface temperature (SST) gradient along the equator and its projection under global warming have received particular attention because of its potential impacts on both the tropical and extratropical weather and climate [e.g., Christensen et al., 2013]. The projected influence in relation to the SST warming pattern is not limited to the mean-state land temperature and precipitation changes; it extends to many other climatological elements, such as frequency of tropical cyclone genesis [e.g., Yokoi and Takayabu, 2009; Murakami et al., 2012] and Antarctic sea ice trends [e.g., Kohyama and Hartmann, 2016].

In this dissertation, we hereafter call a climatological warming pattern “El Niño-like” (“La Niña-like”) when the east (west) equatorial Pacific warms faster than the west (east) equatorial Pacific. Many studies intentionally avoid these terms, which are associated with the El Niño Southern Oscillation (ENSO), 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 explained by Collins et al. [2010]. Other studies, however, continue to use ENSO terminology to characterize the structure of global change [e.g., Held et al., 2010; An et al., 2012] presumably because no other simple, lucid way to describe them has been proposed. We have decided to follow the latter, but we shall use these terms carefully in the sense that ENSO is an interannual climate mode that modulates anomalies
from the mean state, and that it is not necessarily controlled by the factors that control changes in the mean state under greenhouse warming.

The majority of the models that participated in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5) exhibit El Niño-like SST trends under global warming projections, and therefore, the multi-model mean SST trend pattern is also El Niño-like [e.g., Collins et al., 2010; Huang and Ying, 2015; Ying et al., 2016; Zheng et al., 2016]. This SST trend pattern has been believed to be associated with the weakening Walker circulation as explained by Held and Soden [2006] and Vecchi and Soden [2007] from the perspective of the global hydrological cycle. In agreement with this, some studies reported that the observed sea-level pressure gradient along the equatorial Pacific reduced during the past century [e.g., Vecchi et al., 2006; Zhang and Song, 2006; Tokinaga et al., 2012a]. Some observational SST datasets support this viewpoint (Fig. 1.1a, right), though previous studies suggest that the long-term SST trend in the datasets is sensitive to the time period chosen for analysis [e.g., Meng et al., 2012].

On the contrary, other observational SST datasets suggest that the zonal SST gradient along the equator has increased during the past century (Fig. 1.1a, left). Some studies based on observed sea-level pressure trends [e.g., L’Heureux et al., 2013] and paleoproxies [e.g., An et al., 2012] support this evidence as well. The observational uncertainty of the SST and sea-level pressure trends mostly comes from limited data sampling, changing measurement techniques, and different analysis procedures [Christensen et al., 2013]. Though we have better datasets based on satellite observations for the late historical period (1979-2005) that also show a clear La Niña-like trend (Fig 1.1b, upper left), we cannot determine, based on the short time span, whether the trend is purely unforced natural multi-decadal variability or partly a forced response to anthropogenic climate change. Some model-based studies convincingly show that the fast response to global warming should be La Niña-like and the slow response should be El Niño-like [Held et al., 2010; An et al., 2012; Xiang et al., 2014], but this hypothesis has been difficult to test using observations.

The scientific question we address in this dissertation is whether a reasonable explanation
Figure 1.1: (a): Observed sea surface temperature (SST) trends computed relative to the tropical Pacific mean trends (30°S-30°N, 90°E-60°W; black box) in two different datasets. Blue colors denote a warming slower than the tropical Pacific mean, not a cooling. Unit is °C/100 years. (b): As in (a), but for the late historical period. Observations are from the ERA-Interim dataset, and the model output are from the historical runs of GFDL-ESM2M, GFDL-ESM2G, and HadGEM2-CC. Unit is °C/27 years. (c): As in (a), but for GFDL-ESM2M in the RCP 6.0, RCP 8.5, and 1pctCO2 experiments (c-1) and GFDL-ESM2G and HadGEM2-CC under RCP 8.5 (c-2).
can be given to support the notion that the forced response of the mean-state equatorial Pacific to greenhouse warming may actually be La Niña-like. Some earlier studies at the end of the last century showed that the global warming trend should be associated with a La Niña-like SST trend because of a so-called “Ocean Dynamical Thermostat” mechanism [Clement et al., 1996; Cane et al., 1997]. This mechanism, however, was simulated by the Cane-Zebiak model [Zebiak and Cane, 1987], which assumes that the temperature of the climatological upwelling water in the eastern equatorial Pacific remains fixed as a boundary condition under global warming. This assumption is now thought to be problematic, and after this, La Niña-like SST trends associated with global warming has been largely unexplored using state-of-the-art global climate models (GCM) or Earth system models (ESM). This question is still interesting in the sense that, if the warming response is La Niña-like, the recent robust Pacific SST trend during the late historical period (Fig. 1.1b, upper left) could be understood partly as a forced response rather than purely as multi-decadal variability.

This dissertation is organized as follows. Some potential oceanic roles to realize a La Niña-like response are discussed in chapter 2. Then, we propose a nonlinear mechanism for yielding a La Niña-like response in chapter 3. In chapter 4, we further investigate the mechanism and show that climatological thermal stratification may be a key to determine the warming response. Conclusion is presented in chapter 5.
Chapter 2

POTENTIAL OCEANIC ROLES

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2.1 Introduction

Regarding the mean-state SST response to global warming, an interesting member of the CMIP5 model ensemble is the GFDL-ESM2M model (hereafter “M model”) in that it produces a well-defined La Niña-like response under historical forcing (Fig. 1.1b, upper right), the representative concentration pathways (RCP) 6.0 and 8.5 global warming scenarios, and the 1-percent-per-year increase of carbon dioxide (1pctCO2) runs (Fig. 1.1c). Many studies have shown that the ENSO representation of the M model is reasonable [e.g., Bellenger et al., 2014]. The Geophysical Fluid Dynamics Laboratory (GFDL) also developed the GFDL-ESM2G model (hereafter “G model”), which differs from the M model only in its oceanic components [Dunne et al., 2012, 2013], and this model does not exhibit a clear La Niña-like response (Fig. 1.1b and 1.1c-2). Therefore, we hope to identify some important oceanic roles that determine whether the forced response simulated by these models will be El Niño-like or La Niña-like.

In this chapter, our main focus is to compare the M and G models, and also the HadGEM2-CC model (hereafter “Had model”) that exhibits similar SST trends to the multimodel mean El Niño-like pattern (Fig. 1.1c-2), to shed light on the possibility of a La Niña-like mean-state warming. Because the late historical period is only about three-decades long, the similarity of the SST trends between the observations and the M model could be exaggerated by multi-decadal natural variability. Nevertheless, the subtle but detectable
resemblance of the SST warming pattern between the historical period (Fig. 1.1b) and the global warming projections (Fig. 1.1c) in each of these three models motivates us to hypothesize that the observed SST trend during the late historical period could have already be an expression of global warming. This view may appear to be provocative in the sense that the recent La Niña-like trend has widely been believed to be pure natural variability [e.g., Christensen et al., 2013], because of the El Niño-like warming pattern in the majority of the CMIP5 models. It is a hard task to determine whether the M model captures the real world better than other models, but even if its response to warming turns out to be unrealistic, investigating model differences should help us understand the climate system better.

This chapter is organized as follows. The data used in this study are described in the next section. In section 2.3, we describe the time evolution of the zonal SST gradient simulated by the three models and associated atmospheric changes to confirm the importance of the differences. Then, in section 2.4, we show a difference in the models’ simulation of a fundamental observed constraint between the zonal SST gradient and the ENSO amplitude in relation to the ENSO nonlinearity. Moreover, by comparing the control, historical, and global warming experiments, we show that the La Niña-like response of the M model is very likely to be forced by global warming. In section 2.5, we discuss some possible mechanisms whereby the different SST warming responses might be caused by differences of climatology and warming responses in the oceanic interior. Summary and concluding remarks of this chapter are given in section 2.6.

2.2 Data and Methods

The observed monthly SST data used in this study are from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) [Rayner et al., 2003] available online at http://www.metoffice.gov.uk/hadobs/hadisst/index.html and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature V3b (ERSST V3b) [Smith et al., 2008] available online at http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html for the time span from 1870 through 2015. The
horizontal resolution is 1 degree for HadISST, and 2 degrees for ERSST V3b in both zonal and meridional direction. For the late historical period (1979-2005), we also use the monthly European Centre for Medium-Range Weather Forecasts (ECMWF) ERA Interim Reanalysis data [Dee et al., 2011] available online at http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc/ for SST (Fig. 1.1b), zonal wind and vertical motion (Fig. 2.2a) with 3-degree spatial resolution. The starting year of the late historical period (i.e., 1979) is chosen to match the starting year of the ERA-Interim dataset. On the other hand, the ending year of the late historical period (i.e., 2005) is constrained by the CMIP5 experimental design, but the results shown in observations are qualitatively similar even if we extend the time span to be 1979-2015.

The model output of the surface temperature, zonal wind, atmospheric vertical motion, precipitation, oceanic meridional and vertical mass transport, and oceanic potential temperature and density are from the CMIP5 data [Taylor et al., 2012] available at the websites of GFDL Data Portal (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp) and Program for Climate Model Diagnosis and Intercomparison (https://pcmdi.llnl.gov/projects/cmip5/). The experiments considered in this study are the first ensemble member of the preindustrial control (piControl), abrupt quadrupling of CO2 (Abrupt4xCO2), historical, RCP 6.0 and 8.5, and 1pctCO2 runs. At each depth (vertical resolution is 10 m), the oceanic variables are regridded via linear interpolation onto a 2.5° longitude by 2° latitude grid. In addition, we also refer to SST from 4,000 year-long pre-industrial control run of GFDL CM2.1 [Delworth et al., 2006; Wittenberg et al., 2006].

We have also used the RCP Concentration Calculations and Data [Meinshausen et al., 2011] available online at http://www.pik-potsdam.de/~mmalte/rcps/ to make Fig. 2.8. The time series used in this study is the RCP 8.5 anthropogenic forcing from 1860 through 2100. Then, to make Fig. 2.10a, oceanic potential temperature data from reanalysis are obtained from the National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS) [Behringer and Xue, 2004] available online at http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html. The time span used in this
study is 1980-2005 (late historical period, but 1979 is not available). The horizontal resolution is 1° longitude by 1/3° latitude, and the vertical resolution is 10 m for the depth analyzed in this study.

Monthly climatologies are calculated by taking the average for each month over the entire record. The climatology is then subtracted from the data to obtain the anomalies unless noted otherwise. All the analysis methods used in this study are simple regression, correlation, and compositing analyses. When we estimate degrees of freedom in the data for statistical tests, we use a formula given by Bretherton et al. [1999] to take autocorrelations into account.

### 2.3 SST-warming time evolutions and the Walker circulation changes

Figure 2.1 shows the spatial patterns of the bidecadal-mean SST (deviations from the global mean) starting from 2016, 2036, 2056, and 2076 expressed with respect to the decadal-mean starting from 2006. Even in the first bidecade, a hint of difference in the zonal SST gradient is already apparent, especially between the M and Had models. Then, after half a century, the three models start to show their distinct spatial structures. The last bidecadal patterns are essentially the same as those introduced in Fig. 1.1. This temporal evolution confirms that the trend patterns shown in chapter 1 are due to a gradual process during this century.

Next, we investigate the trends of the Walker circulation. Figure 2.2a shows the equatorial meridional-mean trends of zonal wind and vertical motion during the late historical period. During the historical period, both observations and the M model exhibit a strengthening of the Walker circulation. As in the SST trends, however, these trends could be dominated by multi-decadal natural variability, so we cannot use this result to demonstrate that the M model is more reasonable than the others. Nevertheless, this correspondence of the signs of these variables motivates us to hypothesize that some portion of these trends might be explained as a response to warming.

Figure 2.2b shows the same plots as in Fig. 2.2a but for the 21st-Century global warming projections in the three models of interest. The Walker circulation weakens as the SST
Figure 2.1: Left: Bidecadal mean SST (deviations from the global mean) in GFDL-ESM2M under RCP 8.5, starting from 2016, 2036, 2056, and 2076, computed relative to the decadal mean SST starting from 2006. Unit is °C/100years. Middle: As in left, but for GFDL-ESM2G. Right: As in left, but for HadGEM2-CC.
Figure 2.2: (a): Left, Observed and simulated equatorial (10°S-10°N) meridional mean trends of zonal wind during the late historical period. Observations are from the ERA-Interim dataset, and the model output are from the historical runs of GFDL-ESM2M. Contour interval is 0.2 (m/s)/27 years. Zero contours are omitted, and easterly (westerly) anomalies are shaded blue (orange). Right: As in left, but for vertical motion. Contour interval is 2 (hPa/day)/27 years. Upward (downward) anomalies are shaded blue (orange). (b): As in (a), but for GFDL-ESM2M, GFDL-ESM2G, and HadGEM2-CC under RCP 8.5. Contour intervals are 0.5 (m/s)/100 years for zonal wind and 3 (hPa/day)/100 years for vertical motion.
experiences an El Niño-like response in the Had model, as many previous articles have suggested [e.g., Tokinaga et al., 2012b]. By contrast, in the M model, the Walker circulation strengthens as the SST experiences La Niña-like warming. The G model exhibits a weaker signal, particularly in vertical motion, which is consistent with the SST trends without a clear La Nina-like pattern. Though we have no reason to assume that the late historical period is explained by the global warming forcing thus far, the structural resemblance in the Walker circulation change (in particular, the longitudinal correspondence) between the late historical period and the global warming projections by the M model increases the interest in investigating the La Niña-like trend further.

One might wonder how to reconcile the strengthening Walker circulation in the M model with the robust conclusion from the energy and water balances that the atmospheric circulation should weaken under global warming [Held and Soden, 2006]. It is important, however, to remember that this explanation only constrains the global mean change. The scatter plots in Fig. 2.3a show the relationship between the annual-mean temperature change and the precipitation increase under RCP 8.5 expressed with respect to the mean over 2006-2015. Also shown are the least-square best fit line of the precipitation increase and the estimated increase of water vapor due to the Clausius-Clapeyron relationship (7%/K) assuming that the relative humidity remains constant. The explanation given by Held and Soden [2006] is that, to increase precipitation more slowly than 7%/K, the water vapor increase has to be compensated by weakening atmospheric circulation. In the majority of global climate models including the M and Had models, this is true for the global mean circulation as shown in Fig. 2.3a. Figure 2.3b clearly shows that the vertical motion at 500 hPa in the M model is weakening globally except for the tropical Pacific and a few other places. Therefore, the strengthening Walker circulation in the M model does not violate the conclusion derived from the global energy and water balances.
Figure 2.3: (a): Scatter plots showing the relationship between the global mean surface temperature change and the global precipitation change in two models under RCP 8.5. Each dot represents annual mean computed relative to the mean over 2006-2015. The least-square best fit lines are shown in blue, and the estimated increase of water vapor due to Clausius-Clapeyron relationship (7%/K) in red. (b): Product of climatology and warming response in 500 hPa vertical motion of GFDL-ESM2M under RCP 8.5. Climatology is the means over 2006-2035, and the warming response is the epochal differences between 2070-2099 minus 2006-2035. Unit in (hPa/day)$^2$.

2.4 **Fundamental constraint between the multi-decadal SST variability and the ENSO amplitude changes imposed by realistic ENSO nonlinearity, and their warming responses**

In this section, we first focus on multi-decadal natural variability of the tropical SST to show that, if the nonlinearity of ENSO is realistic, multi-decadal variations of the zonal SST gradient are fundamentally tied to the ENSO amplitude variations. The M model reproduces this observed constraint remarkably well, but the G and Had models violate this constraint because these two models do not reproduce the observed ENSO nonlinearity. We then demonstrate that the La Niña-like trend in the M model is a forced response to global warming, which appears to be causally related to the weakening ENSO amplitude.
2.4.1 The role of ENSO nonlinearity in multi-decadal SST natural variability

Before exploring the warming response further, we take a step back and investigate the relationship between the zonal SST gradient and the ENSO amplitude in natural variability. Specifically, we first analyze an observational dataset and the piControl runs of the models. The upper panels of Figs. 2.4a and 2.4b show the 11-month running mean SST averaged over the Niño3 region (5°S-5°N, 150°W-90°W; shown as a black box in the lower panel) for two successive 95-yr time spans starting from Year 211 and Year 306 in piControl of the M model. The earlier (later) time span is chosen to show an example of the era when the ENSO amplitude exhibits a substantial decrease (increase). Interestingly, the lower panels of Figs. 2.4a and 2.4b show a well-defined La Niña-like trend (Years 211-305) and an El Niño-like trend (Years 306-400), respectively.
Except during large El Niño events, the Niño3 SST shown in Fig 2.4 remains about 24 °C. Therefore, at least in the M model, it is more reasonable to assume that the centennial SST trends in piControl are just a manifestation of the ENSO amplitude modulations rather than that the mean state is modulated by some other factors, such as heat advection from the extratropical regions. It is easy enough to understand why the ENSO amplitude variations can rectify the multi-decadal SST trends [e.g., Battisti and Hirst, 1989; Jin et al., 2003; An et al., 2005; Atwood et al., 2016]. For example, the upper panels of Fig. 2.4 show that the SST probability distribution in the M model is highly skewed toward “stronger, less frequent El Niño” and “weaker, more frequent La Niña”. Therefore, if ENSO becomes inactive and the number of large El Niño events decreases, then the mean state is rectified to be La Niña-like, and vice versa. An important implication from Fig. 2.4 is that, to provide a realistic global warming projection of the mean-state SST trends, it is essential for models to reproduce both the ENSO nonlinearity and the ENSO amplitude trends, in addition to mean-state changes that are independent from the ENSO response to warming.

In the real world, it is widely known that ENSO is not a linear phenomenon. The aforementioned asymmetry of ENSO is clearly observed during the satellite era. The lower panel of Fig. 2.5 shows that large El Nino events with SST anomalies of 2 °C or more happened in 1982/83 and 1997/98 in this metric. On the other hand, the La Niña anomalies are always about 1 °C, but are realized more frequently. For an objective measure, skewness of the detrended Niño3 SST anomalies is 0.61 for the entire time span shown in Fig. 2.5 (positive skewness means “stronger, less frequent El Niño” and “weaker, more frequent La Niña”). The mechanism to yield this ENSO asymmetry is comprehensively discussed by Battisti and Hirst [1989] and An and Jin [2004].

