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Reinterpreting the thermocline feedback in the western-central equatorial Pacific and its relationship with the ENSO modulation

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Abstract Vertical stratification changes at low frequency over the last decades are the largest in the western-central Pacific and have the potential to modify the balance between ENSO feedback processes. Here we show evidence of an increase in thermocline feedback in the western-central equatorial Pacific over the last 50 years, and in particular after the climate shift of 1976. It is demonstrated that the thermocline feedback becomes more effective due to the increased stratification in the vicinity of the mean thermocline. This leads to an increase in vertical advection variability twice as large as the increase resulting from the stronger ENSO amplitude (positive asymmetry) in the eastern Pacific that connects to the thermocline in the western-central Pacific through the basin-scale 'tilt' mode. Although the zonal advective feedback is dominant over the western-central equatorial Pacific, the more effective thermocline feedback allows for counteracting its warming (cooling) effect during warm (cold) events, leading to the reduced covariability between SST and thermocline depth anomalies in the NINO4 (160°E–150°W; 5°S–5°N) region after the 1976 climate shift. This counter-intuitive relationship between thermocline feedback strength as derived from the linear relationship between SST and thermocline fluctuations and stratification changes is also investigated in a long-term general circulation coupled model simulation. It is suggested that an increase in ENSO amplitude may lead to the decoupling between eastern and central equatorial Pacific sea surface temperature anomalies through its effect on stratification and thermocline feedback in the central-western Pacific.

Keywords ENSO modulation · Stratification · ENSO asymmetry · ENSO feedbacks · Climate variability

1 Introduction

The El Niño Southern Oscillation results from the interactions between the equatorial Pacific warm waters and the atmospheric general circulation in the Tropics (Wyrtki 1982; Rasmusson and Carpenter 1982). Its energy is provided to a large extent by the so-called warm pool, an extensive region of waters above 28 °C extending from the central Pacific to the eastern Indian Ocean. During El Niño, the warm pool can either undergo a warming of its surface temperature or expand eastward towards the Ecuadorian coasts, leading respectively to the so-called Modoki El Niño (Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009) (or Central Pacific El Niño—hereafter CP El Niño) or Cold Tongue El Niño (McPhaden et al. 1998) (also called Eastern Pacific El Niño—hereafter EP El Niño). The latter type of El Niño has served as a benchmark for building most of existing ENSO theories (Neelin et al. 1998) whereas the former has just recently drawn the attention of the community due to its increased occurrence in the recent decades (Yeh et al. 2009; Lee and McPhaden 2010; Takahashi et al. 2011). It has been argued that the change of the relative occurrence of these two types of El Niño, as evidenced in the recent decades, might be a signature of global warming with the CP El Niño becoming more frequent in a warmer climate (Yeh et al. 2009).

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However, the mechanisms that explain such possible tendency remain unclear.

Since the theoretical works of Hirst (1986) and Jin and Neelin (1993), it is now admitted that ENSO can be understood to a large extent as an air-sea coupled mode that is either stable or unstable depending on the balance between three main processes, the so-called thermocline and zonal advection feedbacks and radiative heating (modelled as a thermal damping term in such a conceptual framework). This view has been extremely fruitful for understanding some of the properties of ENSO, which includes its sensitivity to mean state (An and Wang 2000; An and Jin 2001; Fedorov and Philander 2001; Thual et al. 2011). In such an approach, the equatorial Pacific can be divided into two active regions, the NINO3 (150°W–90°W; 5°S–5°N) region where the thermocline feedback is effective due to the shallow thermocline depth and the NINO4 (160°E–150°W; 5°S–5°N) region where the zonal-advective feedback is dominant due to the strong mean SST zonal contrast at the eastern edge of the warm pool below the strong wind anomalies during ENSO (Picaut et al. 1997). The relative importance of these two feedbacks in these regions determines to a large extent the main characteristics of ENSO (frequency, amplitude and stability), with ENSO being stronger (weaker) with a larger (smaller) period when the thermocline feedback (zonal advective feedback) gets stronger. In particular, the change in ENSO characteristics associated to the 1976 climate shift has been interpreted in the frame of this theory (An and Wang 2000; An and Jin 2000; Moon et al. 2004).

The limitations of the theoretical framework provided by this approach are mostly twofold: (1) first the theory assumes a high degree of linearity of the ENSO feedback processes although the non-linear ENSO processes are fundamental to understand its amplitude modulation in particular (Timmermann et al. 2003; Jin et al. 2003; An 2009); (2) the difficulty to quantify the efficiency of the thermocline feedback in the western-central Pacific because of the deep thermocline. As a matter of fact, the efficiency of the thermocline feedback is commonly estimated from the regression between thermocline depth anomalies and temperature anomalies just below the mixed layer, assuming a direct relationship between heating and the vertical displacements of the isotherms within the well stratified waters (An and Jin 2000, 2001; Thual et al. 2011). It is then assumed that SST changes are provided by vertical advection by the mean upwelling of those temperature anomalies into the mixed layer, which is the so-called thermocline feedback. The estimation of the efficiency factor from a regression analysis between SST and thermocline fluctuations is quite valid in the eastern equatorial Pacific, where the thermocline is shallow and therefore temperature anomalies at the base of the mixed layer are mainly controlled by thermocline depth fluctuations. It is however, more difficult to estimate an efficiency factor in the central Pacific, because of the interplay of various physical processes (e.g. Zelle et al. (2004)).

In this study, our aim is to reinterpret the role of the thermocline feedback in the western-central Pacific considering that it has been disregarded in previous ENSO studies that have rather focused on its role in the eastern equatorial Pacific. Our background motivation is also related to the observations that our current knowledge on the processes responsible for the change in ENSO in a warmer climate is limited, which calls for rethinking the ENSO paradigm with respect to the issues of the ENSO modulation and the decadal variability (Collins et al. 2010). Recent studies indicate that global warming will increase the stratification particularly in the central-western Pacific (Dinezio et al. 2009; Yeh et al. 2009). This will alter the ENSO dynamics in a way that may be already at work, in particular by changing the balance between ENSO feedback processes associated to stratification changes. Before tackling with the climate change problem, a better understanding of the change in ENSO characteristics as observed in recent years and its relationship with change in mean state is required. For instance, the long-term decrease in correlation between the NINO3 and NINO4 indices over the last decades has been attributed to the increase occurrence of the CP El Niño events (Yeh et al. 2009), but the actual mechanisms responsible for such trend remain unclear. As an illustration we present the Fig. 1 which displays the sliding correlation between the two historical El Niño indices for the HadISST SST observations (Rayner et al. 2003) and the SODA Reanalysis (Giese and Ray 2011). Figure 1 first indicates that the agreement between observations and SODA is high only after 1950. Before that, the rms difference of the correlation between both products reaches 0.05, which somehow qualitatively provides a threshold from which increase or decrease in correlation can be considered noticeable. Second, a decrease of the correlation is observed after 1975. We argue that such decrease can be understood in terms of the change in feedback processes in the western-central Pacific associated to stratification increase.

The paper is organized as follows. The Sect. 2 presents the data and methods that are used. The Sect. 3 presents evidence of the increase in the thermocline feedback in the western-central Pacific after the 1970s and estimates its impact on the vertical advection. Section 4 is an analysis of a long-term general circulation coupled model that extends the analysis from SODA. Section 5 is a discussion followed by concluding remarks.

