Improved Representation of Tropical Pacific Ocean–Atmosphere Dynamics in an Intermediate Complexity Climate Model

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ABSTRACT

A new anomaly coupling technique is introduced into a coarse-resolution dynamic climate model [the Liège Ocean Carbon Heteronomous model (LOCH)-Vegetation Continuous Description model (VECODE)-Earth System Models of Intermediate Complexity Climate deBilt (ECBILT)-Coupled Large-Scale Ice-Ocean model (CLIO)-Antarctic and Greenland Ice Sheet Model (AGISM) ensemble (LOVECLIM)], improving the model's representation of eastern equatorial Pacific surface temperature variability. The anomaly coupling amplifies the surface diabatic atmospheric forcing within a Gaussian-shaped patch applied in the tropical Pacific Ocean. It is implemented with an improved predictive cloud scheme based on empirical relationships between cloud cover and key state variables. Results are presented from a perturbed physics ensemble systematically varying the parameters controlling the anomaly coupling patch size, location, and amplitude. The model's optimal parameter combination is chosen through calibration against the observed power spectrum of monthly-mean surface temperature anomalies in the Niño-3 region. The calibrated model exhibits substantial improvement in equatorial Pacific interannual surface temperature variability and robustly reproduces El Niño-Southern Oscillation (ENSO)-like variability. The authors diagnose some of the key atmospheric and oceanic feedbacks in the model important for simulating ENSO-like variability, such as the positive Bjerknes feedback and the negative heat flux feedback, and analyze the recharge-discharge of the equatorial Pacific ocean heat content. They find LOVECLIM robustly captures important ocean dynamics related to thermocline adjustment and equatorial Kelvin waves. The calibrated model demonstrates some improvement in simulating atmospheric feedbacks, but the coupling between ocean and atmosphere is relatively weak. Because of the tractability of LOVECLIM and its consequent utility in exploring long-term climate variability and large ensemble perturbed physics experiments, improved representation of tropical Pacific ocean-atmosphere dynamics in the model may more readily allow for the investigation of the role of tropical Pacific ocean-atmosphere dynamics in past climate changes.

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1. Introduction

The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual variability in the earth's climate system. It affects temperature and precipitation

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patterns worldwide, with global environmental and socioeconomic implications (McPhaden et al. 2006). A hallmark of ENSO is the anomalous associated pattern of sea surface temperature (SST) variation in the eastern tropical Pacific Ocean, alternating between warm phases (El Niño) and cold phases (La Niña). These temperature variations are caused by complex thermal and dynamical ocean-atmosphere interactions and feedbacks. Correctly simulating ENSO behavior in coupled earth system models, including its internal variability and response to external forcings, is of paramount importance to the climate modeling community, particularly because it is currently unclear how this critical component of the earth system may be affected by anthropogenic climate change (e.g., Collins et al. 2010; Vecchi and Wittenberg 2010; Newman 2013).

Comprehensive coupled general circulation models, such as those used in the phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), have become powerful tools for examining ENSO behavior and dynamics (Randall et al. 2007), as well as potential changes in ENSO mean state and variability (e.g., Meehl et al. 2007). However, challenges remain in simulating key statistical features of ENSO, given biases in the current generation of these models. For example, many models are unable to simulate a realistic annual cycle of tropical Pacific SST (Jin et al. 2008), which is important for understanding potential interactions between ENSO variability and the mean state (e.g., Battisti and Hirst 1989; Tziperman et al. 1997; Guilyardi 2006; Stein et al. 2011; McGregor et al. 2012).