This nonlinearity motivates us to define two SST indices between which we expect a reasonably high correlation. The blue curve in the upper left panel of Fig. 2.5 shows the 7-year running standard deviations (RSTD) of Niño3 SST. This index represents whether the ENSO is active or inactive in the given 7-year window. The red curve shows the zonal SST gradient (ZSG) index defined as the 7-year running mean of the SST difference calculated
Figure 2.5: Upper left: Blue, Observed 7-year running standard deviations (RSTD) of the Niño3 SST. RSTD is calculated to represent deviations from the running mean state at each window. Means over the entire time span are removed. Red, Observed zonal SST gradient (ZSG) index defined as the difference “Niño3 minus Niño4” SST for the three runs. 7-year running mean is applied. Means over the entire time span are removed. Upper right: Lag correlation coefficients between the two indices calculated over the time series. Positive (negative) lags mean the Niño3 RSTD is lagging (leading) the ZSG index. Bottom: Observed detrended Niño3 SST anomalies. 11-month running mean is applied. Skewness calculated over the entire period are shown at the bottom right.
in the manner of “Niño3 minus Niño4 (5°S-5°N, 160°E-150°W; shown as a black box in the lower panel of Fig. 2.4a)”. By definition, positive (negative) ZSG index represents El Niño-like (La Niña-like) mean state in the given 7-year window. Both the RSTD and ZSG indices are expressed in unit of °C and the means over the entire record are removed beforehand. Because the typical ENSO period is about 3-5 years, we use the window length of 7 years so that the window covers at least one full cycle. Nevertheless, even if 11-year windows are used, similar results are obtained (not shown). This insensitivity confirms that our results are reasonably window-length independent, so we hereafter use the 7-year window to yield more statistical degrees of freedom.

A trivial reason why the two indices should be highly correlated is as follows. If a 7-year window contains a large El Niño event, the ENSO is defined “active” and the zonal SST gradient tends to be more “El Niño-like” in the 7-year time span, suggesting that both indices are likely to be positive. On the other hand, if a 7-year window does not contain a large El Niño event, the ENSO is generally “inactive” and the zonal SST gradient is relatively “La Niña-like”, suggesting that both indices tend to be negative. Here, the important effect of the ENSO nonlinearity is that, even if the window contains a large La Niña event, the RSTD does not become as large as El Niño counterparts. Whenever ENSO is more active than the norm, more El Niño-like phases are expected rather than La Niña-like phases.

As expected, the two indices exhibit a remarkably high correlation of >0.8 without any detectable lags during the satellite era (Fig 2.5, top panels). In particular, both indices are higher than the norm in the years whose 7-year window includes the large El Niño event in 1997/98. It is also evident that the phases of low frequency variability is determined by the occurrence of El Niño events rather than La Niña events. This asymmetry appears to be because the amplitude of El Niño events tend to vary substantially, but that of La Niña events remains almost constant throughout the entire time span. This observed evidence implies that the ENSO nonlinearity plays an important role in low-frequency SST variations in the equatorial Pacific. We have also detected statistically significant correlations between the two indices using longer records (e.g., correlation = 0.54 for 1921-2015 in HadISST;
significant at the 95% confidence level), but the uncertainty due to sparse observations is so large that the two indices before the satellite era is highly dataset dependent.

2.4.2 Preindustrial control runs with/without realistic ENSO nonlinearity

Next, to further confirm the importance of the ENSO nonlinearity, we use the three models introduced in the former sections. Figure 2.6 shows that the M model exhibits strong nonlinearity (skewness = 0.98), whereas the G (skewness = 0.09) and Had (skewness = -0.05) models exhibit weaker nonlinearity. Because the G model is different from the M model only by its oceanic component, this difference in nonlinearity must originate from the oceanic configurations. The Had model exhibits a negative skewness, suggesting that La Niña events tend to be larger than El Niño events at least in this particular run. In Fig. 3.8, we will show that many other CMIP5 models also fall into this unrealistic “negative skewness” category, but we shall focus on the Had model in this chapter.

If the ENSO nonlinearity is not realistically simulated, the nonlinear rectification effect on the mean-state zonal SST gradient should also be unrealistic. In other words, we have an a priori reason to expect that the correlations between the RSTD and ZSG indices should be lower in the G and Had models than in the M model. The two indices of the three models calculated from the piControl runs verify this expectation (Fig. 2.7). The time series simulated by the M model over five centuries clearly shows that the ENSO amplitude and the mean-state zonal SST gradient are tightly interconnected (correlation = 0.8-0.9), whereas those in the G model only exhibit a moderate correlation (correlation = 0.4-0.5). The correlation in the Had model is even lower (correlation = 0.1-0.2), and during some time spans (e.g., Years 150-180), the two indices are anti-correlated. This may be a manifestation of negative skewness, which is particularly evident in those periods (Fig. 2.6, bottom).

The lag correlation property of the M model suggests that the ENSO amplitude leads the mean-state zonal SST gradient by about 10 months. Even if we divide the 500-year time series into centuries and calculate the correlations separately, this lag correlation robustly appears in all 5 centuries (not shown). This slight lead-lag relationship is consistent with
Figure 2.6: As in the bottom panel in Fig. 2.5, but for the piControl runs of the three models. Note that the length of the time span for HadGEM2-CC is different from the two GFDL models. Skewness calculated over the entire period are shown at the top right.
Figure 2.7: As in the top panels in Fig. 2.5, but for the piControl runs of the three models. Note that the length of the time span for HadGEM2-CC is different from the two GFDL models.
the idea that the ENSO variations cause the mean-state SST modulation within a nonzero time lag, but based on the short record of observations, it is hard to determine whether this modeled lag is realistic. Nevertheless, the evidence that the mean state is lagging, rather than leading, support the notion that the ENSO amplitude does not simply respond to mean-state changes caused by other factors. This notion is consistent with a recent finding by Atwood et al. [2016], who showed using a different GFDL model, GFDL CM2.1, that the mean-state natural variability is an effect, rather than a cause, of the ENSO amplitude variability. The causality between the mean state and the ENSO amplitude will be further discussed in the next section.

2.4.3 Forced ENSO weakening and the La Niña-like response to global warming in the M model

In the former subsections, we have shown that large centennial variations of the zonal SST gradient could result from natural variability of ENSO amplitude variations. Though some strong La Niña-like trends are realized in the piControl run, this large natural variability does not necessarily mean that the La Niña-like trend under warming experiments in the M model should be also regarded as pure natural variability.

The upper panels of Fig. 2.8 show the strength of anthropogenic forcing for the historical (Year 1860-2005), RCP 8.5 (Year 2006-2100), and Abrupt4xCO2 runs (Year 101-300 only). For Abrupt4xCO2, only after Year100 is shown because it takes several decades before the system reaches its quasi-equilibrium. For the former two experiments, the forcing exhibits a monotonic increase, and in particular, the forcing experiences a more rapid increase after the beginning of the satellite era. Then, the forcing becomes stronger following the RCP 8.5 scenario to reach a level comparable to the quadrupling of CO2 at the end of this century.

The lower panels of Fig. 2.8 show the same indices as in the piControl runs but for the runs under the anthropogenic forcing described in the last paragraph. Here the indices are expressed relative to the means over piControl. During most of the historical period, natural variability of both indices is as large as in the piControl run. After the beginning of the
Figure 2.8: Top: Strength of Anthropogenic forcing for the historical, RCP 8.5, and abrupt quadrupling carbon dioxide (Abrupt4xCO2) runs. For Abrupt4xCO2, only after Year100 is shown because it takes several decades before the system reaches its quasi-equilibrium. The equilibrated value of the anthropogenic forcing in the Abrupt4xCO2 run (6.72 W/m$^2$) is estimated by Andrews et al. [2012]. Bottom: As in the top panel of Fig. 2.7, but for the experiments shown in the top panels. The indices are expressed relative to the means over the entire time span of piControl shown in Fig. 2.7. The dashed line shows the least square best fit line calculated from 1979-2100.

satellite era, however, the two indices gradually start to decrease to reach the level of the quadrupled-CO2 run, in which ENSO amplitude and its decadal variations are substantially weakened. In accordance with this weakened amplitude, the mean-state zonal SST gradient in the warmer climate remains La Niña-like for at least two centuries. By comparing the piControl run (Fig. 2.7, top) and the Abrupt4xCO2 run (Fig. 2.8, bottom right) in the M model, it is virtually certain that the weakening ENSO and the La Niña-like shift in the M model are forced responses to global warming, rather than a manifestation of natural variability. The historical and RCP 8.5 runs smoothly connect the two regimes, exhibiting a clear transition toward a warmer climate.

Furthermore, to statistically verify that the ENSO weakening is a forced response, we have calculated the 3-year RSTD of the Niño3 SST in the M model, and this time series exhibits a significant decrease of the ENSO amplitude at the 95% confidence level (not
shown). To show that this amplitude decrease is unlikely to be a result of natural variability, we have then performed the same analysis using the first 2000 years of the 4,000 year-long pre-industrial control run of GFDL CM2.1. Specifically, we have calculated the significance of the amplitude trends for every possible time span with length of 95 years (i.e., Year 2-96, 3-97, ..., and 1904-1999, starting from Year 2 because we calculate 3-year RSTD). Surprisingly, out of the two millennia, only 8 time spans that can be sorted into 3 eras, i.e., Era #1 (95-year time spans starting from Year 125, 126, 127, and 128), Era #2 (starting from Year 297, 298, 299), and and Era #3 (starting from Year 1716) have experienced significant amplitude decrease at the 95% confidence level. In addition, none of them has shown a trend as steep as in the RCP 8.5 run of the M model. Though the source of the ENSO nonlinearity in GFDL CM2.1 appears to be different from that of the M model [Atwood et al., 2016], GFDL CM2.1 is similar to the M model in many respects [Dunne et al., 2012] including the nonlinear rectification effect and the strengthening Walker circulation in response to warming [Tanaka et al., 2005]. These statistical analyses also strongly suggest that the ENSO response in the M model is forced.

An important conclusion derived from this subsection is, to the best of our knowledge, it is very likely that the significant ENSO weakening and the La Niña-like mean-state response in the M model is a forced response to global warming, rather than centennial natural variability. In addition, by analyzing the historical run of the M model, the case has been made that the forced response could have been detectable since the late 20th Century. Then, our next question would be whether the real world behaves like the M model or the other models, but this question is much harder (perhaps impossible) to address. Nevertheless, our analysis suggest that the forced La Niña-like response in the M model appears to be tied to the nonlinearity of ENSO, and that the nonlinearity in the M model is more realistic than those in some other CMIP5 models. In particular, the contrast between the M and G models undoubtedly sheds new light on the role of upper oceanic properties, particularly the ENSO nonlinearity, in determining the mean-state SST response to global warming.

As long as a model simulates realistic ENSO nonlinearity and weakening ENSO ampli-
tude, the aforementioned La Niña-like forcing mechanism at least competes with the other mechanisms that favor El Niño-like warming. Based on the large ENSO amplitude and the strong ENSO nonlinearity of the M model, we could argue that the M model is an exception among the state-of-the-art GCMs due to the strong nonlinear rectification effect. Though the evidence discussed in this study are not enough to conclude that the M model simulates the zonal SST gradient response more realistically, it lends confidence to the notion that the La Niña-like warming scenario may be as reasonable as the El Niño-like warming scenario, since consistent physical mechanisms can be outlined. Considering the fact that previous studies have not reached consensus on how the ENSO amplitude will change under global warming [e.g., Collins et al., 2010], a La Niña-like mean-state response to warming remains a plausible outcome.

### 2.5 Discussion on hypothetical physical mechanisms to yield the inter-model differences

In the previous section, we have mainly discussed the role of the ENSO nonlinearity and the amplitude response in constraining the mean-state response to global warming. The “nonlinear rectification effect” of natural ENSO variability on the mean state was comprehensively discussed by Battisti and Hirst [1989], Jin et al. [2003], and An et al. [2005], for instance. Atwood et al. [2016] recently showed using GFDL CM2.1 that the mean-state SST decadal variability appears to be just a manifestation of the ENSO amplitude variability. Therefore, as in the M model, if a model simulates realistic ENSO nonlinearity, and if ENSO is forced to weaken by global warming, then the nonlinear rectification effect causes a suppression of mean-state warming in the eastern equatorial Pacific, yielding a La Niña-like trend. We refer to this process as the “Nonlinear ENSO Warming Suppression (NEWS)” (Fig. 2.9, red solid arrows), and will discuss further in chapter 3.

On the other hand, many other studies suggest that the mean-state response is the cause, rather than the effect, of the ENSO amplitude changes. For example, by sorting the CMIP5 models into “El Niño-like” and ”La-Niña-like” categories, Zheng et al. (2016) concluded
Nonlinear ENSO Warming Suppression (NEWS) process (Further discussed in chapter 3)

ENSO Responds to Mean State (ERMS) process

ENSO Independent of Mean State (EIMS) process

Greenhouse Forcing

- Strengthened thermal stratification causes the climatological thermocline structure to be more stable and insensitive to the westerly anomalies. This stabilization effect keeps the perturbations linear, and the climatological thermocline becomes harder to perturb and to yield a large El Niño event nonlinearly
- Atmospheric damping feedback (not confirmed in this study)

Weakening ENSO amplitude

- Fewer extreme El Niño events (Nonlinear rectification effect, e.g., Jin et al., 2003)

La Niña-like mean-state warming

- Increased barrier to deep convection reduces rainfall anomalies of ENSO, which weakens the wind response (Zheng et al., 2016)
- Even on long time scales, if the polar amplification is weak enough, the equatorial upwelling water may remain cold enough to steepen the zonal SST gradient
- On short time scales, strong thermal stratification enhances the efficiency of mean equatorial upwelling, allowing the Ocean Dynamical Thermostat (Clement et al., 1996) to keep operating for a while

Figure 2.9: Three possible causal processes among greenhouse forcing, the ENSO amplitude change, and the La Niña-like mean-state response in GFDL-ESM2M. Also shown are examples of physical mechanisms that are potentially important.
that, “in models with an enhanced mean warming in the eastern equatorial Pacific, the barrier to deep convection is reduced, and the intensified rainfall anomalies of ENSO amplify the wind response and hence SST variability” and vice versa. Some other mechanisms are also discussed in Collins et al. [2010]. Therefore, if a certain mechanism favors the La Niña-like mean state, this mechanism can cause the weakening ENSO amplitude. To contrast this mechanism with NEWS, we refer to this process as “ENSO Responds to Mean State (ERMS)” (Fig. 2.9, blue dashed arrows). In addition to NEWS and ERMS, we could also outline a third possibility where the La Niña-like mean state warming and the weakening ENSO amplitude are independently forced by global warming. We refer to this third process as “ENSO Independent of Mean State (EIMS)” (Fig. 2.9, green dotted arrows). We believe, however, EIMS is less likely to be a dominant process, considering the remarkably high correlation between the RSTD and ZSG indices.

The three possible causal processes (i.e., NEWS, ERMS, and EIMS) and some examples of physical mechanisms are summarized in Fig. 2.9 as a potential mechanism to explain the La Niña-like trend in the M model. These mechanisms involve the direction of causality between the zonal SST gradient, ENSO amplitude, and greenhouse gas warming. Though it is not clear which process in Fig. 2.9 is the most important one, we have good evidence to assume that some important oceanic mechanisms must control the zonal SST gradient response to warming, because the M and G models are different only in their oceanic components. In this section, we list some potentially important mechanisms for simulating the La Niña-like warming pattern in the M model by comparing it to the G model.

2.5.1 Potential roles of the climatological thermal stratification and its warming response

One of the major climatological differences in the equatorial Pacific between the M and G models is thermal stratification. Here, thermal stratification is defined as the temperature difference between adjacent depth levels ($dT$) divided by the vertical distance between them ($dz$). Figure 2.10a shows the climatological thermal stratification over the equatorial Pacific for observations and the two GFDL models during the late historical period. The upper
ocean stratification of the M model (and the real world) is generally stronger in the 40-100 m layer in the equatorial Pacific than that of the G model, which means that the mean and variance of vertical heat advection tend to be larger in the M model. In particular, this larger variance of advection is generally associated with the larger ENSO amplitude, which might also indirectly influence the magnitude of the nonlinear rectification effect on the mean-state trends (see Figs. 2.6 and 2.7).

In addition, Fig. 2.10a implies that the mixed layers in the M model and the real world are shallower than that in the G model. If the mixed layer is shallower, the surface heat flux and the Sverdrup transport can more easily recharge the heat into the mixed layer and collapse the climatological thermocline drastically enough for the anomalies to deviate from the range of “linear” perturbations. This deviation from the linear regime is essential to yield the ENSO asymmetry and large El Niño events [An and Jin, 2004]. Therefore, the difference in mixed layer depth is consistent with the evidence that the ENSO nonlinearity is more realistically simulated by the M model than the G model.

The explanations in the previous paragraphs support the NEWS process as a possible cause to simulate the La Niña-like response. On the other hand, the evidence that the M model is more stratified means that the mean equatorial upwelling cools the climatological surface more efficiently. At least in a shorter time scale than a couple of decades, the efficient climatological upwelling would favor the La Niña-like mean-state response due to the Ocean Dynamical Thermostat [Clement et al., 1996]. Though it is not clear whether this mechanism continues to operate in a longer time scale, the difference in the equatorial thermal stratification is at least consistent with the ERMS process as well.