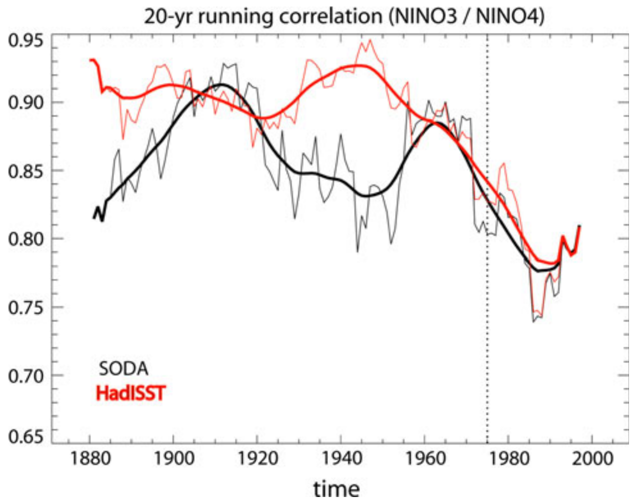

Fig. 1 20-year running correlation between NINO3 and NINO4 for SODA (*black*) and HadISST (*red*)

2 Data and method

We use the SODA Reanalysis recently released for the 1871–2008 period (Giese and Ray 2011) but will focus on the 1950–2008 period in this paper. SODA uses an OGCM based on the Parallel Ocean Program (POP—Smith et al. 1992) with 1/2° resolution and 40 vertical z levels with 10-m spacing near the surface, and 250 m at 5,374 m depth. Assimilated data include temperature and salinity profiles from the World Ocean Database 2001 (Boyer et al. 2002; Stephens et al. 2002; Locarnini et al. 2002), as well as additional hydrography, SST, and altimeter sea level. The model was forced by the 20CRv2 atmospheric dataset (Whitaker et al. 2004; Compo et al. 2006).

We also use an intermediate complexity ocean model as a diagnostic tool of the ENSO feedback processes in SODA. The model is presented in Dewitte (2000) and has been used for similar purpose in a number of studies (Dewitte et al. 2007, 2009; Yeh et al. 2010; Belmadani et al. 2010). The model consists in a three baroclinic mode ocean model coupled to a simple mixed-layer model that neglects mixing and parameterizes heat-flux as a thermal damping term. It is an anomaly model so that a preliminary tuning is carried out that consists in prescribing the mean climatologies (3D velocity and SST) as derived from SODA as well as the stratification parameters, namely the wind projection coefficients and the thermocline coefficients for each of the three gravest baroclinic modes (cf. Dewitte (2000)). The stratification parameters are derived from a vertical decomposition of SODA following Dewitte et al. (1999). In order to account for the low frequency change of the mean state, the low frequency component of the wave parameters and the SST are prescribed in the model. The model mixed layer uses a restoring to the SODA SST anomalies. The drag coefficient of the wind stress anomalies is increased by 20 % in order to have a comparable magnitude of the variability and skewness of the thermocline anomalies (see Sect. 3.3). The ICM within such configuration allows reproducing very well the SODA SST. The correlation over the period of interest reaches 0.94 (0.86) for the NINO3 (NINO4) SST index with a rms difference of 0.40 °C (0.33 °C).

The pre-industrial GFDL CM2.1 long-term simulation spanning 500 years is also used for a consistency check and to extend the analysis. The ocean component is ocean model version 3.1 (Gnanadesikan et al. 2006; Griffies et al. 2005), which is based on Modular Ocean Model version 4 (MOM4) code. The resolution is 50 vertical levels and a 1° × 1° horizontal grid telescoping to 1/3 meridional spacing near the equator. The vertical grid spacing is a constant 10 m over the top 220 m. The atmospheric component is the GFDL AM2p13 atmospheric model. The resolution is 24 vertical levels, and 2° latitude by 2.5° longitude grid spacing. The dynamic core is based on a finite volume (Lin 2004). Air-sea fluxes are computed based on 1-h intervals. For a detailed model description, refer to Delworth et al. (2006) and Wittenberg et al. (2006). The data are available in the CMIP3 archives (https://esg.llnl.gov:8443/home/publicHomePage.do).

Following Kug et al. (2010), for the GFDL run we use modified NINO3 and NINO4 SST indices. This is because the climatological cold tongue extends farther west than observational data would suggest, and because ENSO variability (simulated patterns of tropical Pacific SST, wind stress, and precipitation variability) is also shifted 20°–30° west of the observed pattern (Wittenberg et al. 2006). New indices are therefore defined: NINO3 SST is the averaged SST over 170°–110°W, 5°S–5°N, and NINO4 SST is the averaged SST over 140°E–170°W, 5°S–5°N. Note that the area thus defined is shifted about 20° longitude to the west compared to the conventionally defined area.

3 Long-term change in the thermocline feedback 'strength' in SODA

3.1 Regression analysis between SST and H

As a benchmark and for illustrating the quantities over which we will focus in this study, we present the Fig. 2 that displays the regression between thermocline and the temperature anomalies, at the equator and as a function of longitude and depth. It indicates that the co-variability between temperature anomalies and thermocline depth anomalies is large between around + and −50 m of the mean thermocline depth (blue line). In the eastern Pacific (NINO3 region), where the thermocline is shallow, regression values are strong at the base of the mixed layer (dashed line), which illustrates the thermocline feedback effectiveness. In the central Pacific (~180°E), however, the regression values are relatively weak and even negative. This anti-correlation can be explained by the fact that the zonal advective feedback in dominant in the western-to-central Pacific: During El Niño (La Niña) events, the thermocline tilts zonally and in the meantime the warm waters of the Warm Pool are advected eastward (westward). The tilting of the thermocline induces a warming (cooling) in the eastern Pacific during El Niño (La Niña) through the effective thermocline feedback. However, in the central Pacific, since the thermocline feedback is weak, the zonal advection of warm waters during El Niño (La Niña) induces a warming (cooling) that overcomes the cooling (warming) that would result from the shoaling (deepening) of the thermocline if the thermocline feedback was effective. This explains to a large extent the anticorrelation observed in Fig. 2 that emerges from the zonally varying thermocline feedback strength and the so-called 'tilt' mode (Clarke 2010). The latter is captured by the dominant EOF of temperature anomalies within the first 300 m. The zero contour of the first EOF mode (black full line) intersects the mean thermocline (blue full line) at ~150°W determining the thermocline pivot, but is shifted at the surface to the west in the region controlled by zonal advective processes (160°E). To summarize, the dominant zonal advective feedback in the central Pacific leads to the apparent anticorrelation between temperature anomalies at the base of the mixed layer and thermocline depth anomalies. As a result, a statistical estimation of the thermocline feedback efficiency is misleading in this region. It calls for a different estimation of the thermocline feedback which would have to be based on more dynamical considerations.