Recent work suggests the ability of dynamic models to simulate realistic ENSO variability is closely related to capturing important atmospheric and oceanic processes (Schneider 2002; Guilvardi et al. 2009b; Lloyd et al. 2009, 2012), particularly in simulating key feedback mechanisms (Jin et al. 2006; Kim and Jin 2011). One important relationship is the Bjerknes feedback (Bjerknes 1969), which is a positive feedback mechanism between surface temperature anomalies in the Niño-3 region (5°S-5°N, 150°-90°W) and zonal wind stress anomalies within the Niño-4 region (5°S-5°N, 160°E–150°W). The other relationship is the negative heat flux feedback, which relates surface temperature anomalies to surface heat flux anomalies within the Niño-3 region. Previous results have shown coupled models typically underestimate these feedbacks compared to diagnoses using reanalysis data (Lloyd et al. 2009; Kim and Jin 2011; Lloyd et al. 2012), while atmosphere-only models typically show better agreement with observations (Lloyd et al. 2011).

CMIP5 models appear to show some improvements in simulating ENSO characteristics compared to CMIP3. These improvements are primarily related to decreased model spread in ENSO amplitude, resulting in an ensemble mean that is closer to observations (Guilyardi et al. 2012; Kim and Yu 2012). Preliminary analysis suggests power spectra of monthly SST anomalies in the Niño-3 region ($5^{\circ}S-5^{\circ}N$, $150^{\circ}-90^{\circ}W$) is also improved in the CMIP5 models. However, such ENSO metrics should be treated with caution owing to the relatively short observational record used to gauge model performance. In other words, the observational record typically used to evaluate model performance may not be of sufficient length to capture ENSO statistics robustly (Wittenberg 2009).

Given the high computational cost of running comprehensive, state-of-the-art coupled earth system models, such as those developed by international modeling groups participating in the CMIP3 and CMIP5 projects, it is difficult to utilize these models to examine possible sensitivity of ENSO behavior to systematic variations in the relevant model parameters over their physically plausible ranges. These efforts would require large ensemble experiments run for multiple centuries, or even millennia when considering possible interactions with parameters controlling deep ocean processes (e.g., vertical diffusion, which requires multiple millennia spin ups to achieve approximate dynamic equilibrium of the full ocean). Such efforts are currently not possible using higher-resolution (e.g., $1^{\circ} \times 1^{\circ}$) fully coupled modeling frameworks. In recent decades, more simple minimum physics ENSO models have produced major insights into fundamental ENSO dynamics (e.g., Zebiak and Cane 1987; Karspeck and Anderson 2007; Bejarano and Jin 2008; McGregor et al. 2012). In particular, past theoretical and numerical modeling approaches have shown that capturing a realistic representation of tropical Pacific SST variability hinges on correctly simulating 1) the recharge-discharge of ocean heat along the equator (e.g., Wyrtki 1975; Jin 1997); 2) the Bjerknes feedback (e.g., Bjerknes 1969), which requires an accurate representation of tropical atmospheric dynamics and the Walker circulation; and 3) oceanic Kelvin waves (e.g., McPhaden 1999). A reduced complexity coupled earth system model that is capable of capturing the essential physical processes responsible for ENSO may provide an advantage over more comprehensive CMIP models in examining characteristics of ENSO variability both when long-run (e.g., millennial) simulations are required and where large state spaces (e.g., multidimensional perturbed physics ensembles) are explored.

Here we present findings from a perturbed physics ensemble to optimize the representation of ENSO variability using an intermediate complexity climate model [Liège Ocean Carbon Heteronomous model (LOCH)-Vegetation Continuous Description model (VECODE)-Earth System Models of Intermediate Complexity Climate deBilt (ECBILT)-Coupled Large-Scale Ice-Ocean model (CLIO)-Antarctic and Greenland Ice Sheet Model (AGISM) ensemble (LOVECLIM)]. Our version of the LOVECLIM model includes several key enhancements including a new dynamic cloud scheme, an updated linear balance equation, and implementation of an anomaly coupling technique to improve the representation of oceanatmosphere coupling in the equatorial Pacific. These improvements lead to more realistic ENSO-like variability in the model. The motivation of this work is to highlight the use of an efficient and tractable reduced complexity earth system model that can robustly simulate ENSO-like variability. Such a model may provide a useful tool for examining past and potential future changes in ENSO using multiparameter perturbed physics ensemble approaches, potentially in concert with assimilation of observational and proxy climate data (e.g., Steinman et al. 2012).