In Fig. 2.10b, we also show the warming response of the regionally-averaged (5°S-5°N, 170°W-100°W) equatorial thermal stratification at the 50 m depth (i.e., the typical observed mixed layer depth on the equatorial Pacific). As the climate warms, the climatological stratification consistently strengthens in both models, so one might suspect that no important difference is evident in the warming response. The stronger climatological thermal stratification of the M model, however, also has an implication for this warming response. If the
a) Climatology of the Equatorial Thermal Stratification (dT/dz) (Late Historical)

![Graph showing climatological meridional-mean thermal stratification (dT/dz) over 5°S-5°N in late historical period (1980-2005) for observations and the two GFDL models. Unit is °C/m. Contour intervals are 0.005 °C/m below 0.05 °C/m (solid curves), and 0.02 °C/m above 0.05 °C/m (dashed curves).](image)

b) Warming response of the Thermal Stratification (RCP8.5; 5°S-5°N, 170°W-100°W; 50 m)

![Graph showing regional mean thermal stratification averaged over 5°S-5°N, 170°W-100°W at the 50 m depth under the RCP 8.5 scenario. 3-year (8-year) running mean is applied for the blue (red) curve.](image)

Figure 2.10: (a): Climatological meridional-mean thermal stratification (dT/dz) over 5°S-5°N in late historical period (1980-2005) for observations and the two GFDL models. Unit is °C/m. Contour intervals are 0.005 °C/m below 0.05 °C/m (solid curves), and 0.02 °C/m above 0.05 °C/m (dashed curves). (b): Regional mean thermal stratification averaged over 5°S-5°N, 170°W-100°W at the 50 m depth under the RCP 8.5 scenario. 3-year (8-year) running mean is applied for the blue (red) curve.
equatorial upwelling becomes more efficient than a certain threshold value, the thermocline will be so stabilized that it becomes less likely for the climatological thermocline to collapse. The system, then, no longer yields a large El Niño event, causes the ENSO nonlinearity to dissipate, and weakens the ENSO amplitude. In chapter 3, we will show that this mechanism can be simulated by an idealized model with nonlinear ENSO. Assuming that this mechanism is realistic, we could speculate based on the left panel of Fig. 2.10b that the thermal stratification in the M model appears to “saturate” after about 2070 under RCP 8.5, which causes large El Niño events to die out. Hence, the warming response could also be essential for the inter-model difference in the capability of simulating the NEWS process, and therefore, the La Niña-like mean-state response.

We could speculate that the ultimate cause of the aforementioned difference in upper ocean properties might be related to the difference of equatorial vertical diffusivities. The equatorial diffusivities in the G model below the surface boundary layer are generally small, partly because the interior background values in the G model are parameterized near the equator based on a presumed f-dependence for near-inertial wave-wave interactions [Harrison and Hallberg, 2008]. As the first step, the influence of vertical diffusivity on the mean-state warming response could be tested by analyzing model runs with different background diffusivity values. Nevertheless, the difference of total diffusivity also depends upon the shear mixing scheme, the boundary layer model, the vertical resolution, and the mixing due to truncation errors, so further comprehensive analyses and model runs are needed to determine the root cause of the overall inter-model difference.

2.5.2 Potential mechanism related to the strength of polar amplification

From a more global perspective, we could argue that the strength of polar amplification of global warming may support the ERMS process. Figure 2.11a shows the difference map of the trends of SST (deviations from the global mean) between the M and G models. This map shows that the polar amplification of global warming is weaker in the M model, especially in the eastern Pacific basin. We obtain a similar result between the M and Had models
as well (not shown). Therefore, we could hypothesize that the advection of this cooler water might contribute to the cooler equatorial Pacific via upwelling, because the outcrops of climatological isopycnal surfaces from which the upwelling water originates are generally observed at higher latitudes (Fig 2.11b).

Figure 2.11c shows the difference of the temperature warming response between the two models, juxtaposed with the climatological isopycnal surfaces in the M model. The temperature anomalies reasonably match the climatological isopycnal surfaces, which suggests that the potential temperature anomalies are following the Lagrangian transport of sea water. In particular, the cold anomalies of the Northeast Pacific clearly extend to the eastern equatorial Pacific later this century. With the help of the Ocean Dynamical Thermostat mechanism, this extratropical oceanic teleconnection can cause the La Niña-like trend in this model, and in turn, the weakening ENSO based on the ERMS process. Actually, despite the problem of the Ocean Dynamical Thermostat mentioned in the introduction section, Seager and Murtagudde [1997] validated the dynamical damping mechanism in eastern equatorial Pacific in an oceanic GCM experiment even in the presence of mid-latitude ocean warming. One possibility to explain their result might be that, if the polar amplification is weak enough, then the Ocean Dynamical Thermostat might remain valid for a longer time scale than the majority of the CMIP5 models suggest.

Nevertheless, a caveat of this mechanism is that a large portion of the water in the undercurrent comes from the Southern Hemisphere subtropics [Tsuchiya et al., 1989; Rodgers et al., 2003; Goodman et al., 2005]. The anomalies could also be associated with the inter-model difference of heaving, rather than mass transport. Here, “heaving” means a temperature change at a fixed depth caused by vertical migration of isopycnal surfaces, either adiabatically or through diabatic heat flux divergence [Häkkinen et al., 2016]. Further investigations and some model experiments are needed to verify this hypothesis.
Figure 2.11: (a): Difference of the SST (deviations from the global mean) trends between the two GFDL models under RCP 8.5. Unit is °C/100 years. The region surrounded by the black curve is where the zonal means shown in (b) and (c) are calculated for. (b): Contours, Climatological zonal-mean potential density under RCP 8.5 (2006-2100) for GFDL-ESM2M over the eastern Pacific region shown in (a). Unit in kg/m$^3$, but 1000 kg/m$^3$ is subtracted following the conventional notation. Contour interval is 0.2 kg/m$^3$, and the bold contour shows the 26-kg/m$^3$ isopycnal surface. Arrows: The meridional and vertical mass transport are qualitatively shown. The vertical component is stretched by a factor of 5 for the purpose of visualization. (c): Contours, As in (b), but for bidecadal mean potential density starting from 2016, 2036, 2056, and 2076. Shadings: Same as contours, but the warming response of potential temperature computed relative to GFDL-ESM2G. The warming response is computed as the bidecadal means relative to the decadal mean potential temperature starting from 2006. Unit is °C. Note that the contours show the climatology of GFDL-ESM2M, but the shadings show the inter-model difference of the warming response.
2.6 Summary and concluding remarks

We have shown that GFDL-ESM2M (M model) is an interesting outlier in the CMIP5 models, because it exhibits a La Niña-like response to global warming in the equatorial Pacific. GFDL-ESM2G (G model), which differs from the M model only in the oceanic components, does not yield well-defined La Niña-like warming. Using this difference, we have explored the potential oceanic roles that may be important for the difference in the trends of the zonal SST gradient in the equatorial Pacific. We have also compared the M model with HadGEM2-CC (Had model), which exhibits a typical El Niño-like trend that resembles the multi-model mean response to warming.

First of all, in section 2.3, we have clarified that the La Niña-like warming in the M model is a gradual process that takes almost a full century to reach the mature phase. Then, we have shown that the Walker circulation change associated with the La Niña-like response in the M model has the same sign as the observed change during the late historical period, and the spatial structure of the circulation becomes more similar under RCP 8.5 to what we have observed thus far, which is opposite to what the Had model (and the multi-model mean) project. We are interested in investigating whether the recent strengthening Walker circulation could be partly forced by global warming, but the short record of the late historical period by itself cannot be used to answer this question. Therefore, in the following section, we have further investigated the piControl and Abrupt4xCO2 runs, as well as the historical and RCP 8.5 runs, to show that the La Niña-like response in the M model is, actually, very likely to be forced.

In section 2.4, we have first shown that, given the realistic ENSO nonlinearity, the centennial natural variability must be fundamentally constrained by the ENSO amplitude variability. In both observations and the M model, the probability distribution of ENSO is generally skewed toward “stronger, less frequent El Niño” and “weaker, more frequent La Niña”. Therefore, a time span with active ENSO should trivially correspond to a time span with a El Niño-like mean state, and vice versa, as long as the ENSO nonlinearity is real-
istically simulated. The G and Had models violate this relationship, however, because the ENSO nonlinearity in these models is too small. An important conclusion from this section is that, to project a mean-state SST trend realistically, it is necessary for models to reproduce at least the following three properties: the ENSO nonlinearity, low frequency variations in the ENSO amplitude, and mean-state changes that are independent from the ENSO response to warming.

At least in the M model, by comparing the piControl and Abrupt4xCO2 runs, we can argue with very high confidence that the weakening ENSO amplitude and the La Niña-like mean-state response are forced by global warming (see Figs. 2.7 and 2.8). Interestingly, the historical and RCP 8.5 runs suggest that the forced response could have become detectable as early as the late 20th Century. Of course, it is hard to determine whether this response is more realistic than those in the other CMIP5 models. Nevertheless, by using the M model, i.e., a state-of-the-art model with more realistic ENSO nonlinearity than some other models, we have made a case that the La Niña-like response to global warming could be a plausible outcome, or at least, that this La Niña-like forcing mechanism could compete with the other mechanisms that favors an El Niño-like warming. To the best of our knowledge, these conclusions have not been obtained by previous studies, because the results in those studies are often based on the multi-model means of the CMIP5 models, most of which do not realistically simulate the ENSO nonlinearity.

In section 2.5, we have first argued that three possible causal processes among greenhouse forcing, ENSO amplitude, and the mean-state zonal SST gradient can be outlined to explain the La Niña-like response in the M model (Fig. 2.9). The first one is the Nonlinear ENSO Warming Suppression (NEWS) process, where the greenhouse forcing weakens the ENSO amplitude, which in turn cause the mean state to be La Niña-like (see also chapter 3). The second one is the ENSO Responds to Mean State (ERMS) process, where the greenhouse forcing changes the mean state first, causing the ENSO amplitude change. The third one is the ENSO Independent of Mean State (EIMS) process, where the ENSO amplitude and the mean state are independently forced by greenhouse warming. Considering the reason-
ably high correlation between the ENSO amplitude and the mean-state zonal SST gradient, however, the EIMS might be the least important process of the three.

Then, comparing the two GFDL models whose difference is only the oceanic components, we have discussed some potential physical mechanisms that can simulate the NEWS and ERMS processes in the M model. The most important difference appears to be the upper ocean thermal stratification. The stronger thermal stratification and the shallower mixed layer depth of the M model, both of which are more realistic than those of the G model at least in the historical period, might be the key to explain the realistic nonlinearity in the M model. Because the equatorial properties related to vertical diffusivities are known to be reasonably different in these models, it may be interesting to design some experiments to check the sensitivity of the ENSO nonlinearity to the background diffusivity. To understand the nature of the ENSO nonlinearity is important to evaluate the possibility of the NEWS process. From a more global perspective, on the other hand, the weaker polar amplification in the M model might be related to the import of the anomalously cold equatorial upwelling water from the North Pacific into the equatorial Pacific. This oceanic teleconnection mechanism is a possible mechanism to realize the ERMS process.

One important caveat of this study is that, to focus on the oceanic difference between the M and G model, we have only used three models to do the analyses for this study. Therefore, we have not discussed any potentially important difference in the atmospheric components of the models. To simulate the La Niña-like trend, however, it is virtually certain that the role of the atmosphere is as important as the role of the ocean. For instance, the strength of atmospheric damping feedback (i.e., the SST anomalies in a warmer climate would experience stronger atmospheric damping, due to increase in latent heat release and radiation per 1 °C increase in SST, which leads to smaller SST variance) could have an important influence on the trends of the ENSO amplitude. In addition, the M model is not the only one model reproducing a realistic ENSO skewness [Sun et al., 2016], though it is close to the best. In particular, we will show in Fig. 3.8 that the MIROC5 model exhibits the most realistic ENSO skewness among 32 CMIP5 models, and puzzlingly, that this model exhibits a strong
El Niño-like mean-state warming [see also Huang and Ying, 2015]. MIROC5 will be closely investigated in chapter 4 to help us understand the necessary conditions of a La Niña-like mean-state warming further.

Some recent studies also suggest a possible relationship between the simulated historical mean-state SST and the projected mean-state SST changes [Huang and Ying, 2015; Li et al., 2016; Ying and Huang, 2016], particularly a linkage between the climatological SST bias and the La Niña-like mean-state warming. For instance, Huang and Ying [2015] showed by a multi-model statistical analysis that a warm bias of climatological SST in the southeastern Pacific is significantly correlated with a relatively slow warming in the southeastern Pacific, yielding a La Niña-like warming pattern. The M model exhibits the typical bias pattern found in many GCMs [Zheng et al., 2011], especially the warm bias in the southeastern Pacific and the excessive cold tongue in the western and central Pacific, to which the La Niña-like warming in this model may be attributable. This notion also appears to be consistent with the evidence that the M model exhibits more prominent warm bias in the southeastern Pacific than the G model, though the argument remains speculative without further analyses, comparison, and their physical interpretations.

The La Niña-like response and strengthened Walker circulation in the M model could also be contributed to by some other mechanisms that involve regions outside of the Pacific Basin. For instance, some recent studies have suggested that the excessive warming in the tropical Indian and Atlantic Ocean relative to the tropical Pacific Ocean may have enhanced the Pacific trade winds in recent decades [Luo et al., 2012; McGregor et al., 2014; Zhang and Karnauskas, 2016]. In fact, considering that the inter-basin warming contrast is more prominent in the M model than the G model (Fig. 2.11a), this contrast could potentially play a role to explain the difference in the Pacific response. Nevertheless, the response of atmospheric vertical motion to global warming (Fig. 2.2b) does not suggest any major differences over the tropical Atlantic between the two GFDL models, whereas McGregor et al. [2014] showed using a different model that a strong signal over the Atlantic is required for the mechanism to operate. Hence, this evidence does not support the notion that the
Atlantic-Pacific contrast is a major contributor to the model difference, at the very least, between the two GFDL models. On the other hand, in Fig. 2.2b, some discrepancies in the response of the tropical Indian Ocean between the two models are detectable, so the Indian-Pacific contrast could be of more importance. More comprehensive analyses using other models are required to estimate the importance of this mechanism in the real world relative to the hypotheses proposed in this study.

Preliminary analyses suggest that many other CMIP5 models do not reproduce realistic ENSO nonlinearity, and therefore, do not exhibit the fundamental relationship between the zonal SST gradient and the ENSO amplitude as observed in the real world. It is true that the vast majority of the CMIP5 models and the multi-model mean exhibit El Niño-like response to global warming, but the range of spatial patterns they produce is not consistent. Hence, we do not have a lot of faith in the multi-model mean pattern of the mean-state SST warming. Considering that it is a challenging scientific problem and is important for society, further studies on the possibility of a La Niña-like response are needed.
Chapter 3

NONLINEAR ENSO WARMING SUPPRESSION (NEWS)

The content of this chapter was originally published in *Journal of Climate* as Kohyama and Hartmann [2017].

3.1 Introduction

In the previous chapter, we have shown that GFDL-ESM2M (a GCM developed by Geophysical Fluid Dynamics Laboratory) is an interesting exception in that it produces a well-defined La Niña-like mean-state warming with a clear strengthening of the Walker circulation. Figure 3.1, which is reproduced from the previous chapter, shows the observed SST trends during the historical period (1979-2005) and the modeled SST response of GFDL-ESM2M in some global warming experiments. Using this model, whose ENSO representation is known to be reasonable [e.g., Bellenger et al., 2014], we have made a case in the previous chapter that the La Niña-like trend could be a physically consistent response to warming, and that the forced response could have been detectable since the late 20th Century.

In addition, a remarkable structural resemblance of the strengthening Walker circulation between GFDL-ESM2M and observations during the satellite era (Fig. 2.3) increases the interest in investigating this model further to determine whether this observed circulation change is purely due to natural multi-decadal variability or partly a forced response to global warming. One might be concerned that this strengthening Walker circulation could violate the robust energy and water balance proposed by Held and Soden [2006]. In the previous chapter, however, we have shown that the balance is only required on the global-mean change, but not on a regional response (e.g., the Walker circulation), so it is still possible to simulate a strengthening Walker circulation if the circulation weakens elsewhere. Comparing
Figure 3.1: (a): Observed and modeled sea surface temperature (SST) trends computed relative to the tropical Pacific mean trends (30°S-30°N, 90°E-60°W) during the late historical period. Blue colors denote a warming slower than the tropical Pacific mean, not necessarily a cooling. Unit is °C/century. (b): Top: Strength of Anthropogenic forcing for the historical, representative concentration pathways (RCP) 8.5, and abrupt quadrupling carbon dioxide (Abrupt4xCO2) runs. For Abrupt4xCO2, only after Year100 is shown because it takes several decades before the system reaches its quasi-equilibrium. The equilibrated value of the anthropogenic forcing in the Abrupt4xCO2 run (6.72 W/m²) is estimated by Andrews et al. [2012]. Bottom: Blue, 7-year running standard deviations (RSTD) of SST averaged over the Niño3 region (5°S-5°N, 150°W-90°W). RSTD is calculated to represent deviations from the running mean state at each window. Red, Observed zonal SST gradient (ZSG) index defined as the difference “Niño3 minus Niño4 (5°S-5°N, 160°E-150°W)” SST. 7-year running mean is applied. The dashed line shows the least square best fit line calculated from 1979-2100. Both indices are expressed relative to the means over the entire time span of the preindustrial control (piControl) run (see also Fig. 2.7).
with GFDL-ESM2G, which differs from GFDL-ESM2M only by its oceanic component, the previous chapter suggested that an important oceanic mechanism might play a major role in controlling the mean-state SST warming response, which then determines the atmospheric circulation changes.

In the previous chapter, we have also concluded that GFDL-ESM2M does a particularly good job of reproducing the observed correlation between the zonal SST gradient and the amplitude of ENSO, and that its La Niña-like mean-state warming trend in response to warming may be causally related to the weakening ENSO amplitude (Fig. 3.1b). This relationship is also consistent with a recent paper by Zheng et al. [2016], which showed that a group of four CMIP5 models with a La Niña-like warming shows a weakening of the ENSO amplitude. Therefore, we would like to understand why the ENSO in GFDL-ESM2M is weakened under a warmer climate. The top panels of Fig. 3.2 show the SST during December-January-February (DJF) averaged over the western equatorial warm pool region (5°N-5°S, 130°E-160°E) and the eastern equatorial cold tongue (5°N-5°S, 120°W-90°W), as in Fig. 1 of An and Jin [2004] (hereafter AJ04) but for the preindustrial control (piControl) and abrupt quadrupling carbon dioxide (CO$_2$) (Abrupt4xCO$_2$) runs defined by the CMIP5 project. Only the years after Year 100 are shown for the Abrupt4xCO$_2$ run, because it takes a couple of decades for the climate to reach quasi-equilibrium after the abrupt CO$_2$ increase (not shown). The ENSO amplitude is substantially suppressed in a warmer climate in GFDL-ESM2M, which is consistent with the result shown in the previous chapter.