The location of the thermocline pivot (150°W) also corresponds to the longitude where the SST skewness

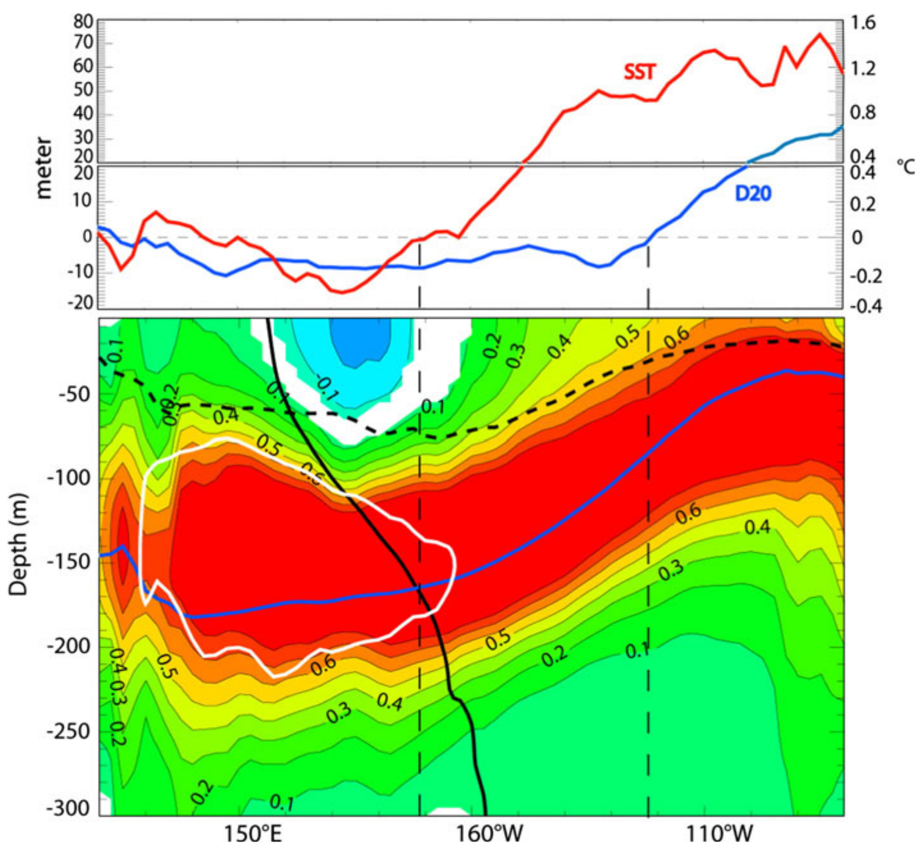

Fig. 2 (*Bottom*) Vertical section of the regression between temperature and thermocline depth anomalies over 1958–2008. The *black thick line* indicates the zero contour of the first EOF mode of temperature anomalies. The *blue thick line* indicates the mean thermocline depth and the *black thick dashed line* indicates the mixed layer depth. The intersection between the *black line* and the *blue line* therefore stands for the position of the thermocline pivot. The *non-colored area* indicates where the regression values is below the 95 % confidence level. The *white contour* indicates the −0.4 °C contour of the dominant EOF of the 7-year low-pass filtered temperature anomalies and indicates where stratification changes at decadal timescale are the largest. (*Top*) The skewness of thermocline depth anomalies (*blue line*—left scale) and temperature anomalies (*red line*—right scale). The *vertical dashed lines* indicate the position of the zero crossing for SST and themocline depth

changes from negative to positive. The skewness for the thermocline depth anomalies is negative over a wider longitude range until 120°W. The difference in zonal contrast of the asymmetry between SST and thermocline depth is also a fundamental characteristics of the thermocline feedback in the central Pacific as will be seen below.

We also plotted on Fig. 2 the region where stratification changes at decadal timescale are the most prominent, which is inferred from the pattern of the dominant EOF of the 7-year low-pass filtered temperature along the equator (contour in thick white line). It is located in the western Pacific in the vicinity of the thermocline (Dewitte et al. 2009), which is just west of the thermocline pivot. After the 1976 climate shift, this region corresponds to negative temperature anomalies of −0.6 °C, which indicates an increased stratification. Increased stratification tends to increase the effectiveness (i.e. the efficiency factor) of the thermocline feedback because the temperature anomalies in the water column associated to the vertical isotherm displacements are enhanced. This can be understood as follows: Assuming that the density changes (at constant depth) are governed by temperature changes (i.e. $\partial\rho \approx -\overline{\rho}\cdot\alpha_T\cdot\partial T$ where $\alpha_T = 2.97\times10^{-4}\mathrm{K}^{-1}$; Gill 1982), the vertical isopycnal displacements $\left(\partial h = \frac{\partial\rho}{\frac{\partial\overline{\rho}}{\partial z}}\right)$ can be related to temperature change using the Brunt Väisälä frequency: $\partial T \approx \frac{\overline{N^2}\partial h}{\alpha_T\cdot g}$. Therefore, increased stratification as it took place after the 1976 climate shift, combined to larger variability in thermocline depth associated to increased ENSO amplitude, may lead to larger temperature changes within the thermocline that in turn influence SST more easily.

Considering that stratification is increasing from before and after the 1976 climate shift, we may expect an increase in the 'strength' of the thermocline feedback, that is the inverse relationship between between SST and thermocline (hereafter H) anomalies over the NINO4 region should be enhanced after the 1970s. The Fig. 3 displays the 15-year running correlation between NINO4 SST and NINO4 H. It appears that the inverse relationship between SST and H is considerably reduced after the 1970s, with a correlation coefficient reaching almost zero. We argue that this counter-intuitive relationship between increased stratification and decreased correlation between SST and H anomalies is due to the inappropriate definition of the thermocline feedback in the western-central Pacific. In fact the strong anti-correlation prior to the 1970s is due to the fact that the thermocline feedback in the western-central Pacific is weak/ineffective, so that during El Niño (La Niña) SST anomalies are mostly driven by zonal advection while thermocline anomalies are negative (positive) due to the tilt mode. On the other hand, when stratification increases like after the 1970s, the mean vertical advection of anomalous temperature can contribute to SST changes (negative feedback) leading to a drastic reduction of the correlation. In order to check that such change in thermocline feedback does not results from change in ENSO itself, we also display on Fig. 3 the 15-year running partial correlation between SST and H considering the NINO3 SST index. With this method, the influence of ENSO (i.e. NINO3 index) on the central-western Pacific (i.e. NINO4 index) is removed to examine the relationship between SST and H over the NINO4 region. The result indicates that the change in thermocline feedback 'strength' is not due to the change in ENSO variability since the curve has a similar shape than the 15-year running correlation between SST and H except it is shifted by $\sim$0.3. This shift is due to the fact that prior to the 1970s, the tilt mode is weakened during non-ENSO periods, whereas after the 1970s, the partial correlation procedure removes the influence of the positive feedback of the zonal-advective feedback on the SST anomalies, producing SST anomalies of the same sign than the H anomalies in the central-western Pacific.

The following is devoted to a reformulation of the thermocline feedback that takes into account the change in stratification.

3.2 Heat budget analysis

In order to refine the estimate of the change in thermocline feedback taking into account the fundamental processes of ENSO, we consider the following simplified heat-budget equation for the mixed-layer:

$$\frac{\partial T'}{\partial t} = -u'\cdot\frac{\partial\overline{T}}{\partial x} - \overline{w}\cdot\frac{\partial T'}{\partial z} - \eta\cdot T' \quad (1)$$

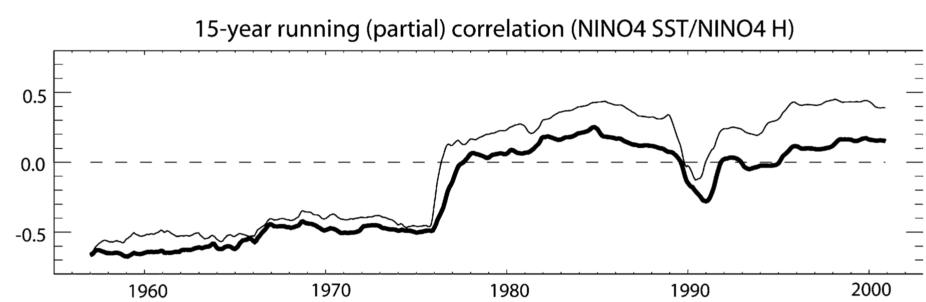

Fig. 3 15-year running correlation (*thick line*) and partial correlation (*thin line*) between SST and thermocline anomalies in the NINO4 region. The partial correlation uses the NINO3 SST index as the controlling variable