More importantly, the SST time series of Abrupt4xCO$_2$ show no extreme El Niño (EEN) events. Here, if the cold tongue SST closely approaches or surpasses the warm pool SST, then we refer to these El Niño events as EENs. In the observed record, the El Niños in 1982/83 and 1997/98 are classified as EENs as we will show later in this section. Jin et al. [2003] and AJ04 called the western warm pool SST “the upper bound” of the eastern cold tongue SST, defining this upper bound as the maximum potential intensity (MPI) of an El Niño. One of the main conclusions of Jin et al. [2003] and AJ04 is that, during EENs, the climatological conditions of the ocean and atmosphere are completely collapsed and that one cannot treat
Figure 3.2: Top panel, SST averaged over December-January-February (DJF), simulated by GFDL-ESM2M under piControl and Abrupt4xCO₂ scenarios. Red curves show the SST time series averaged over the western warm pool (5°S-5°N, 130°E-160°E), and the blue curves show those of the eastern cold tongue (5°S-5°N, 120°W-90°W). For Abrupt4xCO₂, only after Year100 is shown because it takes several decades before the system reaches its quasi-equilibrium. Middle and Bottom panels, Nonlinear Dynamical Heating (NDH; middle) and Linear Dynamical Heating (LDH; bottom) time series calculated using equation (3.1) for the same model runs as in the top panel, averaged over 5°S-5°N, 170°E-100°W. 3-month running mean is applied to both time series.
EENs as linear perturbations from the climatological mean. In Fig. 3.3, we have reproduced some figures shown in AJ04 but with a longer record. The SST spatial pattern during the EEN in 1997/98 DJF shows a completely different structure than the climatological SST. Moreover, the equatorial upper ocean temperature clearly shows that, during the EEN, the thermocline is almost flat across the equatorial Pacific. This is virtually the largest El Niño that can potentially occur, which is why AJ04 defined the warm pool SST as the MPI. The eastern equatorial SST is bounded by the MPI, and the MPI is, in turn, determined by the radiative-convective equilibrium temperature [Waliser and Graham, 1993].

The next question, then, is whether the mechanisms that cause EENs and normal ENSO events are different. Jin et al. [2003] and AJ04 addressed this question by performing a heat budget analysis of the upper ocean by decomposing the dynamical heating terms into “Linear Dynamical Heating (LDH)” and “Nonlinear Dynamical Heating (NDH)”. The heat budget of the mixed layer, whose depth is assumed to be fixed at 50 m, can be written in the form of the following equation:

\[
\frac{\partial T'}{\partial t} = \left( -u' \frac{\partial T'}{\partial x} - v' \frac{\partial T'}{\partial y} - w' \frac{\partial T'}{\partial z} - \bar{u} \frac{\partial T'}{\partial x} - \bar{v} \frac{\partial T'}{\partial y} - \bar{w} \frac{\partial T'}{\partial z} \right) + \left( -u' \frac{\partial T'}{\partial x} - v' \frac{\partial T'}{\partial y} - w' \frac{\partial T'}{\partial z} \right) + R'
\]

where \( t \) denotes time, \( x, y, \) and \( z \) denote the zonal, meridional, and vertical coordinates, respectively, and \( T, u, v, \) and \( w \) are mixed layer temperature, eastward, northward, and upward velocities, respectively. Overbars denote the monthly climatological mean, and primes denote the deviations therefrom. Surface heat flux and subgrid-scale contributions are all included in the residual term \( R \). AJ04 defined the terms in the first (second) bracket as LDH (NDH).

Most important among the NDH terms is the vertical component. During El Niño events, anomalous downwelling tends to occur simultaneously with anomalously strong stratification; therefore, NDH warms the mixed layer. During La Niña events, however, anomalous upwelling occurs with anomalously weak stratification. In other words, the upwelling advects anomalously warm water from the bottom, so NDH again warms the mixed layer. Mathe-
Figure 3.3: (a): Left panel, Observed SST climatology during December-January-February (DJF). Contour interval is 1°C. Right panel, As in left, but for 1997/98 DJF. (b): As in (a), but for observed upper ocean potential temperature. (c): As in Fig. 3.2, but for observations.
matically, the covariance between downwelling \((-w')\) and the temperature gradient \((\partial T'/\partial z)\) remains positive in both El Niños and La Niñas. Hence, the resulting total dynamical heating flux \((\text{LDH} + \text{NDH})\) warms the surface more in El Niño events and cools the surface less in La Niña events. This asymmetry helps explain why large SST anomalies in the cold tongue region are skewed towards warm events (i.e., EENs). In addition, as seen in the time series of MPI, the cold tongue SST, NDH and LDH calculated for the uppermost 50m in Fig. 3.3c, LDH is always important, but NDH is comparable to LDH only for EENs (i.e., 1982/83 and 1997/98).

Though the available observational record is short, it is suggestive that the NDH contribution is almost negligible after 1999. Interestingly, at least by this metric, the recent large El Niño in 2015/16 may not be classified an EEN, which is consistent with the fact that the El Niño in 2015/16 was the largest in historical record in terms of the Niño 3.4 index (SST averaged over 5ºN-5ºS, 170ºW-120ºW) but not in terms of the Niño 3 index (5ºN-5ºS, 150ºW-90ºW) (not shown). Though we are aware that the necessity of NDH for EENs remains an open question [e.g., Boulanger et al., 2004; Levine et al., 2016], we assume in this study that NDH is important for EENs, following what AJ04 suggested. This assumption is also based on what we have detected in the other EENs, the nonlinear ENSO theory, and the model outputs from GFDL-ESM2M introduced in this study.

Based on the observational evidence shown by AJ04, we hypothesize that, at least in GFDL-ESM2M, the reason why EENs are not detected in Abrupt4xCO\(_2\) may be that NDH becomes less important in a warmer climate. The middle and bottom panels in Fig. 3.2 show the time series of NDH and LDH for the upper 50 m, respectively, in both piControl and Abrupt4xCO\(_2\). As expected, NDH becomes much weaker in the warmer run, whereas LDH remains stationary to first order. This dominance of LDH means that ENSO in a warmer climate becomes almost linear, and the dissipation of NDH is a main contributor to the weakening ENSO amplitude in this model.

Hence, the questions we try to address in this chapter are as follows: (i) Why does NDH become unimportant in a warmer climate in GFDL-ESM2M? (And, as a corollary, can we
expect that fewer EENs will be observed in the future?) (ii) Can the weakening of the ENSO amplitude due to the weakening of NDH cool the mean-state SST of the cold tongue? (iii) Is the weakening ENSO amplitude a cause or an effect of the La Nina-like mean-state warming in GFDL-ESM2M (or neither)? (iv) Why does GFDL-ESM2M simulate these processes but other models do not? (What are the necessary conditions for simulating those processes? Are those processes realistic?) (v) Do these mechanisms also have implications for multi-decadal natural variability? Despite some risk in exploring processes simulated by only a minority of models, we would like to understand why GFDL-ESM2M can be the minority in such a major property of GCMs. Considering its challenge as a scientific problem and its societal impact, the outcome is so important that we believe we must understand this inter-model difference better.

This chapter is organized as follows. The data and an idealized model used in this study are described in the next section. In section 3.3, the idealized model is used to explore why NDH becomes negligible in a warmer climate; furthermore, we confirm that these ideas are consistent with GFDL-ESM2M output. Then, in section 3.4, we further compare the idealized model, observations, and GFDL-ESM2M output to propose a mean-state warming suppression mechanism as a forced response of the cold tongue to global warming. We also discuss the reason why only GFDL-ESM2M can simulate this mechanism, as well as the important difference between gradual and abrupt CO₂ increases. In section 3.5, we explore some implications of the above mechanism for multi-decadal natural variability and global warming hiatuses. Conclusions of this chapter are given in section 3.6.

### 3.2 Data and an Idealized Model

#### 3.2.1 Data

Observed monthly SSTs are from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) [Rayner et al., 2003] available online at [http://www.metoffice.gov.uk/hadobs/hadisst/index.html](http://www.metoffice.gov.uk/hadobs/hadisst/index.html) for the period 1880 through 2015. Except for Fig. 3.13, we
use SST data from the period 1965 through 2015, during which we expect the data to be less influenced by limited data sampling, changing measurement techniques, and analysis procedure dependence [Christensen et al., 2013]. Whenever we show time series, we add the data of the first half of 2016 so that we do not miss the 2015/16 El Niño. The spatial resolution is 1° latitude by 1° longitude. Oceanic potential temperature and horizontal velocity reanalysis data are obtained from the National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS) [Behringer and Xue, 2004] available online at http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html. The horizontal resolution is 1° longitude by 1/3° latitude, with a vertical resolution of 10 m for uppermost 230 m (no data deeper than 230 m are used in this study). The oceanic vertical motion at the 50 m depth is calculated assuming mass continuity with negligible density tendency, which exhibits very good agreement with vertical motion data available at the NCEP GODAS website. This agreement confirms the validity of this assumption and the algorithms we use for the model output described later.

We have used the representative concentration pathways (RCP) Concentration Calculations and Data [Meinshausen et al., 2011] available online at http://www.pik-potsdam.de/~mmalte/rcps/ to make Fig. 3.1. The time series presented in the figure is the RCP 8.5 anthropogenic forcing from 1860 through 2100. In addition, annual-mean, global-mean observed surface temperature is downloaded from the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP) [Hansen et al., 2010] produced by GISTEMP Team 2016 at the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies. The data was accessed on 2016-07-07 at http://data.giss.nasa.gov/gistemp/, to make Fig. 3.13.

The surface temperature, oceanic potential temperature, and horizontal velocity output from GFDL-ESM2M are taken from the GFDL Data Portal (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp). The experiments considered in this study are the first ensemble member of the piControl, historical, Abrupt4xCO₂, 1% per year increase in CO₂ (1pctCO₂), RCP 6.0, and RCP 8.5 runs. At each depth, the oceanic variables are regridded
via linear interpolation onto a 2.5° longitude by 2° latitude grid; the oceanic data have a vertical resolution of 10 m for the uppermost 230 m. The oceanic vertical motion at 50 m depth is calculated using the same procedure as described above. We also use other CMIP5 [Taylor et al., 2012] model output available at the Program for Climate Model Diagnosis and Intercomparison website (https://pcmdi.llnl.gov/projects/cmip5/) for making Fig. 3.8 and Table 3.1.

An important caveat of this chapter is that our results from GFDL-ESM2M are based on a single ensemble member for each experiment. In principle, we should test our results using multiple ensembles, but at the time of this writing, only a single ensemble member is available for each experiment of GFDL-ESM2M at the GFDL Data Portal. Nevertheless, by analyzing the piControl (500 years), historical (146 years), RCP 6.0 (95 years), RCP 8.5 (95 years), 1pctCO$_2$ (200 years) and Abrupt4xCO2 (300 years) runs, it turns out it is virtually certain that the nonlinear ENSO in this model is forced to weaken by global warming, and that the warming response of the mean-state zonal SST gradient in this model is La Niña-like, at the very least. These relatively robust warming responses of GFDL-ESM2M are the two main ingredients of the mechanism proposed in this chapter.

Using the aforementioned oceanic data, LDH and NDH of the mixed layer are calculated using the equation (3.1) at each gridpoint, assuming that the mixed layer depth is fixed at 50 m. As in AJ04, we have confirmed that the results shown in this chapter are not sensitive to the choice of the mixed layer depth and its variability. To calculate LDH and NDH, the monthly climatology (\(\bar{T}, \bar{u}, \bar{v}, \bar{w}\)) is calculated as the mean over the entire record for each month, except that linear trends are also added in RCP8.5, because the mean-state climatology also warms in this run. The LDH and NDH time series are calculated as the regional average over 5°N-5°S, 170°W-100°W, following AJ04. The oceanic reservoir temperature beneath the thermocline (\(T_o\)) is calculated as the temperature at 100m below the thermocline (the thermocline depth is defined as the depth with the maximum vertical temperature gradient). The results are not sensitive to this choice of depth (i.e., 100m), unless it is too close to the thermocline where the temperature has a larger interannual
3.2.2 Idealized Model

We use an idealized nonlinear recharge oscillator model introduced by Jin [1998] and Timmermann et al. [2003] and its modified versions. This model is essentially a simplified, two-box approximation of the Cane-Zebiak model [Zebiak and Cane, 1987]. The tendency of the temperature of the oceanic mixed layer in the western warm pool ($T_1$) and the eastern cold tongue ($T_2$) are:

$$\frac{dT_1}{dt} = -\alpha(T_1 - T_a) - \frac{u}{L/2}(T_2 - T_1)$$  (3.2)

$$\frac{dT_2}{dt} = -\alpha(T_2 - T_a) - \frac{w}{H_m}(T_2 - T_{sub})$$  (3.3)

where $1/\alpha$ denotes a thermal damping time scale, $T_{sub}$ denotes subsurface temperature, and $u$ and $w$ are eastward and upward oceanic velocities, respectively. $H_m$ and $L$ are the mixed layer depth and the basin width, respectively. $T_a$ denotes the zonally uniform lower atmospheric reservoir temperature, but except for section 3.5, $T_a$ is replaced by the radiative-convective equilibrium temperature $T_r$ as in Jin [1998] and Timmermann et al. [2003]:

$$T_a = T_r$$  (3.4)

Both $T_1$ and $T_2$ are relaxed toward $T_a$ by the first terms of the equations (3.2) and (3.3), and the second terms of (3.2) and (3.3) express the zonal and vertical temperature advection, respectively. Then, the wind stress $\tau$, $u$, and $w$ are expressed as:

$$\tau = -\mu(T_1 - T_2)/\beta$$  (3.5)

$$\frac{u}{L/2} = \epsilon \beta \tau$$  (3.6)

$$\frac{w}{H_m} = -\zeta \beta \tau$$  (3.7)

where $\mu$ is the sensitivity of the trade wind to the zonal SST gradient, and $\epsilon$ and $\zeta$ are zonal advection and upwelling efficiency (i.e., sensitivities of zonal and vertical oceanic currents to
the trade wind), respectively. Parameterization of $T_{\text{sub}}$ is given by Jin [1996] as:

$$T_{\text{sub}} = T_a - \frac{T_a - T_o}{2} \left(1 - \tanh \frac{H + h_2 - z_0}{h^*}\right)$$  \hspace{1cm} (3.8)

where $T_o$ is the oceanic reservoir temperature beneath the thermocline, $h_2$ is the departure of the eastern thermocline depth from the reference depth $H$, $z_0$ is the depth at which $w$ takes its characteristic values, and $h^*$ is a scale parameter that controls the sharpness of the thermocline. The thermocline depth departure $h_1$ (west) and $h_2$ (east) follow the recharge oscillator [Jin, 1997] formulations:

$$\frac{dh_1}{dt} = -r h_1 - \left(\frac{rbL}{2}\right) \tau$$ \hspace{1cm} (3.9)

$$h_2 = h_1 + bL \tau$$ \hspace{1cm} (3.10)

where $1/r$ denotes the damping time scale of the anomaly, and $b$ is the sensitivity of the thermocline to the trade wind change due to the Sverdrup transport. The parameter values used in this study follow AJ04 ($\alpha = 1/180 \text{ day}^{-1}$, $r = 1/400 \text{ day}^{-1}$, $H_m = 50 \text{ m}$, $H = 100 \text{ m}$, $z_0 = 75 \text{ m}$, $h^* = 62 \text{ m}$, $\mu = 0.0026 \text{ K}^{-1} \text{ day}^{-1}$, $\mu bL/\beta = 22 \text{ m K}^{-1}$, $\zeta = 1.3$, $\epsilon = 0.11$, and $L = 15 \times 10^6 \text{ m}$) except for some modifications described below.

Timmermann et al. [2003] and AJ04 introduced $T_r$ ($T_a$) and $T_o$ as constant parameters equaling 29.5 °C and 16 °C, respectively. Here, to simulate the change of the radiative-convective equilibrium temperature and the reservoir temperature associated with global warming, we modify $T_r$ and $T_o$ to be simple linear functions of time:

$$\frac{dT_r}{dt} = Q_r, \hspace{1cm} \text{or} \hspace{1cm} T_r = Q_r t + T_C$$ \hspace{1cm} (3.11)

$$\frac{dT_o}{dt} = Q_o, \hspace{1cm} \text{or} \hspace{1cm} T_o = Q_o t + T_D$$ \hspace{1cm} (3.12)

where $Q_r$, $Q_o$, $T_C$, and $T_D$ are test parameters that we will vary in the following sections. One of the main ideas presented in this chapter is that $T_a - T_o$ ($= T_r - T_o$ except for section 3.5) is a key parameter that determines the prominence of NDH and EENs. In “fixed reservoir temperature difference” experiments, we set $Q_r = Q_o = 0$, and in “increasing reservoir temperature difference” experiments, we set $Q_r > Q_o > 0$. 

In section 3.5, we further generalize the idealized model, particularly equation (3.4), so that \(T_a\) becomes capable of responding to the eastern equatorial mean-state multi-decadal variability. As shown in Kosaka and Xie [2013] and many others, a La Niña-like mean climate generally enhances the atmospheric cooling by the eastern equatorial Pacific, leading to global warming hiatuses or slowdowns. An El Niño-like mean-state, on the other hand, suppresses the atmospheric cooling rate. Therefore, the tendency of \(T_a\) and its heating rate \(R_a\) are expressed as the following equations:

\[
\frac{dT_a}{dt} = R_a \tag{3.13}
\]

\[
\frac{dR_a}{dt} = -\omega^2(T_a - T_r) - \gamma(T_a - T_2) \tag{3.14}
\]

where \(\gamma\) denotes the sensitivity of atmospheric heating rate to the cold tongue SST, and \(\omega\) is a normal-mode angular frequency of generalized multi-decadal atmospheric natural variability that restores the atmospheric temperature toward radiative-convective equilibrium. This natural variability could be a synthesized effect of, for instance, the Planck feedback, water vapor feedback, ice-albedo feedback, cloud feedback, and so on. Therefore, the restoring effect expressed as the first term in the equation (3.14) is not a simple relaxation that involves only negative feedbacks; rather, it excites an oscillatory behavior that involves both positive and negative feedbacks. The second term expresses a forcing by the eastern equatorial Pacific that cools the atmosphere, and we try to understand the atmospheric temperature variability as a forced oscillation. In this configuration, we could interpret the equation (3.4) as a limit of infinitesimal atmospheric sensitivity to the Pacific cold tongue (\(\gamma = 0\)) and infinitesimally low frequency of the atmospheric normal mode (\(\omega = 0\)) with initial conditions of \(T_a(t = 0) = T_c\) and \(R_a(t = 0) = Q_r\). The parameter values are tuned to \(\gamma = 0\) (zero sensitivity experiments) or \(2 \times 10^{-9} \text{ day}^{-2}\) (i.e., \(1/13700 \text{ year}^{-2}\)) (non-zero sensitivity experiments) and \(\omega = 2\pi/90\) rad year\(^{-1}\) so that the model realistically simulates the phenomena of interest.

Following Timmermann et al. [2003], the above idealized model is integrated forward in time using a Runge-Kutta method of fourth order with a time step of 1 day. The results presented in section 3.3 and 3.4 are not sensitive to initial conditions if realistic initial
conditions are chosen. In section 3.5, however, because of the more complicated model configuration, the range of initial conditions that reproduce our results appears to be narrower. In our study, we have used the initial conditions of $T_1 = 27 \degree C$, $T_2 = 20 \degree C$, $h_1 = 70$ m, $T_a = T_r = 29.5 \degree C$, $T_o = 15 \degree C$, and $R_a = 0 \degree C$/century at $t = 0$.

### 3.3 Dissipation of nonlinear dynamical heating (NDH) and extreme El Niño (EEN) events due to an increasing temperature difference between the atmospheric and oceanic reservoirs

In this section, we first use the idealized nonlinear recharge oscillator model to obtain some ideas for why NDH becomes unimportant in warmer runs of GFDL-ESM2M. Then, we further analyze the output from GFDL-ESM2M to show that the idealized model captures the behavior of GFDL-ESM2M reasonably well.

#### 3.3.1 Key parameter $T_a - T_o$

Figure 3.4a shows MPI (i.e., warm pool SST, $T_1$), the cold tongue SST ($T_2$), and the NDH time series simulated by the idealized model with fixed reservoir temperature difference $T_a - T_o = 12.0 \degree C$, $13.9 \degree C$, $14.1 \degree C$, and $14.3 \degree C$. Here we fix $T_a = 29.5 \degree C$ and vary $T_o$ to realize different values of $T_a - T_o$, but we obtain nearly identical results if we fix $T_o$ and change $T_a$ instead. As Timmermann et al. [2003] showed by changing either the zonal advection ($\epsilon$) or upwelling efficiency ($\zeta$), some different regimes of the ENSO variability are identifiable. The regime with $T_a - T_o = 12.0 \degree C$ corresponds to a regime with strong zonal advection, where all ENSO events are EENs (i.e., the cold tongue SST always reaches the MPI). As $T_a - T_o$ becomes larger ($T_a - T_o = 13.9 \degree C$), the frequency of EENs decreases with lengthening, intermittent linear periods in between EENs, whose basic dynamics can be explained by the linear recharge oscillator system. Then, the intervals between EENs become longer and irregular at $T_a - T_o = 14.1 \degree C$, and the EENs finally vanish at the $T_a - T_o = 14.3 \degree C$ regime. In this last regime, the ENSO becomes completely linear and no EENs are detected. These four experiments are consistent with observations that NDH is only important for EENs as
shown in Fig. 3.3c and by AJ04.

Based on the results obtained from the “fixed reservoir temperature difference” runs, we surmise that a “threshold reservoir temperature difference” at which the importance of NDH bifurcates exists between 14.1 °C and 14.3 °C. To test this idea, we have performed an “increasing reservoir temperature difference” run, where we gradually increase the $T_a - T_o$ linearly in time. As an analogue for global warming, we have simulated the increasing temperature difference by setting different heating rates, $Q_r = 1$ °C/century and $Q_o = 0.3$ °C/century, for the atmospheric and oceanic reservoirs, respectively. Figure 3.4b shows the result of this run, and, as expected, the intervals between the EENs become gradually longer (from about 12 to 18 year intervals) as the system warms, and the system exhibits no EENs and NDH after $T_a - T_o$ surpasses 14.2 °C in Year 100.

Mathematically, it is easy enough to understand why the system exhibits the same regime shift as the one shown in Timmermann et al. [2003]. In their Fig. 6, for a given efficiency of zonal advection ($\epsilon$), they varied the efficiency of upwelling ($\zeta$) with $T_a$ and $T_o$ fixed, whereas we have varied $T_a - T_o$ with $\zeta$ fixed. It turns out that varying $T_a - T_o$ yields essentially the same effect as changing the upwelling efficiency $\zeta$. Because variations of $T_a - T_o$ only influence equation (3.8), the increase of $T_a - T_o$ means a decrease of $T_{sub}$, or an increase of $(T_2 - T_{sub})/H_m$ (vertical temperature gradient) in the equation (3.3). Because $(T_2 - T_{sub})/H_m$ is multiplied by $w = -\zeta\beta\tau H_m$ in equation (3.3), it is evident that increased $T_a - T_o$ has the same effect on the tendency of $T_2$ as increased $\zeta$.

Physically, the above mathematical explanation can be translated as follows. If global warming heats the lower atmosphere faster than the ocean interior beneath the thermocline, it tends to enhance the upper ocean stratification, which in turn enhances the mixed-layer cooling by the equatorial upwelling. Hence, this overwhelming upwelling prevents the thermocline from recharging the heat enough to collapse its climatological mean structure. This “rigid” climatological thermocline means a complete damping of NDH, making it difficult for a warm SST anomaly to mature in response to westerly wind anomalies (see also the schematics in Figs. 3.10 a and b).
Figure 3.4: (a): As in the top and middle panels in Fig. 3.2, but for the idealized model. Each panel shows a simulation with fixed temperature difference between the atmospheric and oceanic reservoir \((T_a - T_o)\) indicated at the top left. (b): As in (a), but increasing \(T_a - T_o\) following the equation shown at the top left. The dashed line shows the time when \(T_a - T_o\) reaches the threshold that bifurcates the importance of the ENSO nonlinearity.
3.3.2 Comparison with GFDL-ESM2M

In state-of-the-art GCMs and in the real world, the lower atmospheric temperature should warm faster than the ocean interior beneath the thermocline, because of the large oceanic heat capacity and the slow oceanic circulation compared to the atmospheric counterparts. Therefore, as a transient response to global warming, $T_a - T_o$ should become larger as the Earth warms, and this may be why no NDH and EENs are detected in a warmer climate in GFDL-ESM2M. To test this hypothesis, we have calculated the time series of $T_a - T_o$ in GFDL-ESM2M using the warm pool SST as a proxy for $T_a$ (because, in section 3.3, $T_a$ is equal to the radiative-convective equilibrium temperature) and the temperature 100 m below the thermocline, averaged over the cold tongue region ($5^\circ S-5^\circ N$ and $120^\circ W-90^\circ W$), as a proxy for $T_o$ (see also section 3.2). For reference, the typical thermocline depth for this region is about 50 m.

Figure 3.5 shows the time series of MPI, the cold tongue SST, NDH, and $T_a - T_o$ for the piControl, RCP8.5, and Abrupt4xCO$_2$ runs of GFDL-ESM2M. As already pointed out in Fig. 3.2, GFDL-ESM2M occasionally exhibits EENs and NDH in piControl (nonlinear regime), but no EENs and NDH in Abrupt4xCO$_2$ (linear regime). In accordance with a gradual warming in RCP 8.5, the model exhibits a clear transition from the nonlinear regime to the linear regime. More importantly, our key parameter $T_a - T_o$ also increases by about 1 °C as the regime shifts, suggesting that the ideas obtained from the idealized model experiments are consistent with the behavior of GFDL-ESM2M.

To further confirm the consistency between the idealized model and GFDL-ESM2M, in Fig. 3.6, we have also plotted phase diagrams showing the relationship between the cold tongue SST anomalies and western thermocline depth departure anomalies. The phase diagrams of both models exhibit a reasonable resemblance with each other, and the mechanism can be explained as follows. In the nonlinear regime with low upwelling efficiency, the Sverdrup transport caused by the trade wind recharges the heat in the equatorial mixed layer and the thermocline depth gradually becomes deeper than the norm, which in turn causes
Figure 3.5: As in the top and middle panels of Fig. 3.2, but panels for RCP 8.5 scenario is inserted between piControl and Abrupt4xCO₂. The scale of the horizontal axes for RCP 8.5 is expanded by a factor of 2. Also shown at the bottom is 15-year running mean $T_a - T_o$ during DJF estimated as described in the text. The dashed line shows the time when $T_a - T_o$ reaches the threshold that bifurcates the importance of the ENSO nonlinearity.
inefficient upwelling, and finally, an extremely warm SST anomaly in the cold tongue (i.e., EEN). In the linear regime with high upwelling efficiency, however, the trade wind cannot recharge the heat in the mixed layer because of the stronger upwelling cooling, so the thermocline cannot become deep enough to excite an event with a huge SST anomaly in the east.

### 3.4 Nonlinear ENSO Warming Suppression (NEWS) causing a La Niña-like mean-state response to global warming

In this section, we further compare the idealized model with observations and GFDL-ESM2M output to show that the forced, nonlinear EEN dissipation due to the transient increase of $T_a - T_o$ has a warming suppression effect on the mean state of the eastern equatorial Pacific SST. We also explore some necessary conditions to simulate this mechanism by comparing GFDL-ESM2M to other models. Furthermore, we focus on the different mean-state responses between gradual and abrupt warming runs to emphasize the transient aspect of this mechanism and to determine the direction of causality between the ENSO amplitude change and the mean-state change.

#### 3.4.1 NEWS as a forced response to global warming

In the previous section, we have shown that El Niño events cannot become huge in a warming climate in GFDL-ESM2M, because the transient heating rate difference between the atmospheric and oceanic reservoirs enhances the cooling effect of the mean upwelling, which in turn damps NDH necessary to produce a large positive eastern equatorial SST anomaly. In section 3.1, we reviewed AJ04’s observational evidence that NDH causes the El Niño-La Niña amplitude asymmetry and that the NDH warming effect is comparable to LDH only for EENs. Therefore, due to the NDH dissipation, if El Niño events are weakened but La Niña events remains almost unchanged, then we expect a nonlinear rectification effect on the climatological mean state [Battisti and Hirst, 1989; Jin et al., 2003], which causes a La Niná-like mean-state SST response to global warming.
Figure 3.6: (a): Phase diagrams showing the relationship between the cold tongue SST ($T_2$) anomalies and the western thermocline depth departure ($h_1$) anomalies simulated by the idealized model. The left (right) panel shows the one with $T_a - T_o$ below (above) the threshold that bifurcates the importance of the ENSO nonlinearity. The point ($T'_2, h'_1$) circles clockwise as the model is integrated forward in time. (b): As in (a), but for GFDL-ESM2M under RCP8.5. The western thermocline depth is defined as the depth at which the vertical temperature gradient reaches its maximum, and is averaged over 5°S-5°N, 140°E-150°W. After removing monthly climatology and centennial linear trends, 3-month running mean is applied.
Figures 3.7a and 3.7b show the results of the idealized model runs with weak and strong greenhouse forcing. We use the parameters of $Q_r = 1.0$ (°C/century) and $Q_o = 0.3$ (°C/century) for the weak greenhouse forcing run (identical to Fig. 3.4b), and $Q_r = 2.5$ (°C/century) and $Q_o = 1.8$ (°C/century) for the strong greenhouse forcing run. For both runs, we kept $Q_r - Q_o$ (therefore $T_a - T_o$) the same, 0.7 °C/century, but only changed the magnitude of warming. As discussed in the last section, the key parameter for the importance of NDH is $T_a - T_o$, rather $T_a$ or $T_o$ individually, so the nonlinear behaviors are reasonably similar between the two runs except for minor differences due to the chaotic nature of the dynamical system.

In both experiments, the warm pool SST (i.e, the MPI) warms with a strict upper bound of the radiative-convective equilibrium temperature. Comparing the first century (nonlinear regime) with the second century (linear regime), the mean-climate warm pool SST warms accordingly. On the other hand, because of the EEN cessation at about Year100 (i.e., $T_a - T_o = 14.2$ °C), the mean-state cold tongue SST experiences cooling (weak greenhouse forcing) or slow warming (strong greenhouse forcing) during the two centuries. In particular, it is interesting that global “warming” forcing by itself can even “cool” the eastern equatorial Pacific, if the forcing is not too strong. Of course, this cooling does not violate the second law of thermodynamics. The reason why the cold tongue SST cools is simply because the upwelling of the cool water is no longer interrupted by EENs in a warmer climate. We believe this cooling is hard to be realized solely by the Ocean Dynamical thermostat [Clement et al., 1996], because both the radiative-convective equilibrium temperature and the upwelling water temperature, in this particular experiment, are designed to warm. Then, the strong greenhouse forcing run clearly shows that, even if the EEN dissipation cooling effect is much weaker compared to the radiative warming, the EEN effect is still detectable in the form of zonal difference of the warming rate.

In summary, the warm pool SST is almost solely bounded by the radiative convective equilibrium temperature change, but the cold tongue SST is controlled by two competing effects: the radiative warming and the EEN-dissipation cooling. Therefore, at least in this
Figure 3.7: (a): As in Fig. 3.4b, but with the mean SST over the years before (colored solid) and after (colored dashed) the time when the ENSO nonlinearity becomes unimportant (black dashed). Orange (magenta) lines show the mean SST of the western warm pool (eastern cold tongue) SST. Also shown is the prescribed radiative-convective equilibrium temperature (gray). (b): As in (a), but for stronger greenhouse forcing with $T_a - T_o$ kept the same as in (a). (c): As in (a), but for observations during DJF. Also shown is the map of the annual-mean observed SST trends during 1965-2015 computed relative to the tropical Pacific mean trends (30°S-30°N, 90°E-60°W). Blue color denotes a warming slower than the tropical Pacific mean, not necessarily a cooling. Unit is °C/century. (d): As in (c), but for GFDL-ESM2M under RCP8.5.
idealized model, the western equatorial Pacific warms faster than the east due to a forced response to global warming. We have hypothesized that this mechanism may be the cause of the La Niña-like mean-state warming in GFDL-ESM2M, and possibly cause part of the observed trend during the satellite era. We hereafter refer to this mechanism as the Non-linear ENSO Warming Suppression (NEWS), and will further explore whether it is actually realistic. The essential physics of the NEWS mechanism is that the increasing \( T_a - T_o \), due to the transient heating rate difference between the atmospheric and oceanic reservoir, dissipates EENs due to the enhanced upwelling efficiency, and then as suggested by Jin et al. [2003], the weakened nonlinear ENSO amplitude causes a rectification cooling effect on the climatological-mean cold tongue SST.

The upper panel of Fig. 3.7c shows the warm pool and cold tongue SST observed during DJF from 1965/66 through 2015/16. As we have already seen in Fig. 3.3, the nonlinear regime continued toward the end of the past century, and since then it has been almost linear. At least by this metric, the warm pool is warming much faster than the cold tongue (where the SST has slightly cooled), which is consistent with the NEWS mechanism. Though this mean cooling is undoubtedly exaggerated by natural variability, our point here is that, even if the cold tongue has been cooling during the past half a century, part of this trend in the tropical Pacific may be forced by global warming, as shown in Fig. 3.7a. Because of the zonal difference of the warming rate, the spatial pattern of the SST trend looks like a La Niña-like warming (Fig. 3.7c, lower).

GFDL-ESM2M is also consistent with NEWS. Figure 3.7d shows the modeled warm pool and cold tongue SST during DJF in RCP 8.5. As we have seen in Fig. 3.5, the nonlinear regime appears to end in about 2070. This run looks more similar to the strong greenhouse forcing experiment in the idealized model (Fig. 3.7b). Because of the strong greenhouse forcing, one might have the impression that the NEWS effect appears to be subtle in the time series (Fig. 3.7d, upper). The spatial pattern of the trend (Fig. 3.7d, lower), however, undoubtedly shows that the west Pacific warms faster than the east, which is consistent with the NEWS mechanism.
3.4.2 Necessary conditions of NEWS

We expect that the atmospheric heating should be faster than the oceanic heating in most CMIP5 models, not only GFDL-ESM2M. Why, then, do the majority of the CMIP5 models lack the La Niña-like trend associated with NEWS? As shown in the idealized model experiments, the nonlinear dynamics of ENSO is an essential ingredient of NEWS. If GCMs do not capture realistic nonlinear ENSO dynamics, the NEWS mechanism cannot operate, which could have implications for the reliability (or lack thereof) of tropical mean-climate change projections by those models.

Figure 3.8a (and Table 3.1) shows the relationship between the ENSO nonlinearity and the zonal SST gradient response to warming calculated for 32 CMIP5 models and observations. Here, the ENSO nonlinearity is defined as the skewness of detrended 11-month running mean SST anomalies, and is averaged over the Niño3 region so that positive skewness means larger El Niños and smaller La Niñas. The zonal SST gradient is defined as Niño3 SST anomalies minus Niño4 (5°S-5°N and 160°E-150°W) SST anomalies as in the previous chapter so that a positive Δ(Niño3-Niño4) means an El Niño-like mean-state warming. Interestingly, the majority of the models exhibit little nonlinearity of ENSO and large El Niño-like warming trends, but observations and GFDL-ESM2M both show large nonlinearity and La Niña-like warming trends. Therefore, it is possible that only GFDL-ESM2M can capture the Pacific SST response to warming in the real world. The larger zonal SST gradient change in GFDL-ESM2M (RCP8.5) than in observations (1965-2015) could partly be explained by the greenhouse warming strength, but it could also be attributed to the ENSO amplitude bias of GFDL-ESM2M (Figs. 3.8b and c).

Figures 3.8d through 3.8f show some examples of detrended 11-month running mean Niño3 time series from the CMIP5 models. Figure 3.8d shows three models, HadGEM2-CC, MPI-ESM-LR, and CSIRO-Mk3-6-0, which exhibit opposite or insufficient ENSO asymmetry compared to observations. CSIRO-Mk3-6-0 has a strong warming near the Niño4 region, and therefore it exhibits an extremely negative Δ(Niño3-Niño4) (Fig. 3.8a). Nevertheless,
Figure 3.8: (a): Scatter plot showing the relationship between the ENSO nonlinearity (defined as the skewness of detrended 11-month running mean Niño3 index) and the zonal SST gradient change (defined as the centennial linear trend of Niño3 minus Niño4) under RCP8.5, calculated for GFDL-ESM2M (red) and other 31 CMIP5 models (black). Also shown is the value for observations during 1965-2015 (blue), which should not be directly compared to the projections under RCP 8.5. (b): Detrended Niño3 SST anomalies (SSTA) for observations. 11-month running mean is applied. (c): As in (b), but for GFDL-ESM2M under RCP8.5. (d): As in (c) but for CMIP5 models with negative or small skewness. (e): As in (d), but with few extreme El Niño events. (f): As in (d), but with excessive extreme El Niño events.
Table 3.1: Table showing the numerical values shown in Fig. 3.8a. Unit of $\Delta$(Niño3-Niño4) is °C/century. The values obtained from observations during 1965-2015 are 0.77 and -0.15 °C/century for the Niño3 skewness and $\Delta$(Niño3-Niño4), respectively.