The assumption is that the rate of SST change is driven by the terms in the right-hand side of Eq. 1, respectively the zonal advective feedback, the thermocline feedback and the thermal damping (An and Jin 2001). Note that it is often assumed in the literature that the thermocline feedback can be inferred from the magnitude or variability of $-\overline{w} \cdot \frac{\partial T'}{\partial z}$. Thermocline feedback is in fact the "strength" with which the thermocline depth fluctuations influence the rate of SST changes so it is included in $-\overline{w} \cdot \frac{\partial T'}{\partial z}$. In simple to intermediate complexity models of ENSO, the latter is parameterized as a function (linear or hyperbolic functions) of thermocline depth anomalies (Hirst 1986; Zebiak and Cane 1987). Simply put, this consists in approximating $-\overline{w} \cdot \frac{\partial T'}{\partial z}$ by $\alpha \cdot h'$ where h' is the thermocline depth anomaly and α the thermocline feedback "strength". The latter models a complex combination of processes (mixing, diffusion and entrainment) in particular in the western-central Pacific where the thermocline is deep. Therefore, based on Eq. 1, α in the central-western equatorial Pacific can be derived from the regression analysis between h' and $\frac{\partial T'}{\partial t} + u' \cdot \frac{\partial \overline{T}}{\partial x} + \eta \cdot T'$ averaged over the NINO4 region. We choose a typical value $\eta \sim 100\ \text{days}^{-1}$ (Dewitte 2000). u' is estimated from the average of the first four upper-levels of the SODA outputs and we consider a climatologically varying $\frac{\partial \overline{T}}{\partial x}$ that is estimated from SODA over the period 1950–2008. The Fig. 4a displays the low frequency evolution of α obtained from 11-years running chunks over the period 1958–2000. It confirms that the thermocline feedback undergoes a drastic change in the 1970s. Note that a similar analysis performed over the NINO3 region leads to a very weak low frequency variability of α but with a stronger mean value ($\alpha \sim 2 \times 10^{-2}$ °C/month/m) (not shown). The negative value of α on average over the NINO4 region indicates the cooling (warming) effect of the thermocline feedback during El Niño (La Niña) consistent with the tilt mode. According to the results of Fig. 4a, this effect would be the strongest over the period 1955–1976 ($a \sim -0.8 \times 10^{-2}$ °C/month/m). However, we argue that the thermocline feedback is actually weak over this period and that such a large negative value for α reflects that h' and T' over the western-central Pacific vary in out-of-phase because of the tilt mode and because T' is dominantly controlled by the positive zonal advective feedback. On the other hand, the sharp change of α in the 1970s traduces that the thermocline feedback does contribute to SST anomalies. This is primarily due to the increased stratification that allows for a more effective influence of the thermocline depth fluctuations on the mixed-layer. The Fig. 4b illustrates the change in stratification over 1955–2003. We considered the temperature anomalies in the NINO4z region (150°E–150°W; 100–150 m) as defined in Dewitte et al. (2009), namely where the largest changes at low-frequency are observed. This index is compared to the wind projection of the wind stress for the second baroclinic mode that best mimics changes in stratification in this region (Dewitte et al. 2007, 2009). Changes in stratification are correlated to changes in α [correlation between NINO4z (P_2) and α is 0.67 (0.66)], which supports the former statements that increased stratification leads to a more effective thermocline feedback.

As a consistency check, we verified that similar changes in thermocline feedback are obtained in the linear model (Fig. 5). Note that this validates the estimate of zonal advection in the linear model. The largest difference between the SODA estimate and the LODCA estimate is for the period 1989–1992, which may be due to peculiarities of the 1991 El Niño that are not well simulated by LODCA.

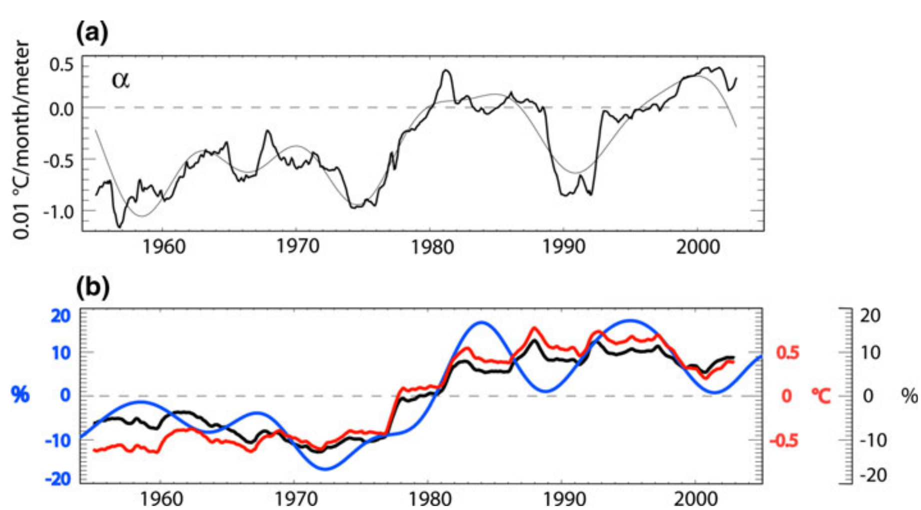

Fig. 4 **a** 11-year running regression coefficient between thermocline anomalies and $\frac{\partial T'}{\partial t} + u' \cdot \frac{\partial \overline{T}}{\partial x} + \eta \cdot T'$ (cf. Eq. 1 in text). **b** 11-year running mean of the NINO4z index (*red curve*, in °C), of the wind projection coefficient of the second baroclinic mode (*black curve*, in % of the mean value), and of the wind projection coefficient of the second baroclinic mode as derived from the 7-year low pass filtered mean stratification (*blue curve*, in % of the mean value)

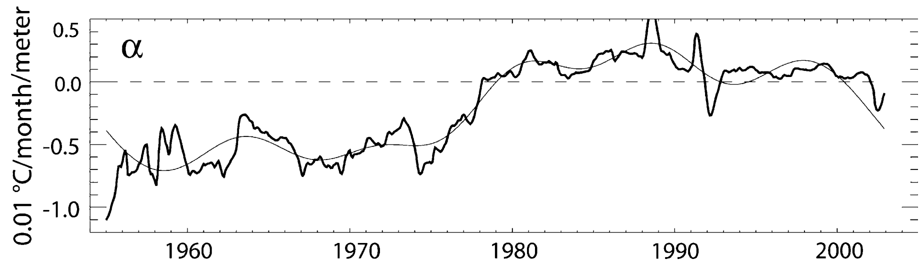

Fig. 5 Same as Fig. 4a but for the outputs of the LODCA model

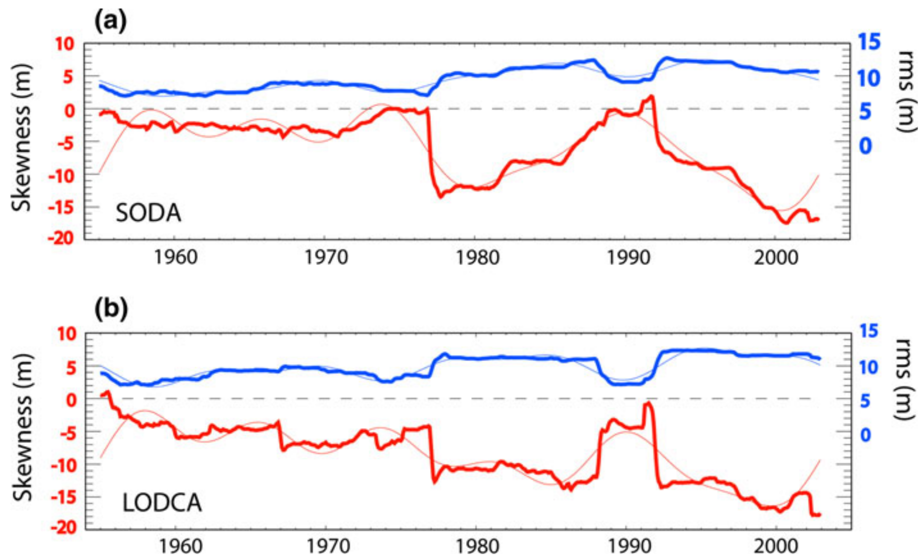

Fig. 6 11-year running variability (*blue curves*) and weighted skewness (*red curves*) of thermocline anomalies in the NINO4 region for **a** SODA and **b** LODCA. Unit is m