<table>
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<tr>
<th>Model</th>
<th>Niño3 Skewness</th>
<th>$\Delta$(Niño3-Niño4)</th>
<th>Model</th>
<th>Niño3 Skewness</th>
<th>$\Delta$(Niño3-Niño4)</th>
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The spatial pattern looks more like the multi-model mean El Niño-like pattern (not shown; qualitatively similar to the right panel of Fig. 3.9b). Figure 3.8e shows two models, CESM1-CAM5, and IPSL-CM5A-MR, which exhibit better asymmetry. These models still do not have EENs that are strong enough for the NEWS effect to be important. An interesting outlier is MIROC5 [Watanabe et al., 2010] shown in Fig. 3.8f. This model is the only model that exhibits more realistic skewness than GFDL-ESM2M (Fig. 3.8a), but it also exhibits the largest positive $\Delta$(Niño3-Niño4), or a strong El Niño-like warming. The time series shows a large number of EENs, so it is possible that NDH in this model may be too large, more like the upper left panel of Fig. 3.4a with small climatological $T_a - T_o$. Thus, it may be hard for $T_a - T_o$ to surpass the threshold at which the importance of ENSO nonlinearity bifurcates. In the next chapter, we discuss why MIROC 5 does not simulate NEWS despite its realistic nonlinearity.
3.4.3 Transient feature of NEWS and the direction of causality between the ENSO amplitude change and the mean-state trends

Though we have used piControl and Abrupt4xCO$_2$ to show the EEN dissipation in the previous section, the rectification effect on the mean-state SST exhibits some important differences between a gradual CO$_2$ increase and an abrupt one. Figures 3.9a and 3.9b show the spatial pattern of the SST trend relative to the Pacific mean trend for gradual and abrupt CO$_2$ increases. As we have discussed so far, the mean-state SST responses in the gradual CO$_2$ runs are clearly La Niña-like, which we believe are associated with NEWS. The warming response of the abrupt runs (expressed as Abrupt4xCO$_2$ minus piControl), however, exhibits more zonally uniform warming. If we look at this pattern carefully, the west Pacific exhibits a reasonably similar spatial structure to the gradual runs, but it also exhibits additional warming anomalies in the east.

The 300-year trends calculated for Abrupt4xCO$_2$ might reveal the cause of its different behavior (Fig. 3.9b, right). The spatial structure of this trend pattern looks quite similar to the multi-model mean calculated for CMIP5 [Ying et al., 2016; Zheng et al., 2016]. Given that this multi-model-mean El Niño-like pattern is associated with the slow response of the Walker Circulation change [Held and Soden, 2006; Vecchi and Soden, 2007; Held et al., 2010] or the ocean dynamics [Luo et al., 2015, 2016], the spatial pattern of the “Abrupt4xCO$_2$ minus piControl” could be interpreted as the superposition of the slow El Niño-like pattern and the transient La Niña-like pattern associated with NEWS. This idea of superposition is consistent with the fact that the trends shown in the second century of the 1pctCO$_2$ run is overall weaker than those shown in the first century, because the NEWS mechanism is slow but transient, and that the trend pattern calculated for the full two centuries in 1pctCO$_2$ does not look too different from the “Abrupt4xCO$_2$ minus piControl” (not shown).

The transient feature of NEWS is schematically shown in Fig. 3.10. If we transiently warm the atmosphere faster than the ocean, the resulting temperature difference would tend to enhance the climatological upwelling efficiency, which annihilates EENs. As we have
Figure 3.9: (a): As in the bottom panel in Fig. 3.7d, but for RCP 6.0, RCP 8.5, and the first and second halves of the 1% per year increase in CO$_2$ (1pctCO$_2$) run. (b): Left panel, warming response calculated as difference of SST climatology in the manner of Abrupt4xCO$_2$ (Year101-300) minus piControl. Unit is °C. Right panel, As in (a), but for Abrupt4xCO$_2$ (Year1-300). Unit is °C/century.
repeatedly explained, this contrast between a normal climate (Fig. 3.10a) and a transiently warming climate (Fig. 3.10b) is the basis of the NEWS mechanism. Once the system reaches its equilibrium, however, the oceanic temperature increase catches up with that of the atmosphere, which may eventually establish EENs again (Fig. 3.10c). Therefore, the NEWS effect is not necessarily expected to continue perpetually in an equilibrated warmer climate. This renewal of EENs, however, cannot be detected under Abrupt4xCO2 as shown in Fig. 3.5, which may be partly because the 200-year time span might be too short for the oceanic reservoir temperature to catch up with the radiative-convective surface temperature.

We have to remember, however, that the CO2 increase in the real world should be gradual, not abrupt. Therefore, at least based on these results from GFDL-ESM2M, the realistic SST warming pattern during this century should be closer to the La Niña-like one associated with the transient NEWS mechanism. Some previous studies [e.g., Held et al., 2010] have shown that the La Nina-like fast response to abrupt CO2 forcing might be due to the Ocean Dynamical Thermostat [Clement et al., 1996]. The response time scale of the Ocean Dynamical Thermostat, however, is too short to appear in the centennial trend of the gradual warming runs, because the shallow oceanic overturning circulation that largely controls the thermostat mechanism takes only about a couple of decades at the longest to complete its full circuit and to reach quasi-equilibrium. This time scale is clearly different from the ENSO response to global warming, which takes almost a full century for multiple EENs to dissipate and for the NEWS effect to emerge.

The different response between the gradual and abrupt runs could also help elucidate the direction of causality between the EEN dissipation and the mean-state SST change. As we have shown, in the Abrupt4xCO2 run, the mean-state warming response is zonally uniform because the slow El Niño-like response also contributes to the total trend. Interestingly, however, the ENSO amplitude still keeps its weakened amplitude, without any EENs, even in late third century (Fig. 3.5). This weakened amplitude means that the nonlinear ENSO amplitude is not affected by the zonally-uniform mean-state change in the abrupt run, though we see a hint of increased LDH (Fig. 3.2). Therefore, at least in GFDL-ESM2M, the
Figure 3.10: (a): Schematic showing the relationship between the atmospheric/oceanic reservoir temperature difference \((T_a - T_o)\) and the nonlinear ENSO dynamics in a normal climate. The blue arrow shows the efficiency of climatological upwelling. Contours show the meridional-mean equatorial potential temperature of the upper Pacific ocean (0-200 m). (b): As in (a), but for a transiently warming climate. (c): As in (a), but for an equilibrated warmer climate.
weakened nonlinear ENSO amplitude is more likely to be a cause, rather than an effect, of the La Niña-like mean-state change in the gradual CO$_2$ increase runs. This result questions the views presented in some earlier studies that treated ENSO as more like a linear mode [e.g., Timmermann et al., 1999; An and Jin, 2000; Fedorov and Philander, 2000; Urban et al., 2000; Wang and An, 2001, 2002], but is consistent with a submitted work by Atwood et al. (2016) where they took nonlinearity into account (currently available at http://www.atmos.washington.edu/~david/Atwood_etal_ENSO_submitted_2016.pdf). We believe, however, that this argument remains to be too speculative and insufficient to demonstrate causality. Closer investigation is needed to further verify the causality.

3.4.4 The Pacific mean-state climate change as a forced response to global warming

Figure 3.11 presents three warming scenarios that can be simulated by state-of-the-art GCMs. Figure 3.11a shows the NEWS scenario, where gradual global warming increases $T_a - T_o$ and triggers the transient NEWS mechanism to yield a La Niña-like trend (Fig. 3.9a). To the best of our knowledge, this scenario is only simulated by GFDL-ESM2M, which exhibits the second most realistic ENSO nonlinearity among the 32 CMIP5 models investigated here. As shown by the previous chapter in their Fig. 3, the La Niña-like trend then strengthens the Walker circulation, whose structure is remarkably similar to the observed trend during the satellite era. Because the NEWS effect is so strong, GFDL-ESM2M does not use the Walker circulation for weakening the global-mean atmospheric circulations to sustain the energy and water balance [Held and Soden, 2006], as the majority of GCMs do [Vecchi and Soden, 2007]. The previous chapter also showed that the strengthening Walker circulation in GFDL-ESM2M is still consistent with the global mean energy-water balance [Held and Soden, 2006]. On the other hand, the reason why the majority of the CMIP5 models do not simulate NEWS appears to be that the ENSO nonlinearity of these models is unrealistic (Figs. 3.8 and 3.11b).

Figure 3.11c shows the Abrupt Warming scenario, where CO$_2$ is abruptly increased instantaneously. Even for the abrupt increase, the increase of $T_a - T_o$ dissipates EENs as
Figure 3.11: (a): Flow chart showing the scenario where the Nonlinear ENSO Warming Suppression (NEWS) mechanism works, which appears to be realized only by GFDL-ESM2M with a gradual increase of CO₂. (b): As in (a), but without NEWS. The majority of the CMIP5 models follows this scenario. (c): As in (a), but for an abrupt warming scenario.
shown in Fig. 3.2, so the NEWS mechanism is expected to work. The mean-state SST rectification effect of NEWS, however, appears to be masked by other mechanisms as follows. First, because of the short time span of the CO$_2$ increase, the effect of Ocean Dynamical Thermostat [Clement et al., 1996] might dominate the fast SST response as suggested by Held et al. [2010]. Moreover, once the system reaches its quasi-equilibrium, the energy-water balance eventually starts to weaken the Walker Circulation as a slow response, which helps an El Niño-like trend emerge (Fig. 3.9b, right). It is also possible that the ocean dynamics could also contribute to the El Niño-like trend, as recently shown by Luo et al. [2015, 2016]. Therefore, by subtracting the piControl climatology from the equilibrated Abrupt4xCO$_2$ climatology, we detect a superposition of the La Niña-like trend caused by the transient mechanisms and the El Niño-like trend caused by the energy-water balance, which is a more zonally-uniform SST warming (Fig. 3.9b). Despite the zonally-uniform mean-state SST change, the nonlinear part of the ENSO amplitude is kept suppressed in a warmer climate (Fig. 3.2). Therefore, though our explanation remains speculative, we believe it is more likely that the weakening ENSO amplitude under gradual warming is a cause, rather than an effect, of the mean-state SST change.

### 3.5 Implications for multi-decadal natural variability of the Pacific SST and global warming hiatuses

Because the NEWS mechanism is driven by the reservoir temperature difference between the atmosphere and ocean, the root cause of this difference does not have to be greenhouse forcing, as long as the Earth is transiently heated and the lower atmosphere warms faster than the oceanic interior. Therefore, even if the Earth is warmed by natural variability, rather than an anthropogenic forcing, the NEWS mechanism should still operate. The opposite mechanism might also work if the Earth is cooled by a certain cause. In this section, we further explore the idealized model and the piControl run to investigate some implications of NEWS for multi-decadal natural variability of the Pacific SST. We then discuss the effect of this natural variability on global warming.
3.5.1 IPO-like natural multi-decadal variability explained by the NEWS-NECS cycle

If the Earth’s atmosphere were cooled by a random natural cause, this cooling would transiently decrease $T_a - T_o$, making upwelling less efficient and producing more EENs with nonlinear ENSO dynamics. The increased number of EENs must then have a rectification warming effect on the mean-state cold tongue SST, producing an El Niño-like mean climate. If the NEWS mechanism is realistic, this opposite mechanism should also operate. Hereafter, we refer to this mechanism as the Nonlinear ENSO Cooling Suppression (NECS).

Moreover, as Kosaka and Xie [2013] and many others have discussed in relation to the recent global warming slowdown, it is known that a prolonged La Niña-like mean-state cools the atmospheric temperature, and vice versa. Therefore, we expect that the effect of NEWS (NECS) can eventually cause NECS (NEWS), and the repetition of NEWS and NECS might contribute to multi-decadal natural variability. The idea can be summarized into five steps as follows:

1. When the atmosphere is warmed, the NEWS mechanism yields a La Niña-like Pacific mean climate.

2. The prolonged La Niña-like Pacific mean climate eventually cools the atmosphere.

3. When the atmosphere is cooled, the NECS mechanism yields an El Niño-like Pacific mean climate.

4. The prolonged El Niño-like Pacific mean climate eventually warms the atmosphere.

5. Repeat 1-4.

Based on this idea, we have further generalized the idealized model by making the atmospheric reservoir temperature sensitive to the cold tongue SST as described in section 3.2. In this model, the atmosphere has also its normal mode of natural variability that restores the atmosphere toward the radiative-convective equilibrium temperature, and is forced by the
cold tongue SST. Figure 3.12a shows the warm pool and cold tongue SST simulated by the idealized model. Because of the forced oscillation of the atmospheric reservoir temperature, $T_a - T_o$ exhibits a sinusoidal variation so that it crosses the threshold that bifurcates the importance of the ENSO nonlinearity (i.e., $T_a - T_o = 14.2\, ^\circ\text{C}$). Therefore, during a nonlinear ENSO phase, EENs emerge and suppress the cooling rate of the atmosphere by the cold tongue. The resulting warming pushes the system toward a linear ENSO phase by the NEWS mechanism. On the other hand, during a linear ENSO phase, EENs dissipate, and the cold tongue enhances the cooling rate of the atmosphere. The resulting cooling pushes the system toward a nonlinear ENSO phase by the NECS mechanism. This NEWS-NECS cycle exhibits a clear multi-decadal oscillation that is reasonably similar to the Interdecadal Pacific Oscillation (IPO) observed in the real world.

Next, it would be interesting to investigate if GFDL-ESM2M reproduces this NEWS-NECS cycle. By taking a careful look at the piControl run shown in Fig. 3.5, one finds that NDH and EENs are weakened during about Year 300±50. Therefore, we hypothesize that this amplitude variation might be understood in the context of the NEWS-NECS cycle. Figures 3.12b and 3.12c show the warm pool and cold tongue SST, $T_a - T_o$, and the SST trend pattern during Year 211-400. During the first half of this period (Fig. 3.12b), $T_a - T_o$ has a clear positive trend, EENs dissipate in about Year 260, and the Pacific SST exhibits a La Niña-like trend. Therefore, the first half of the period is consistent with the NEWS mechanism as described in the previous section. On the other hand, during Year 306-400 (Fig. 3.12c), a negative trend of $T_a - T_o$, an increasing number of EENs, and an El Niño-like trend are detected, which is consistent with the NECS mechanism.

Because the normal mode frequency of the atmospheric natural variability ($\omega$) and the sensitivity of atmospheric heating rate to the cold tongue SST ($\gamma$) are free parameters that are difficult to estimate based on currently available observational records, the aforementioned mechanism remains speculative in the sense that we have arranged the system to cross the $T_a - T_o$ threshold for producing realistic decadal variability. A more rigorous heat budget analysis is also needed to confirm that the natural $T_a - T_o$ variation in GFDL-ESM2M is
Figure 3.12: (a): As in Fig. 3.4a, but the atmospheric reservoir is not fixed to the radiative-convective equilibrium temperature. Also shown at the bottom is $T_a - T_o$. (b): Top and Middle panels, As in (a), but for GFDL-ESM2M under piControl (Year211-305, DJF). 15-year running mean is applied to $T_a - T_o$. Bottom panel, As in the bottom panel of Fig. 3.7d, but for piControl (Year211-305). (c): As in (b), but for Year306-400.
induced by the modulation of heating by the Pacific mean-state SST variations. Nevertheless, the mechanism makes physical sense, so it is expected to contribute to the observed IPO-like multi-decadal SST variability at least to some extent. The remarkable resemblance between the idealized model and GFDL-ESM2M also increases the interest in investigating this NEWS-NECS hypothesis further as one of many possible mechanisms of low frequency natural SST variability, such as the IPO. It is also consistent with previous studies that suggested that the ENSO nonlinearity and/or EENs may play a role in rectifying the mean-state SST [e.g., An et al., 2005] or in changing the phase of the IPO [e.g., Meehl et al., 2016]. Model-based process studies using GCMs, and if possible, observational verifications might shed new light on our understanding of the tropical Pacific multi-decadal natural variability.

3.5.2 Implications for global warming hiatuses

The main idea presented by Kosaka and Xie [2013, 2016] was to explain the global warming hiatuses and slowdowns by prescribing the Pacific multi-decadal SST variability. Therefore, if we hypothesize that the NEWS-NECS cycle explains part of the Pacific low-frequency natural SST variability, one straightforward societal application of the NEWS-NECS cycle may be an attempt to explain global warming hiatuses. In this subsection, we further investigate global warming hiatuses using the idealized model and compare them to the observed global warming hiatuses.

Figure 3.13a shows the atmospheric natural variability simulated by the idealized model with zero sensitivity to the cold tongue SST. The heating rate of radiative-convective equilibrium temperature and oceanic reservoir temperature are chosen to be \( Q_r = 2.0 \, ^\circC/\text{century} \) and \( Q_o = 1.9 \, ^\circC/\text{century} \), respectively. The atmospheric reservoir temperature is strongly restored toward the prescribed, increasing radiative-convective equilibrium temperature that serves as an analog of greenhouse forcing. From this simulation, it is confirmed that, though the atmospheric temperature exhibits weak oscillations and slowdowns, occasional negative decadal trends such as those observed in the real world are not simulated solely by the atmospheric natural variability under the parameter values and initial conditions used here.
Figure 3.13: (a): Atmospheric reservoir temperature simulated by the idealized model with zero atmospheric sensitivity to the cold tongue SST (navy blue). Also shown is the prescribed radiative-convective equilibrium temperature (gray). (b): Top panel, As in (a), but for non-zero atmospheric sensitivity to the cold tongue SST. Also shown are the periods of global warming hiatuses (green). Middle and Bottom panels, As in Fig. 3.12a, but increasing the radiative-convective equilibrium temperature and oceanic reservoir temperature. (c): As in the top and bottom panels of (b), but for observations. Atmospheric reservoir temperature is replaced by annual-mean, global-mean surface temperature relative to the base period of 1951-1980. SST is averaged over DJF.
Next, as described in section 3.2, we have allowed ocean-atmosphere interaction to operate in the idealized model. Figure 3.13b shows the result of this simulation. Because the atmosphere is sensitive to the cold tongue SST, the model exhibits well-defined hiatus periods where the atmospheric temperature does not experience a monotonic increase. It is consistent with the NEWS-NECS cycle that the warming trend of the atmospheric temperature is boosted by the emergence of EENs at the end of the hiatus periods, and is moderated by the absence of EENs during the prolonged linear ENSO phase. As a feature of the forced oscillation, the frequency of the atmospheric variability is slightly modulated by the IPO-like multi-decadal SST variability. For the ocean, on the other hand, relatively large variations of $T_a - T_o$ forced originally by the low-frequency variations of EENs, are in turn necessary to repeatedly cross the threshold temperature (i.e., $T_a - T_o = 14.2 \degree C$) to maintain the low-frequency variations of NDH and EENs. If this is the case, both atmospheric and oceanic roles regarding the NEWS-NECS cycle are important for amplifying the emergence and termination of multiple hiatus periods, instead of the atmosphere being unidirectionally forced by the “prescribed” SST multi-decadal variability. In addition, considering that the key metric of the NEWS-NECS cycle is the ENSO nonlinearity, the lack of realistic ENSO nonlinearity may be one of many reasons why some GCMs have difficulty reproducing the global warming hiatiuses, at least without prescribing observed SSTs [Kosaka and Xie, 2013, 2016] or trade winds [Watanabe et al., 2014] in the eastern Pacific. On the other hand, it is also reported that other GCMs reproduces the most recent slowdown [Meehl et al., 2014; Liu et al., 2016]. Therefore, it remains uncertain how much the NEWS-NECS cycle contributes to hiatiuses and slowdowns in the real world.

Though the data quality of the observational datasets is limited before the middle of the past century, we have further attempted to compare this result to observations. Figure 3.13c shows the annual-mean, global-mean surface temperature time series in place of the atmospheric reservoir, and SST (the warm pool and cold tongue SST) during DJF of 1880-2015. Overall, the qualitative features are similar to the results simulated by the idealized model. Particularly similar is the feature that the EENs in 1982/83 and 1997/98 (and
possibly 1972/73) appear to have boosted the global warming trend during the early satellite era, which is also consistent with previous studies suggesting a relationship between global warming hiatuses and IPO phase changes. Based on the idea of the NEWS-NECS cycle, we also expect some EENs during about 1910-1930, which were not as clearly observed as during the early satellite era. It is also possible, however, that the lack of EENs during 1910-1930 is, in part, due to the relatively poor data quality during this period.

3.6 Conclusions

In this chapter, we have investigated observational data and model output from an idealized nonlinear recharge oscillator model and GCMs (with an emphasis on GFDL-ESM2M) to obtain the following conclusions.

3.6.1 A nonlinear theory shows that extreme El Niño (EEN) events may currently be becoming less frequent, and if global warming continues, EENs may not be observed at the end of this century. At least one GCM is consistent with this theory.

Some earlier studies that suggested an increase of the ENSO variance under global warming treated ENSO as a linear mode. This study, on the other hand, incorporates nonlinear ENSO dynamics and reconsiders future changes to ENSO. In our idealized model and GFDL-ESM2M (which has the second-most realistic ENSO nonlinearity of the 32 CMIP5 models investigated here), the ENSO amplitude weakens substantially in a warmer climate. Due to the transient heating rate difference between the atmospheric and oceanic reservoir, the upwelling efficiency tends to become enhanced under global warming. When the reservoir temperature difference (and therefore upwelling cooling efficiency) surpasses a certain threshold, the equatorial thermocline cannot recharge the heat enough to collapse the climatological mean state, so that the nonlinear heating effect no longer works to yield EENs (Figs. 3.2 through 3.6).

When the system approaches the threshold, the idealized model and GFDL-ESM2M predict that EENs become less frequent (Figs. 3.4 and 3.5). Though we do not have enough
observational evidence to verify this behavior, it is at least consistent with the available observational evidence that relatively large El Niño events were observed in 1972/73, 1982/83, 1997/98, and 2015/16, and thus the interval between events has increased from 10, to 15, to 18 years. Based on this idea, one might speculate that the next large El Niño event may perhaps occur around 2035/36, although other chaotic variability and forcings may work to the contrary. If global warming continues, the theory further predicts that ENSO becomes more linear and that EENs might not be observed at the end of this century.

3.6.2 A reasonable La Niña-like warming scenario can be envisioned using the Nonlinear ENSO Warming Suppression (NEWS) mechanism as a forced response to global warming.

The forced weakening of ENSO amplitude has a rectifying cooling effect on the mean-state cold tongue SST (Fig. 3.7). Due to the nonlinear heating effect, the number of large El Niño events decreases while the number of La Niña events remains nearly constant. Therefore, the mean climate becomes La Niña-like. This nonlinear rectification effect by itself is essentially the same but opposite to the effect that Jin et al. [2003] showed for the strengthening ENSO amplitude and the warming cold tongue SST. The novelty of the NEWS mechanism is that the weakening ENSO can be explained as a forced response to global warming (Conclusion a), which then yields the La Niña-like mean state by the nonlinear rectification effect.

3.6.3 NEWS is different from the Ocean Dynamical Thermostat

Some earlier studies at the end of the past century showed that the forced response should be La Niña-like, because the climatological upwelling cooling effect will compensate the radiative warming in the east but not in the west [Cane et al., 1997]. This mechanism is called the Ocean Dynamical Thermostat [Clement et al., 1996]. The mechanism is, however, now thought to be less likely to explain a centennial trend, because the upwelling water in the cold tongue becomes warmer and reaches equilibrium after only a couple of decades,
when the warmed extratropical surface water arrives in the equatorial thermocline through the upper oceanic subtropical cell.

The NEWS mechanism is essentially different from the Ocean Dynamical Thermostat. The NEWS mechanism involves nonlinear ENSO dynamics, whereas the Ocean Dynamical Thermostat does not invoke ENSO at all. One important difference between them is the time scale of the La Niña-like warming. Because the NEWS mechanism takes time for multiple EENs to dissipate, it requires almost a full century to produce the mature La Niña-like trend (see also Fig. 2 in the previous chapter). The time scale of the Ocean Dynamical Thermostat, however, is less than a couple of decades at the slowest.

3.6.4 The well-known El Niño-like mean-state warming is only a “majority decision” based on currently available GCMs, most of which exhibit unrealistic nonlinearity of the ENSO dynamics. A particularly important metric that needs urgent improvement in GCMs is the ENSO nonlinearity.

The majority of the CMIP5 models exhibit an El Niño-like mean-state warming. Therefore, widely believed by the ENSO research community is that the warming response is more likely to be El Niño-like, and that the La Niña-like trend during the satellite era is a manifestation of pure natural variability. We have shown here, however, this could be only a “majority decision” by the GCMs with unrealistic ENSO nonlinearity (Fig. 3.8). To the best of our knowledge, only one state-of-the-art GCM, GFDL-ESM2M, simulates the La Niña-like warming by the NEWS mechanism. Nevertheless, based on the realistic ENSO nonlinearity of this model and the remarkable structural resemblance of the Walker circulation change to that of observations (Fig. 2.2 in the previous chapter), we believe this could be an equally realistic (or even more plausible) response to warming. Further investigation is needed using some of the new GCMs in upcoming CMIP phases, which we hope will better reproduce the observed ENSO nonlinearity. In the previous chapter, we have pointed out that the La Niña-like warming might be related to the upper ocean diffusivity and thermal stratification, the latter of which will be further discussed in the next chapter. Improving these upper
ocean properties might solve the problems of the unrealistic nonlinearity evident in most CMIP5 models. Some recent studies also support our notion that the ENSO nonlinearity is important for future projections of the mean-state SST patterns [Yeh and Kirtman, 2007; Karamperidou et al., 2016].

3.6.5 Even for a first-order problem, “Warmer minus Control” is not necessarily a good analogue of a gradual global warming.

Our results show that the La Niña-like warming happens only when the greenhouse forcing is increased gradually (Fig. 3.9). In the abrupt increase of CO$_2$, the warming response is more like a zonally uniform warming, due to the influence of a slow El Niño-like response in addition to the transient NEWS mechanism (Fig. 3.11). Therefore, we should emphasize that “Warmer minus Control”, which is often used in global warming research, is not necessarily a good analogue of a gradual global warming even for a first-order feature of GCMs, since the transient response could be different from the equilibrium response and depend on the rate of warming.

3.6.6 At least in GFDL-ESM2M, the ENSO amplitude variation appears to be a cause, rather than an effect, of the mean-state SST variation. Our argument, however, remains too speculative to determine the causality with certainty.

Interestingly, even if the mean climate experiences a zonally uniform warming (Conclusion e), the nonlinear ENSO amplitude has no dependence on the mean-state SST change in a warmer climate (Figs. 3.2 and 3.5). Therefore, it could be possible to hypothesize that the ENSO amplitude variation in GFDL-ESM2M may be a cause, rather than an effect, of the mean-state SST variation.

We must admit, however, that our argument about the causality in GFDL-ESM2M remains uncertain (For alternative mechanisms, see also the previous chapter). Therefore, at this stage, what we would like to show in this particular study is as follows. We propose the NEWS mechanism, which can be simulated by an idealized model. We have detected
some evidence to support the notion that GFDL-ESM2M (and maybe the real world) is influenced by NEWS. The importance of NEWS compared to other processes remains difficult to quantify, but NEWS is as plausible as some other processes, such as the Ocean Dynamical Thermostat. Because the direction of causality is important for the NEWS mechanism to dominate the global warming response, further rigorous verifications are needed.

3.6.7 EENs might better be treated as a completely different phenomenon than the linear ENSO mode.

Some earlier studies regarded ENSO as a linear mode and predicted an increase of ENSO variance under global warming. If nonlinear ENSO dynamics are taken into account, however, one reaches the conclusion that ENSO variance should decrease. Because EENs have huge amplitudes compared to the linear ENSO mode, we expect the teleconnections to the extratropical regions should also be substantially different. For example, the area with SST warmer than 28°C (the threshold at which deep convection can occur in the current climate) is much larger in EENs. This large area cannot be described as a linear perturbation from the climatological mean, as suggested in Fig. 3.3. Many other features that have been believed to be typical for ENSO could be made radically different by the nonlinearity of EENs. Further investigation is needed to shed light on the abnormality of EENs compared to the known linear ENSO mode.

3.6.8 Understanding EENs may aid the understanding of Pacific multi-decadal natural variability and change. NEWS-NECS cycle serves as one of many possibilities.

We have also introduced the opposite mechanism to NEWS, the Nonlinear ENSO Cooling Suppression (NECS), by which “global cooling” suppresses the upwelling efficiency, excites EENs, and yields an El Niño-like cooling. Because a La Niña-like (El Niño-like) mean state eventually cools (warms) the Earth, the effect of NEWS can excite NECS, and vice versa. Though whether this NEWS-NECS cycle operates in the real world remains speculative, our idealized model and GFDL-ESM2M suggest that this NEWS-NECS cycle may partly
contribute to the multi-decadal natural SST variability in the Pacific (Fig. 3.12), including the Interdecadal Pacific Oscillation (IPO), whose phase change is thought to be causally related to an occurrence of a large El Niño [e.g., Meehl et al., 2016] as the piControl run of GFDL-ESM2M suggests.

Some previous studies suggest that global warming hiatuses and slowdowns may be related to the multi-decadal variability of Pacific SSTs [e.g., Kosaka and Xie, 2013, 2016]. If the IPO can be partially explained by the NEWS-NECS cycle, then both atmospheric and oceanic roles must be important to understand the hiatuses in relation to nonlinear ENSO dynamics (Fig. 3.13). If the nonlinearity plays a role in producing the Pacific multi-decadal variability, global warming hiatuses should not be understood as a unidirectionally forced response of the atmosphere to the “prescribed” SST variations, but rather, as two-way ocean-atmosphere interaction between the global mean atmospheric reservoir and the Pacific cold tongue. To realistically simulate global warming hiatuses, state-of-the-art GCMs may require further improvements to their ENSO nonlinearity.
Chapter 4

TWO MODELS WITH REALISTIC ENSO NONLINEARITY

The content of this chapter has been submitted to Geophysical Research Letters.

4.1 Introduction

Despite the El Niño-like warming response projected by the majority of the CMIP5 models [e.g., Ying et al., 2016; Zheng et al., 2016], we have shown in the previous chapters that, given the realistic ENSO nonlinearity, a La Niña-like response also remains physically consistent. In GFDL-ESM2M, the ENSO nonlinearity is minimized under global warming, and the extreme El Niños dissipate, but La Niñas remain almost unchanged. This asymmetric weakening response can rectify the mean-state SST to become La Niña-like, and we have referred to this mechanism as NEWS. In the previous chapter, we have concluded that a necessary condition to simulate NEWS is realistic ENSO skewness, and the lack thereof is why most CMIP5 models exhibit El Niño-like responses. Realistic ENSO skewness, however, is not a sufficient condition to simulate NEWS. Figures 4.1a and 4.1c show that, though both GFDL-ESM2M and MIROC5 exhibit realistic ENSO skewness, MIROC5 exhibits a strong El Niño-like response unlike GFDL-ESM2M. This difference motivates us to understand why the ENSO nonlinearity is not the only requirement for a La Niña-like response.

State-of-the-art GCM have had difficulty reproducing the features of the observed ENSO, including its amplitude, irregular frequency, non-Gaussianity, and their impacts on the extratropics [e.g., Collins et al., 2010; Bellenger et al., 2014; Zhang and Sun, 2014]. Despite the difficulty of simulating ENSO, it has been common to choose a subset of GCMs that reproduce a particular observed feature well, and to assume that this subset makes more reliable future projections than the multi-model mean [e.g., Risbey et al., 2014]. Based on
Figure 4.1: (a): Relationship between the Niño3 SST skewness and the zonal SST gradient change defined as the linear trend of “Niño3 minus Niño4” SST. The black and red dots represent models and the blue dot represents observations. Reproduced from the previous chapter. (b): Monthly Niño3 SST anomalies. Standard deviations are shown at the bottom right. (c): SST warming trends calculated at each grid relative to the tropical Pacific mean trend (30°S-30°N, 90°E-60°W). Blue colors denote a warming slower than the tropical Pacific mean, not necessarily a cooling.
this assumption, in this chapter, we project the future ENSO amplitude responses using GFDL-ESM2M and MIROC5 that realistically reproduce the observed ENSO nonlinearity, because of which warm anomalies tend to be larger than cold anomalies (El Niños tend to be stronger than La Niñas). Figure 4.1a shows the relationship between the ENSO skewness (a measure of the ENSO nonlinearity) and the zonal SST gradient change simulated by GCMs under global warming. This figure shows that GFDL-ESM2M and MIROC5 are the two models that reproduce the observed ENSO skewness better than most of the other models that participated in the CMIP5 [Taylor et al., 2012]. We analyze these two GCMs.

Figure 4.1b shows the time series of SST anomalies averaged over the Niño3 region (5°S-5°N, 150°W-90°W), a common index of ENSO. The left column shows the Niño3 SST for the historical climate of the two GCMs. Though GFDL-ESM2M exhibits an excessively large ENSO variance, both models quantitatively exhibit realistic ENSO nonlinearity as suggested in Fig. 4.1a. The right column shows the same time series but for a warmer climate. Interestingly, compared to the historical climate, the ENSO amplitude of GFDL-ESM2M is reduced by about 40% in its standard deviation, whereas that of MIROC5 remains almost constant in a warmed climate. Our motivations are to understand this difference in the amplitude responses and to make a physically reasonable projection of the future ENSO change.

This chapter is organized as follows. Data and methods are described in the next section. In section 4.3, we show that the response of subsurface temperature to the thermocline depth anomalies is the source of the ENSO nonlinearity in these models. Then, we propose a nonlinear mechanism for how the climatological upper ocean thermal stratification determines the ENSO amplitude response to warming. We also compare the observed thermal stratification with the modeled ones. Conclusions are presented in section 4.4.
4.2 Data and Methods

4.2.1 Data

The monthly surface temperature, oceanic potential temperature, and wind stress output of GFDL-ESM2M [Dunne et al., 2012, 2013] are from the GFDL Data Portal (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp), and those of MIROC5 [Watanabe et al., 2010] are from the Program for Climate Model Diagnosis and Intercomparison (https://pcmdi.llnl.gov/projects/cmip5/). We analyze the first ensemble member of the historical (Years 1966-2005) and abrupt4xCO₂ runs (Years 101-150 after the abrupt change are used). In the Abrupt4xCO₂ runs, Year 101 starts when 100 years have passed after the abrupt quadrupling of carbon dioxide, and the qualitative argument regarding the ENSO amplitude is not sensitive to this choice of the 50-yr time span (see also the previous chapter). At each depth, the oceanic variables are regridded using linear interpolation onto a 2.5° longitude by 2° latitude grid. To produce Fig. 4.1, the first ensemble member of the representative concentration pathway (RCP) 8.5 (Year 2006-2100) runs are used. Detailed descriptions of the CMIP5 project are presented by Taylor et al. [2012].

The reanalysis monthly oceanic potential temperature is from the National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS) [Behringer and Xue, 2004] at http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html. The horizontal resolution is 1° longitude by 1/3° latitude, and the vertical resolution is 10 m for uppermost 230 m and becomes coarser toward the deeper levels. The zonal wind field at the 10 m level and the SST are from the European Center for Medium range Weather Forecasting (ECMWF) ERA-Interim reanalysis data [Dee et al., 2011] at http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc/. The resolution is 1° in both longitude and latitude. The time span used in this study is from 1980 through 2016 for all the reanalysis data.
4.2.2 Methods

Decomposing the sources of the ENSO nonlinearity

Following An and Kim [2017], we decompose the source of the ENSO nonlinearity into three components: (i) “SST modulates winds”, (ii) “winds excite oceanic waves”, and (iii) “oceanic waves that have propagated to the east modulate subsurface temperature”. To measure the relative impact of these 3 sources of nonlinearity, we draw scatter plots between two area-averaged anomalies in the manner of: (i) SST (170°W-120°W, 5°S-5°N) and zonal wind stress (120°E-80°W, 5°S-5°N); (ii) zonal wind stress (120°E-80°W, 5°S-5°N) and thermocline depth (120°E-80°W, 5°S-5°N); (iii) eastern thermocline depth (170°W-120°W, 5°S-5°N) and subsurface temperature at a depth of 45 m (170°W-120°W, 5°S-5°N). These anomalies are deviations from monthly climatology calculated as the average over the full time span for each calendar month. The thermocline depth is defined as the level of maximum vertical temperature gradient. For observations, 10 m wind is used as a proxy of wind stress.