3.3 Role of stratification change versus ENSO amplitude modulation on vertical advection

While changes in stratification directly impact the thermocline feedback, changes in ENSO amplitude impact the amplitude (variability) of $-\overline{w}\cdot\frac{\partial T'}{\partial z}$ which also needs to be considered in order to understand changes in SST in the central-western Pacific. As a first step, we note that the variability and skewness of thermocline depth fluctuations in the NINO4 region increase after the 1976 climate shift (Fig. 6). This is related to the observed increase in ENSO amplitude/asymmetry in the east (An 2009) and to the tilt mode that implies large negative thermocline fluctuations in the western-central Pacific during large El Niño events. Here, we wish to estimate how changes in ENSO amplitude relate to changes in variability of $-\overline{w}\cdot\frac{\partial T'}{\partial z}$. This can be done from the LODCA heat budget (see Sect. 2), considering that LODCA does not include changes in thermocline feedback related to low frequency changes in stratification (basically because $\frac{\partial T'}{\partial z}$ depends only on h' in the model and $\overline{w}$ is inferred from the wind stress). As an anomaly model, LODCA can only account for the impact of low-frequency changes in stratification on the wave dynamics. The estimate of the variability of $-\overline{w}\cdot\frac{\partial T'}{\partial z}$ from LODCA can then be compared to an estimate of the vertical advection that considers the change in stratification on the thermodynamical processes. Based on the previous results, the latter can be defined as follows: Since the running variance of α (Fig. 4a) accounts for the change in thermocline feedback due to change in stratification, we define an estimate of vertical advection in the central-western equatorial Pacific as: $-(\sigma+\alpha(\overline{t}))\cdot\langle h'(t)\rangle_{NINO4eq}$ where $\langle X\rangle_Y$ indicates the spatial average of X over the region Y. $\overline{t}$ refers to the 11-year running variance timescale and σ is an offset coefficient that is used to fit the variance of the vertical advection to the LODCA estimate over the period 1955–1970 when the thermocline feedback is steady and weak. This is equivalent to have: $rms[(\sigma+\alpha(\overline{t}))\cdot\langle h'(t)\rangle_{NINO4eq}]_{1955-1970} = rms\left[\overline{w}\cdot\frac{\partial T'}{\partial z}\right]_{1955-1970}$ where $rms[X]_P$ is the root mean square of X over the period P and $-\overline{w}\cdot\frac{\partial T'}{\partial z}$ is provided by the LODCA simulation. σ is estimated to 1.5 10^{-2} °C/month/m. The Fig. 7 provides the results of both estimates of the running variability of vertical advection. Note that the timeseries do not cover the exact same period because $\alpha(\overline{t})$ is already obtained from a

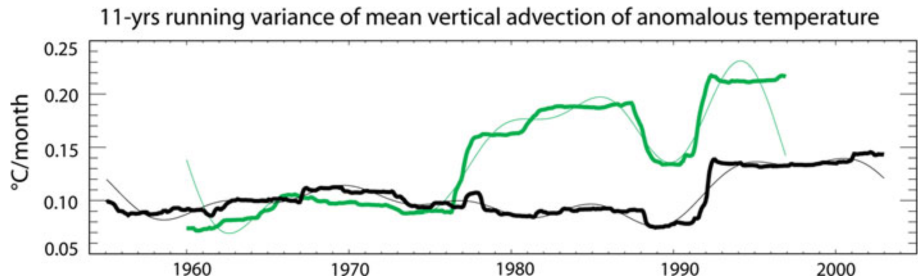

Fig. 7 11-years running variance of the mean vertical advection of anomalous temperature averaged over the NINO4 region for LODCA (*black curve*) and for the empirical formulation of the thermocline feedback (*green curve*, see text)

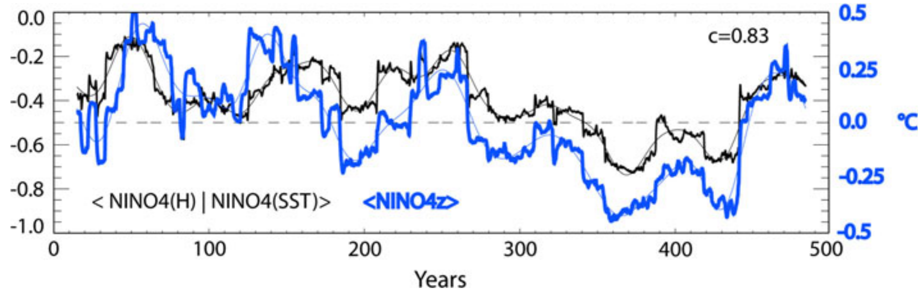

Fig. 8 31-year running correlation between SST and thermocline anomalies over the NINO4 region (*black curve*) and 31-year running variance of the NINO4z index (*blue curve*). The NINO4z is defined as the averaged temperature anomalies in the region (140°E–170°W, 75–100 m)

11-year running regression analysis similar to the one used to derive (Fig. 4a). Over the period 1955–1970 both estimates have comparable amplitude by construction. However, from the 1970s, the variability of vertical advection that includes the effect of the change in stratification increases more than the estimate from LODCA, reaching twice its value from after 1980. This indicates that the increase in the variability of vertical advection after the 1970s is dominated by the increase in stratification rather than the increase in ENSO amplitude. The effect of the increase in ENSO amplitude is noticeable only from the 1990s from which both estimates are highly correlated.

We thus demonstrated that both the increase of the stratification in the central-western Pacific and of the ENSO amplitude in the eastern Pacific lead to the increase in the vertical advection variability over the warm-pool region.

4 The GFDL_CM2.1 simulation

In order to overcome limitations associated to the relatively short record of the SODA data and, as a consistency check of the relationship between change in stratification and change in thermocline feedback "strength", we make use of the long-term GFDL_CM2.1 simulation (see Sect. 2) that has been extensively investigated for ENSO studies (Kug et al. 2009; Choi et al. 2011, 2012; Dewitte et al. 2012). This simulation does not exhibit shifts comparable to the 1976 climate shift but rather alternation of periods of weaker and stronger stratification in the central-western Pacific associated to the change in CP/EP El Niño frequency of occurrence (Choi et al. 2012). The Fig. 8 presents the 31-year running correlation between the modified NINO4 D20 and NINO4 SST indices (see Sect. 2). The results indicate that the 'strength' of the thermocline feedback in the western-central Pacific undergoes a low-frequency modulation, with also a long-term trend over the 500 years. In order to relate these changes to the stratification changes, we define a NINO4z index for the low-frequency temperature change based on the mode pattern of the first EOF of the 30-year low-pass filtered equatorial temperature in the first 500 m. The latter exhibits a peak anomaly in the western-central Pacific in the depth range [75–100] m (not shown here—see Fig. 5 of Choi et al. (2012)). We thus define the NINO4z index as the temperature anomalies averaged over (140°E–170°W; 75–100 m). The 31-year running variance of the NINO4z is displayed in Fig. 8. Note that it is highly correlated to the timeseries of the EOF mode (c = 0.79). Consistently with the results derived from SODA, the low-frequency change in stratification is highly correlated to change in 'strength' of the thermocline feedback (c = 0.83), supporting the large sensitivity of the thermocline feedback in the western-central Pacific to stratification change there. Choi et al. (2011) showed from the same model that the first EOF of low-frequency temperature change is highly correlated to the change in frequency of occurrence of the CP (EP) El Niño (their Fig. 6), with periods of reduced (increased) vertical stratification favouring the occurrence of CP (EP) El Niño events. This means that periods of increased occurrence of EP El Niño correspond to periods of increased thermocline feedback in the central-western central Pacific.

The long-record of the GFDL_CM2.1 simulation also offers the opportunity to test if the process of the modulation of the thermocline feedback by the change in stratification can be favoured by a positive feedback. In particular, we expect that change in stratification in the central-western Pacific (associated to a flattening thermocline) leads to increased ENSO amplitude in the eastern Pacific (Dewitte et al. 2007), which in turn can produce large thermocline fluctuations in the central-western Pacific through the tilt mode. Due to the ENSO positive (negative) asymmetry in the east (west), rectification processes are potentially at work which may favour either the increase or decrease of the stratification in the central-western Pacific. To test this hypothesis, we compute the co-variability mode (Singular Value Decomposition—hereafter SVD) between the low frequency changes in mean and skewness of the temperature anomalies along the equator. The Fig. 9 displays the results for the dominant SVD mode (co-variance = 98 %). It indicates that the low-frequency change in mean stratification that correlates to change in thermocline feedback (Fig. 8) may result from a rectification of the ENSO variability (i.e. asymmetry) since the SVD modes for the mean and skewness explain a significant share of the variance and their associated time series are highly correlated. The correlation between the timeseries associated to the mean (skewness) and the strength of the thermocline feedback (blue curve in Fig. 8) also reaches 0.61 (0.87).

5 Discussion and conclusions

The thermocline feedback in the western-central Pacific has been somewhat disregarded in the literature because of the deep thermocline and the dominant role of the zonal advective feedback. Current conceptual ENSO models are actually based on this assumption (An and Jin 2001; Timmermann et al. 2003; Thual et al. 2011). Recent concerns about the possibility that the central Pacific thermocline might strengthen in a warmer climate (DiNezio et al. 2009; Yeh et al. 2009) has raised the issue whether such change could lead to change in the ENSO feedback processes and how their balance might be modified (Collins et al. 2010). Here we document the change in feedback processes in the central-western equatorial Pacific based on the SODA Reanalysis focusing on the role of stratification and ENSO amplitude in modifying the "strength" of the thermocline feedback and the vertical advection variability, respectively. Based on the regression analysis between SST and H anomalies in the NINO4 region, the thermocline feedback exhibits a sharp apparent reduction associated to the 1976 climate shift. This actually reflects that the thermocline fluctuations become more influential on SST after the late 1970s due to the increased stratification. As a matter of fact, the strong anti-correlation between SST and H anomalies prior to the 1970s is due to the thermocline tilt mode which implies negative (positive) H anomalies during positive (negative) SST anomalies in the central-western Pacific associated to the anomalous zonal advection of

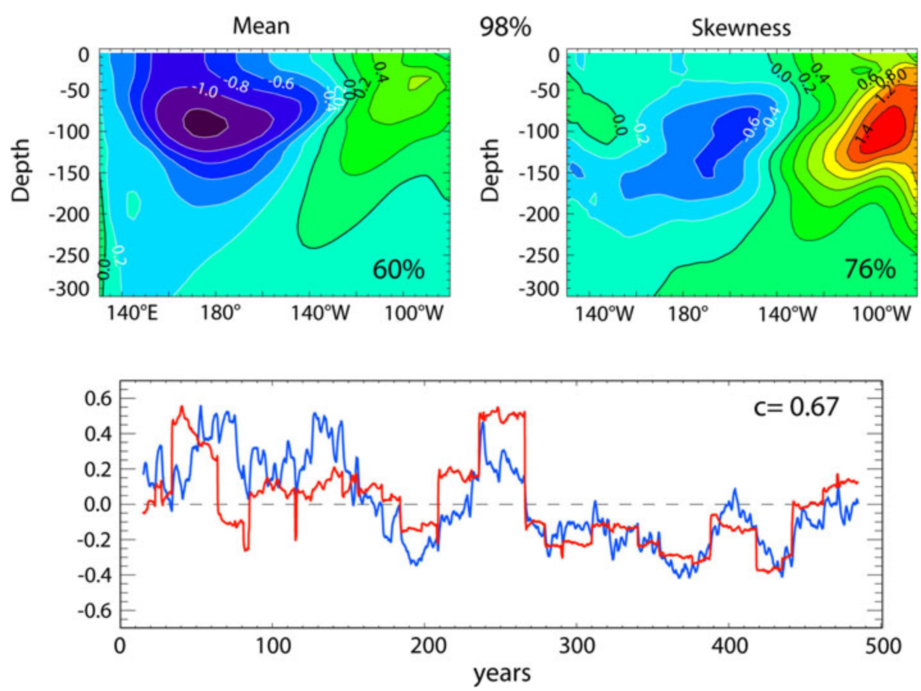

Fig. 9 First SVD mode between the 31-year running mean and skewness of temperature anomalies along the equator and in the first 500 m: mode patterns for **a** mean and **b** skewness; associated timeseries for the mean (*blue*) and skewness (*red*). The percentage of explained variance of the mode is indicated in each panels. The covariance of the mode is indicated between **a** and **b**

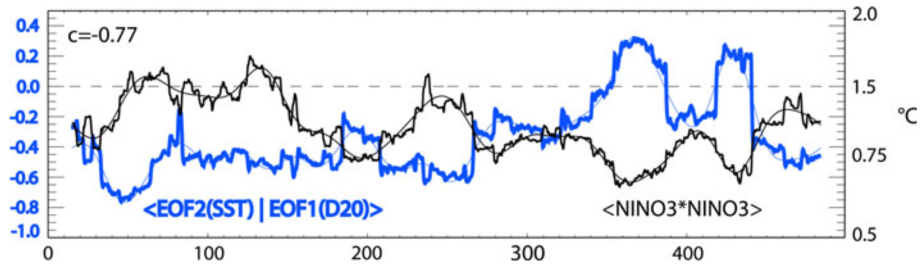

Fig. 10 31-year running correlation between the second EOF of SST anomalies and the first EOF of thermocline anomalies (tilt mode) between 12°S and 12°N across the Pacific (*blue curve*—left scale). 31-year running variance of the NINO3 SST index (*black curve*—right scale)