To draw each scatter plot, we first calculate the lead-lag relationship between the two variables and choose the lags with maximum correlations. The chosen lags are within a half-year difference from the results shown in An and Kim [2017], which are (i) zero-lag, (ii) wind stress leads the thermocline depth by 12-months, and (iii) the thermocline depth leads subsurface temperature by 3 months. For further physical explanation, readers are referred to An and Kim [2017].

The best-fit lines are drawn based on the standardized data. Linear regression and principle component analysis yield almost identical linear fits. In Fig. 4.2, following An and Kim [2017], the asymmetry index is defined as

\[
\text{Asym} = \frac{S_p - S_n}{S_p + S_n}
\]

(4.1)

where \(S_p\) (\(S_n\)) is the slope of the red (blue) best-fit lines calculated using the data only with the positive (negative) values in the horizontal axis. In Fig. 4.3, after drawing the best-fit lines, the original standard deviations are multiplied back so that the data have physical
units.

**Idealized model**

We use a modified version of the nonlinear recharge oscillator ENSO model introduced by Jin [1998] and Timmermann et al. [2003]. This model is a simplified, two-box approximation of the Cane-Zebiak model [Zebiak and Cane, 1987]. Detailed descriptions of the model and our modifications are given in the previous chapter.

4.3 **Results**

4.3.1 **Source of the ENSO nonlinearity**

Figure 4.2a shows the observed three potential sources of ENSO nonlinearity. Among the three, the asymmetry index is largest for (iii), so the observational ENSO nonlinearity mainly originates from the subsurface temperature response to oceanic waves. This result may appear inconsistent with An and Kim [2017] who showed that (ii) is the source of the nonlinearity. This inconsistency, however, may originate from their method to calculate the thermocline depth. An and Kim [2017] used the 17°C isotherm as the proxy of the thermocline, and we have confirmed that a similar conclusion to their study is derived by doing so. Nevertheless, by definition, the depth of the maximum vertical temperature gradient is a more appropriate measure of the thermocline depth. Though the proxy of the 17°C isotherm works well when linearity is assumed, it is not ideal to use it for investigating nonlinearity, because the difference between the location of the 17°C isotherm and the maximum temperature gradient may yield spurious nonlinearity or cancel true nonlinear signals.

Figure 4.2b shows the same scatter plots but for the historical runs of GFDL-ESM2M and MIROC5. These two GCMs reproduce the observed relationships of (i)-(iii) well, suggesting that the source of the nonlinearity in the model is (iii). The responses to increasing CO2 are different between the two GCMs, however. Figure 4.2c shows the same plots but for the warmer climate, where the (iii) component becomes virtually linear in GFDL-ESM2M but
Figure 4.2: (a): Three potential sources of the ENSO nonlinearity presented as the observed, lagged relationships between monthly area averaged standardized anomalies described in the axis labels. Lags are chosen to realize the maximum correlations as described in section 2.2. The values of the asymmetry index are shown at the top. The red (blue) best-fit lines are calculated using the data only with the positive (negative) values in the horizontal axis.

(b): As in (a), but for models for the historical climate.

(c): As in (b), but for the warmer climate.
not in MIROC5. The asymmetry index of (iii) in GFDL-ESM2M changes from 0.97 to 0.22 with warming, whereas in MIROC5 only from 0.90 to 0.81. Though the mechanism for the ENSO nonlinearity for the historical climate is similar between the two models, the warming response of nonlinearity is different.

4.3.2 Mechanism for the different ENSO warming responses

In the previous chapter, we have concluded that the climatological temperature difference between the atmosphere near the surface and the ocean below the thermocline serves as a determinant of the nonlinear response to warming. Therefore, we first compare the climatological upper ocean temperature between the two models.

Figure 4.3a shows the equatorial climatological temperature difference between the two models. For the historical climate, temperature below the thermocline is cooler in GFDL-ESM2M than in MIROC5, whereas temperature above the thermocline is warmer (Fig. 4.3a, top). That is, the equatorial ocean interior is more thermally stratified and stable in GFDL-ESM2M than in MIROC5. This difference in the stability becomes more evident in the warmer experiment (Fig. 4.3a, bottom). This intensification of the stability difference under global warming may be due to a positive feedback as follows. If the ocean is more stable, the warmer water in the upper ocean is less likely to be vertically mixed with the colder water in the deeper ocean. The suppressed vertical heat exchange further stabilizes the system.

If the ocean becomes more stable, the equatorial thermocline becomes less sensitive to winds due to the following mechanism. Figure 4.3c shows a schematic of the equatorial thermocline presented as a 1.5-layer model. Hydrostatic balance and no motion in the lower layer are assumed, because in principle, no energy enters the lower layer at sufficiently high frequencies. Hence, the pressure gradient at a reference level in the lower layer is zero:

$$\rho_1 h_1 + \rho_2 h_2 = \rho_1 h_3 + \rho_2 h_4$$

or

$$\rho_1 \frac{h_1 - h_3}{L} = \rho_2 \frac{h_4 - h_2}{L}$$

(4.3)
Figure 4.3: (a): Difference in climatological oceanic potential temperature averaged over 5°S-5°N between the two models. (b): As in the middle column of Figs. 4.2b and 4.2c, but with physical units. The best-fit lines are calculated using the entire data, and the slopes are shown at the top. (c): Schematic showing the relationship between the slope of the ocean surface and thermocline for the historical climate. (d): As in (c), but for the transiently warming climate. (e): As in the right column of Figs. 4.2b and 4.2c, but with physical units. The historical and warmer experiments are shown in the same plot.
where $L$ denotes the width of the basin in the longitudinal direction, $\rho_1$ ($\rho_2$) denotes the upper (lower) layer density, and $h_i$ denotes the layer depth. For $h_i$, the index $i$ denotes the upper (lower) layer by $i = 1, 3$ ($i = 2, 4$), and the western (eastern) edge of the basin by $i = 1, 2$ ($i = 3, 4$) as described in Fig. 4.3c. Using the definition of the slopes, $-\alpha \equiv [(h_3 + h_4) - (h_1 + h_2)]/L$ and $\beta \equiv (h_4 - h_2)/L$ where $\alpha > 0$, $\beta > 0$, we get

$$\rho_1(\alpha + \beta) = \rho_2\beta$$

(4.4)

or

$$\beta = \frac{\alpha}{\rho_2/\rho_1 - 1}$$

(4.5)

Differentiating both sides, and assuming that the easterly wind stress anomalies $(-d\tau)$ is proportional to the sea level tilt anomalies ($d\alpha \propto -d\tau$) [Li and Clarke, 1994], we get

$$d\beta \propto -\frac{d\tau}{\rho_2/\rho_1 - 1}$$

(4.6)

This equation 4.6 means that the sensitivity of the thermocline tilt anomalies to wind stress, or $1/(\rho_2/\rho_1 - 1)$, depends upon the ratio of the densities between the two layers. Therefore, if the ocean becomes more stable as the climate warms, the denominator $\rho_2/\rho_1 - 1$ becomes larger and the equatorial thermocline depth becomes less sensitive to winds, as schematically shown in Fig. 4.4d. Using the reduced gravity $g' = g(\rho_2/\rho_1 - 1)$, the equation (4.6) could be also written as

$$d\beta \propto -\frac{d\tau}{g'}$$

(4.7)

where the constant $g$ is omitted. Equations 4.6 and 4.7 both indicate that the thermocline slope is less sensitive to wind stress for a more stable ocean.

Based on this mechanism, the sensitivity of thermocline to winds shown in Fig. 4.3b is consistent with the thermal stratification shown in Fig. 4.3a. For the historical climate, GFDL-ESM2M has a more stable ocean and exhibits a smaller sensitivity of the thermocline to winds than MIROC5 by about 30%. We could call the thermocline in GFDL-ESM2M "stiffer" than in MIROC5. For the warmer climate, the difference in thermocline sensitivity
between the two models becomes larger, because the upper ocean in GFDL-ESM2M warms faster and the stability is increased more.

Because the thermocline varies less in GFDL-ESM2M, equatorial waves with large amplitudes are hard to excite, and the resultant modulations of the eastern thermocline are also minimized. Figure 4.3e robustly shows that, in the warmer experiment in GFDL-ESM2M, the subsurface temperature does not “swing” enough to support a large ENSO amplitude due to the muted perturbations by waves. This small amplitude appears to be why the ENSO in GFDL-ESM2M becomes almost linear for the warmer climate. In MIROC5, however, the variations of the eastern thermocline are kept large enough to sustain the nonlinear response of subsurface temperature. Due to the weak historical thermal stratification, the thermal stratification in MIROC5 does not become stronger as rapidly as in GFDL-ESM2M. Due to the small stability, the thermocline responds strongly to winds. This more “reactive” thermocline allows larger anomalies to enter the eastern thermocline, which supports strong, nonlinear subsurface temperature variations.

4.3.3 Idealized model experiments

To verify the mechanism by numerical simulations, we have performed two idealized model experiments with different stability. In the “More Stable” experiment (Fig. 4.4a, top), the temperature difference between the atmosphere near the surface and the ocean below the thermocline \( T_a - T_o \) is initially set to be 13.5 °C, and the \( T_a - T_o \) is increased with the rate of 0.7 °C / century, expressing that the atmosphere warms faster than the ocean due to the different heat capacity. In the “Less Stable” experiment (Fig. 4.4a, bottom), \( T_a - T_o \) is initially set to be 12.5 °C, and the \( T_a - T_o \) is increased with the rate of 0.4 °C / century. The \( T_a - T_o \) is increased more rapidly in the “More Stable” experiment to incorporate the effect of the suppressed vertical heat exchange.

Figure 4.4a shows the SST time series in the two experiments. In the “More Stable” experiment, which is designed to imitate GFDL-ESM2M, strong El Niños are terminated at the threshold of \( T_a - T_o \sim 14.2^\circ C \). This termination is because the “stiff” thermocline
Figure 4.4: (a): Idealized model experiments that simulate the western (red) and eastern (blue) SST variability. The climatological reservoir temperature difference between the atmosphere near the surface and the ocean below the thermocline (\(T_a - T_o\)) is gradually increased with the rate shown at the top left. (b): As in Fig. 4.3a, but the difference between observations and models in the late historical period (1980-2005).
cannot recharge the heat in the equatorial upper ocean to yield a strong El Niño (see also the previous chapter). By contrast, in the “Less Stable” experiment, which is designed to imitate MIROC5, strong El Niños are not terminated because $T_a - T_o$ does not reach the threshold of $\sim 14.2^\circ C$ even after the two-century run. Rather, because of the warming western Pacific, which serves as the upper bound of the ENSO intensity [An and Jin, 2004], the ENSO amplitude strengthens by about 10% during the two centuries. This difference in the existence of the nonlinearity termination between the two experiments is consistent with the mechanism explained in the previous subsection.

4.3.4 Comparison with observations

We also compare the two models with the observations to project the future ENSO change. Figure 4.4b shows the same temperature plot as in Fig. 4.3a but for observations relative to the two models. The observed equatorial upper ocean is more stable than the GFDL-ESM2M, which is more stable than MIROC5. This observed strong stability is more favorable for $T_a - T_o$ to reach the threshold that terminates strong El Niño events than in the two models. Though this conclusion is derived only from the two GCMs and idealized model experiments, it makes physical sense to project that, based on the observations and the available models with realistic nonlinearity, ENSO may weaken nonlinearly sooner than the model-based projections.

4.4 Conclusions

4.4.1 The ENSO nonlinearity matters to the ENSO and mean-state responses to global warming

Under global warming, the ENSO amplitude in GFDL-ESM2M weakens, but that in MIROC5 remains almost constant (Fig. 4.1b). Decomposing the potential source of the ENSO nonlinearity into three components, we have demonstrated that the difference in the ENSO amplitude responses between the two models is associated with the nonlinear subsurface
temperature response to oceanic waves, rather than the wind response to SST or the oceanic wave response to winds (Figs. 4.2 and 4.3e).

Many GCMs show strengthening of ENSO in response to warming [Collins et al., 2010], but they do not reproduce the ENSO nonlinearity as realistically as GFDL-ESM2M and MIROC5 (Fig. 4.1a). Our preliminary analysis suggests that many CMIP5 models do not reproduce the nonlinear subsurface temperature response to waves. Without the possibility of the nonlinear regime shift, one might project that the ENSO amplitude will strengthen. We should, however, pay more attention to the GCMs that reproduce the realistic ENSO nonlinearity, because ENSO in the real world is nonlinear.

Based on the NEWS mechanism, the nonlinear ENSO response to global warming can rectify the mean-state SST. Therefore, the difference of the nonlinear ENSO response between GFDL-ESM2M and MIROC5 could have an important implication for whether the response will be El Niño-like or La Niña-like (Fig. 4.1). Considering the scientific and societal impacts, the ENSO nonlinearity is a key characteristic and should not be considered to be a minor, higher-order correction of the linear ENSO.

4.4.2 An urgent task is to improve the reproducibility of the thermal stratification in GCMs because it determines the nonlinear ENSO response

With strong climatological thermal stratification in the upper ocean, ENSO may weaken nonlinearly in response to warming. This conclusion is particularly important, considering that the observed thermal stratification is stronger than the two models analyzed in this chapter (Fig. 4.4b). The mechanism is explained as follows. If the thermal stratification becomes stronger, weaker thermocline variations can keep the ocean in hydrostatic balance (Figs. 4.3c, d and Equation 4.6). The resultant “stiffer” thermocline depth is less sensitive to winds (Fig. 4.3b), which minimizes the nonlinear response of the eastern subsurface temperature. Importantly, despite the small difference in thermocline sensitivity, the nonlinearity produces a huge difference in the amplitude of the subsurface temperature (Fig. 4.3e).

The idealized model confirms that the climatological temperature difference between the
atmosphere near the surface and the ocean below the thermocline \((T_a - T_o)\) is an important parameter (Fig. 4.4a). Here, \(T_a - T_o\) could be regarded as the first order approximation of the climatological thermal stratification. Once \(T_a - T_o\) reaches a certain threshold value, strong El Niños become terminated (see also the previous chapter). This sudden loss of strong El Niños is consistent with the two GCMs. In GFDL-ESM2M, because the thermal stratification is strong, ENSO becomes almost linear. By contrast, ENSO keeps its amplitude in MIROC5, because the weak thermal stratification is unfavorable to reach the threshold for the ENSO to weaken. It might be interesting to warm MIROC5 more and check whether the ENSO in MIROC5 can be weakened.
Chapter 5

CONCLUSION

The tropical Pacific Ocean is one of the main contributors to variability in the Earth’s climate system, but whether the mean-state sea surface temperature (SST) response of this region to global warming should be “El Niño-like” (SST warms faster in the east) or “La Niña-like” (SST warms faster in the west) is uncertain from the perspective of observations [Rayner et al., 2003; Smith et al., 2008; Christensen et al., 2013], models [Knutson and Manabe, 1995; Cane et al., 1997; Vecchi and Soden, 2007; Kim et al., 2014], and theory [Clement et al., 1996; Collins et al., 2005, 2010; Xie et al., 2010; Held et al., 2010; An et al., 2012]. In global warming projections, however, it is extremely important to understand possible processes that determine the mean-state changes in this region and to narrow their major uncertainties, because the tropical Pacific mean-state variability and its changes are expected to have substantial scientific and societal impacts on not only the tropics and sub-tropics (e.g., droughts, floods, heat waves, poor harvests, changing marine ecosystems) but also the mid-latitudes and high-latitudes (e.g., cold spells, changing tropical cyclone genesis frequency, modulating Antarctic sea ice trends) [Yokoi and Takayabu, 2009; Murakami et al., 2012; Christensen et al., 2013; Kohyama and Hartmann, 2016].

In this regard, this dissertation have shown that GFDL-ESM2M is an interesting exception in that it produces a physically-consistent La Niña-like mean-state warming with a clear strengthening of the Walker circulation. This result may appear to be provocative to the research community, because the recent La Niña-like trend has widely been believed to be the result of purely natural variability [e.g., Christensen et al., 2013]. This belief, however, depends to a large extent on the evidence that the majority of the CMIP5 models exhibit El Niño-like warming patterns. In this sense, the previous studies may have resorted to
a “majority decision” among imperfect models. Of course, it is a hard task to determine whether this outlier, GFDL-ESM2M, captures the real world better than other models, so it may be early to determine this with certainty. It is, however, not too early to discuss the potential mechanisms further, such as NEWS, since the tropical Pacific response to warming is one of the key uncertainties in climate projections that will have a substantial practical impact in the near term.

We have identified that at least two conditions are required to realize NEWS: ENSO nonlinearity and strong thermal stratification. The NEWS mechanism is summarized as follows. In response to greenhouse gas forcing, strong thermal stratification rapidly increases the stability of the upper ocean. The increased stability causes the thermocline depth to be less sensitive to wind stress perturbations. The “stiffer” thermocline inhibits the subsurface temperature variations, which weakens the ENSO amplitude. During this ENSO weakening process, extreme El Niños dissipate, but La Niñas are not influenced as much, due to the ENSO nonlinearity. This asymmetric weakening response can rectify the mean-state SST to become La Niña-like.

GFDL-ESM2M and MIROC5 suggests that, if thermal stratification is large for the historical climate, it will increase rapidly under a warming climate. This intensification of thermal stratification makes physical sense, because the suppressed vertical mixing will inhibit the vertical heat exchange. The observed thermal stratification is larger than the modeled ones for the historical climate. Therefore, based on our discussion in this dissertation, the observed strong thermal stratification may terminate extreme El Niños sooner than the model based projections. GFDL-ESM2M exhibits the termination of extreme El Niños in Year 2070 for the RCP8.5 scenario, so the observed strong thermal stratification leads us to speculate that the regime shift might happen in a couple of decades. Hence, we conclude that the forced La Niña-like response to global warming could be detected during this century.


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VITA

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