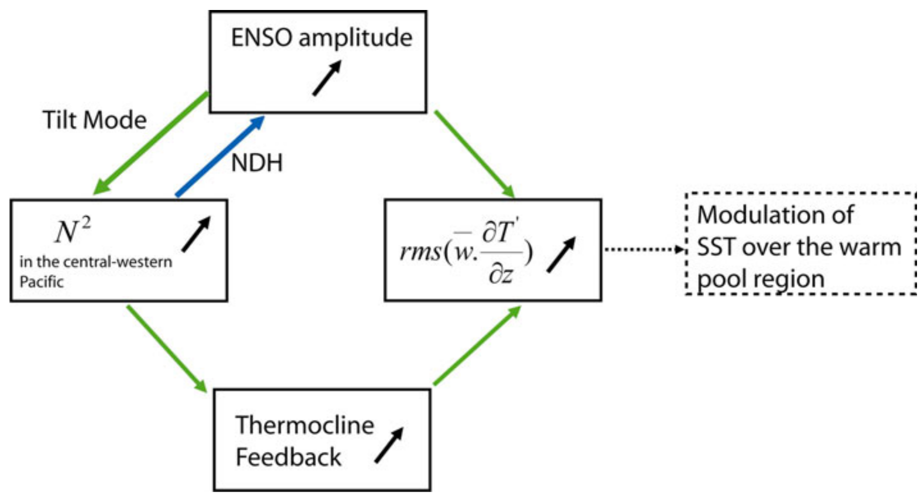

Fig. 11 Schematic of the mechanism of the modulation of the thermocline feedback in the central-western Pacific suggested in this study. The *green arrows* stand for the processes documented in this study, the *blue arrow* refers to a process suggested in Dewitte et al. (2007), that is an increased stratification (i.e. flattening thermocline) leads to an increased in ENSO amplitude through the increase in the non-linear dynamical heating (NDH). The *dotted arrow* stands for the process that our results call for investigating and that is beyond the scope of the study

mean SST. After the 1970s, the increased stratification makes the H anomalies more influential on SST, reducing the anti-correlation to almost zero, which corresponds to an increase of the strength of the thermocline feedback. This counter-intuitive relationship between the "SST-H correlation" in the central western Pacific and the "strength" of the thermocline feedback calls for revisiting the parameterization of the thermocline feedback in the western Pacific. Here we propose that thermocline feedback should be based on direct estimate of the stratification characteristics rather than the observed linear relationship between SST and H. Based on this observation, we showed that the increase in stratification after the 1990s results in an increase in variability of the mean vertical advection of anomalous temperature that is twice the one associated to the increase in ENSO amplitude.

In order to overcome limitations associated to the relatively short record of the SODA data set, we verified that stratification change in the western-central Pacific is highly correlated to the strength of the thermocline feedback in a long-term CGCM simulation. This simulation exhibits an alternation of periods of high-occurrence of CP and EP El Niño events (Kug et al. 2010). It is observed that the periods of increased stratification (flattening thermocline) are associated to the periods of increased occurrence of the EP El Niño, consistently with the remote effect of stratification change on the ENSO amplitude in the eastern Pacific described in Dewitte et al. (2007). Therefore increased stratification is associated to the increase in ENSO amplitude in the eastern Pacific, which in turn may favour the accumulation of negative temperature anomalies (because ENSO is positively skewed in the eastern Pacific) in the vicinity of the thermocline through the tilt mode on the mean stratification in the western-central Pacific. As a result, the low-frequency changes in mean temperature covary with the low-frequency changes of its asymmetry in the vicinity of the thermocline in the long-term simulation (Fig. 9). This is also observed in SODA but with less statistical confidence due to the shorter length of the record (Dewitte et al. 2009). It indicates that the modulation of the thermocline feedback by the low-frequency changes in stratification in the western-central Pacific is associated to the ENSO amplitude modulation in the eastern equatorial Pacific. Simply put, such mechanism implies that the relationship between the second EOF mode of the SST anomalies [that accounts for SST anomalies in the NINO4 region—cf. Ashok et al. (2007)] and the first EOF mode of thermocline anomalies (i.e. tilt mode, cf. Clarke (2010)) is correlated to the ENSO amplitude modulation in the eastern equatorial Pacific. This is verified in the long-term simulation used in this study (Fig. 10). This has of course implications for the understanding of the ENSO modulation because the increase in thermocline feedback in the central-western Pacific during periods of high ENSO amplitude also implies a modulation of the zonal advection processes through the changes in the zonal SST contrast across the equatorial Pacific. The schematic of Fig. 11 illustrates the processes that are documented in this study and how they may interact towards modulating the SST over the warm-pool region.

Summarizing, we showed that the eastern and central-western Pacific variability are linked through the change in vertical stratification in the central-western Pacific. In other words, there is a relationship between change in ENSO asymmetry/amplitude in the eastern equatorial Pacific and stratification changes in the central-western equatorial Pacific (connected through the tilt mode) that modifies the balance between feedback processes in the central-western Pacific. This mechanism is suggested to be part of the ENSO modulation mechanism of the tropical Pacific and could be incorporated into the current tropical theories of the ENSO decadal modulation (Timmermann et al. 2003) considering that they do not consider the vertical advection process in the central-western Pacific. In particular, our study provides material for revisiting the role (and parameterizations) of the thermocline feedback in the western-central equatorial Pacific in conceptual to intermediate complexity models. It suggests that such a parameterization should more directly depend on the stratification characteristics rather than on the mean observed correlative relationship between SST and H anomalies. Our study also indicates that the thermocline feedback in the central-western Pacific should depend on the ENSO amplitude. With such a new parameterization, it is likely that the sensitivity of the ENSO stability to changes in stratification may be different than the one evidenced in former studies (Fedorov and Philander 2001; Thual et al. 2011). This issue is worth tackling with considering that vertical stratification in the warm pool region will keep increasing due to global warming (An et al. 2008; Yeh et al. 2009) and that there is still a debate on the selection mechanisms of the El Niño type of event.

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References

An S-I (2009) A review of interdecadal changes in the nonlinearity of the El Nino-southern oscillation. Theor Appl Climatol 97:29–40

An S-I, Jin F–F (2000) An eigen analysis of the interdecadal changes in the structure and frequency of ENSO mode. Geophys Res Lett 27:1573–1576

An S-I, Jin F–F (2001) Collective role of thermocline and zonal advective feedbacks in the ENSO mode. J Clim 14:3421–3432

An S-I, Wang B (2000) Interdecadal change of the structure of the ENSO mode and its impact on ENSO frequency. J Clim 13:2044–2055

An S-I, Kug J-S, Ham Y-G, Kang I-S (2008) Successive modulation of ENSO to the future greenhouse warming. J Clim 21:3–21

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T (2007) El Niño Modoki and its possible teleconnection. J Geophys Res 112:C11007

Belmadani A, Dewitte B, An S-I (2010) ENSO feedbacks and associated time scales of variability in a multimodel ensemble. J Clim 23:3181–3204

Boyer TP, Conkright ME, Antonov JI, Baranova O, Garcia HE, Gelfeld R, Johnson D, Locarnini RA, Murphy PP, O'Brien TD, Smolyar I, Stephens C (2002) NOAA Atlas Nesdis 43 World Ocean Database, 2001. Volume 2: temporal distribution of bathythermograph profiles. U.S. Gov. Printing Office, Washington DC

Choi J, An S-I, Kug J-S, Yeh S-W (2011) The role of mean state on changes in El Nino's flavor. Clim Dyn 37:1205–1215

Choi J, An S-I, Yeh S-W (2012) Decadal amplitude modulation of two types of ENSO and its relationship with the mean state. Clim Dyn 38:2631–2644

Clarke AJ (2010) Analytical theory for the quasi-steady and low-frequency equatorial ocean response to wind forcing: the "Tilt" and "Warm Water Volume" modes. J Phys Oceanogr 40(1): 121–137

Collins M, An S-I, Cai W, Ganachaud A, Guilyardi E, Jin F–F, Jochum M, Lengaigne M, Power S, Timmermann A, Vecchi G, Wittenberg A (2010) The impact of global warming on the tropical Pacific Ocean and El Niño. Nat Geosci 3:391–397

Compo GP, Whitaker JS, Sardeshmukh PD (2006) Feasibility of a 100-year reanalysis using only surface pressure data. Bull Am Meteorol Soc 87:175–190. doi:10.1175/BAMS-87-2-175

Delworth TL et al (2006) GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. J Clim 19:634–674

Dewitte B (2000) Sensitivity of an intermediate coupled ocean-atmosphere model of the tropical Pacific to its oceanic vertical structure. J Clim 13:2363–2388

Dewitte B, Reverdin G, Maes C (1999) Vertical structure of an OGCM simulation of the equatorial Pacific Ocean in 1985–1994. J Phys Oceanogr 29:1542–1570

Dewitte B, Yeh S-W, Moon B-K, Cibot C, Terray L (2007) Rectification of the ENSO variability by interdecadal changes

in the equatorial background mean state in a CGCM simulation. J Clim 20(10):2002–2021
Dewitte B, Thual S, Yeh S-W, An S-I, Moon B-K, Giese B (2009) Low frequency variability of temperature in the vicinity of the equatorial thermocline in SODA: role of equatorial wave dynamics and ENSO asymmetry. J Clim 22:5783–5795
Dewitte B, Choi J, An S-I, Thual S (2012) Vertical structure variability and equatorial waves during central Pacific and eastern Pacific El Niños in a coupled general circulation model. Clim Dyn 1–15. doi:10.1007/s00382-011-1215-x
DiNezio P, Clement A, Vecchi G, Soden B, Kirtman B, Lee S-K (2009) Climate response of the equatorial Pacific to global warming. J Clim 22(18):4873–4892. doi:10.1175/2009JCLI2982.1
Fedorov AV, Philander SG (2001) A stability analysis of Tropical Ocean–Atmosphere interactions: bridging measurements and theory for El Niño. J Clim 14(14):3086–3101
Giese B, Ray S (2011) El Niño variability in simple ocean data assimilation (SODA):1871–2008. J Geophys Res 116:C02024. doi:10.1029/2010JC006695
Gill AE (1982) Atmosphere-ocean dynamics. Academic Press, New York
Gnanadesikan et al (2006) GFDL's CM2 global coupled climate models. Part II: The baseline ocean simulation. J Clim 19:675–697
Griffies SM et al (2005) Formulation of an ocean model for global climate simulations. Ocean Sci 1:45–79
Hirst AC (1986) Unstable and damped equatorial modes in simple coupled ocean-atmosphere models. J Atmos Sci 43(6):606–632
Jin F–F, Neelin JD (1993) Modes of interannual tropical ocean-atmosphere interaction—a unified view. Part I: numerical results. J Atmos Sci 50:3477–3503
Jin F–F, An S-I, Timmermann A, Zhao J (2003) Strong El Nino events and nonlinear dynamical heating. Geophys Res Lett 30:1120
Kao H-Y, Yu J-Y (2009) Contrasting Eastern-Pacific and Central-Pacific types of ENSO. J Clim 22:615–632
Kug J-S, Jin F–F, An S-I (2009) Two-types of El Niño events: Cold Tongue El Niño and Warm Pool El Niño. J Clim 22:1499–1515
Kug J-S, Choi J, An S-I, Jin F–F, Wittenberg A-T (2010) Warm Pool and Cold Tongue El Niño events as simulated by the GFDL2.1 coupled GCM. J Clim 23:1226–1239
Lee T, McPhaden M (2010) Increasing intensity of El Nino in the central-equatorial Pacific. Geophys Res Lett 37:L14603. doi:10.1029/2010GL044007
Lin S-J (2004) A "vertically Lagrangian" finite-volume dynamical core for global models. Mon Wea Rev 132:2293–2307
Locarnini RA, Conkright ME, Antonov JI, Baranova O, Boyer TP, Garcia HE, Gelfeld R, Johnson D, Murphy PP, O'Brien TD, Smolyar I, Stephens C (2002) NOAA Atlas Nesdis 45 World Ocean Database, 2001. Volume 4: Temporal distribution of temperature, salinity and oxygen profiles. U.S. Gov. Printing Office, Washington DC
McPhaden MJ, Busalacchi AJ, Cheney R, Donguy JR, Gage KS, Halpern D, Ji M, Julian P, Meyers G, Mitchum GT, Niiler PP, Picaut J, Reynolds RW, Smith N, Takeuchi K (1998) The Tropical Ocean-Global Atmosphere (TOGA) observing system: a decade of progress. J Geophys Res 103:14169–14240
Moon B-K, Yeh S-W, Dewitte B, Jhun J-G, Kang I-S, Kirtman BP (2004) Vertical structure variability in the equatorial Pacific before and after the Pacific climate shift of the 1970 s. Geophys Res Lett 31:L03203. doi:10.1029/2003GL018829
Neelin JD, Battisti DS, Hirst AC, Jin F–F, Wakata Y, Yamagata T, Zebiak SE (1998) ENSO theory. J Geophys Res Oceans 103:14261–14290
Picaut J, Masia F, du Penhoat Y (1997) An advective-reflective conceptual model for the oscillatory nature of the ENSO. Science 277(5326):663–666
Rasmusson EM, Carpenter TH (1982) Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. Month Weather Rev 110:354–384
Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res 108(D14):4407. doi:10.1029/2002JD002670
Stephens C, Conkright ME, Antonov JI, Baranova O, Boyer TP, Garcia HE, Gelfeld R, Johnson D, Locarnini RA, Murphy PP, O'Brien TD, Smolyar I (2002) NOAA Atlas Nesdis 44 World Ocean Database, 2001. Volume 3: temporal distribution of conductivity/salinity-temperature-depth (pressure) casts. U.S. Gov. Printing Office, Washington DC
Smith RD, Dukowicz JK, Malone RC (1992) Parallel ocean general circulation modelling. Physica D 60:38–61
Takahashi K, Montecinos A, Goubanova K, Dewitte B (2011) ENSO regimes: reinterpreting the canonical and Modoki El Niño. Geophys Res Lett 38:L10704. doi:10.1029/2011GL047364
Thual S, Dewitte B, An S-I, Ayoub N (2011) Sensitivity of ENSO to stratification in a recharge–discharge conceptual model. J Clim 24(16):4332–4349
Timmermann A, Jin F–F, Abshagen J (2003) A nonlinear theory for El Niño bursting. J Atmos Sci 60(1):152–165
Whitaker JS, Compo GP, Wei X, Hamill TM (2004) Reanalysis without radiosondes using ensemble data assimilation. Month Weather Rev 132:1190–1200
Wittenberg A, Rosati TA, Lau N-C, Ploshay JJ (2006) GFDL's CM2 global coupled climate models. Part III: Tropical Pacific climate and ENSO. J Clim 19:698–722
Wyrtki K (1982) The southern oscillation, ocean-atmosphere interaction and El Niño. Mar Tech Soc J 6(1):3–10
Yeh S-W, Kug S-J, Dewitte B, Kwon M-H, Kirtman BP, Jin F–F (2009) El Niño in a changing climate. Nature 461:511–514
Yeh S-W, Dewitte B, Yim BY, Noh Y (2010) Role of the upper ocean structure in the response of ENSO-like SST variability to global warming. Clim Dyn. doi:10.1007/s00382-010-0849-4
Zebiak SE, Cane MA (1987) A model of El Niño-southern oscillation. Mon Wea Rev 115:2262–2278
Zelle H, Appeldoorn G, Burgers G, van Oldenborgh GJ (2004) The Relationship between sea surface temperature and thermocline depth in the eastern Equatorial Pacific. J Phys Oceanogr 34(3):643–655