The paper is organized as follows: section 2 describes the version of LOVECLIM used in this study, including details about modifications and the anomaly coupling parameterization; section 3 outlines the model experiments and the perturbed physics ensemble design; section 4 describes the calibration method and results; section 5 contains discussion of the results and interpretations; section 6 provides caveats and a discussion of open questions; and section 7 summarizes our main findings and implications.

2. LOVECLIM

We use a modified version of the fully coupled earth system model LOVECLIM, version 1.2 (Goosse et al. 2010; Loutre et al. 2011). The LOVECLIM version used in this study consists of a roughly 5.6° latitude by 5.6° longitude grid (spectral T21) three-level quasigeostrophic atmosphere component (ECBILT2), which includes also parameterizations of the ageostrophic circulation, coupled to a 3° by 3° ocean general circulation model with 20 vertical levels and includes a thermodynamic-dynamic representation of sea ice (CLIO3). Compared to earlier versions, the ECBILT model version employed here includes an updated balance equation, which accounts for the effect of divergent zonal winds onto geopotential height, following a simplified version of the balance equation used in Davis and Emanuel (1991). ECBILT-CLIO is coupled to a land vegetation model (VECODE) that includes dynamic representation of trees, grasses, and desert. LOVECLIM contains two additional model components, simulating ocean biogeochemical cycles (LOCH) and ice sheet dynamics (AGISM), which are not used in the present study. We introduce two notable modifications to LOVECLIM including (i) development of a new dynamic cloud scheme based on observed relationships between cloud distribution and reanalyzed spatial fields of state variables and (ii) implementation of an anomaly coupling technique to improve the representation of coupled ocean–atmosphere processes (and thus potentially the faithfulness of interannual variability) in the equatorial Pacific. These modifications are described in the following sections.

a. Dynamic cloud scheme

The standard version of LOVECLIM uses either a prescribed observed cloud cover field based on present day climatology or a highly simplified diagnostic cloud scheme. To address potential shortwave and longwave cloud feedbacks, we incorporated a new empirical cloud scheme derived from spatial, long-term (1960-2000) mean fields of the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) (Uppala et al. 2005). While the standard version of LOVECLIM contains a simplified diagnostic cloud scheme, it is common practice to use prescribed climatological cloud fields. Thus, improving the model cloud representation can be useful for climate change experiments considering changes in radiative feedbacks, and it can result in better simulation of ENSO variability (Kim et al. 2008; Neale et al. 2008).

The new scheme predicts cloud cover in LOVECLIM based on observed relationships between key state variables in ERA-40 and total cloud cover from the International Satellite Cloud Climatology Project (ISCCP) product (Rossow and Schiffer 1999), calculated using cloud fields between about 1983 and 2001. No differentiation into different cloud levels was undertaken. We used the alternating conditional expectation (ACE) value algorithm (e.g., Timmermann et al. 2001) to derive a nonparametric, multiple regression,

$$y = C_1(x_1) + C_2(x_2) + C_3(x_3) + C_4(x_4),$$

where the observed long-term mean (1983–2001 time average) ISCCP total cloud coverage y at each grid point depends on the following four long-term mean state variables at the same grid point: vertical velocity at 400 hPa x_1 , surface temperature x_2 , precipitation x_3 , and relative humidity in the boundary layer x_4 . By using long-term means, rather than daily or monthly fields, we make the implicit assumption that short-term (synoptic, intraseasonal–interannual) variability of the predictors does not project onto the predicted long-term mean cloud cover due to nonlinear processes. The corresponding lookup tables for the general transforms C_i are relatively smooth and can be fitted using cubic polynomials (Fig. 1). The nonparametric fit of these four variables resolves more than 80% of the variance of the observed annual mean clouds. The vertical range (minimum to maximum) of the lookup tables provides important information on the relative contribution of the respective variables to the total cloud cover. We find that the y range of the lookup tables C_1 , C_3 for vertical velocity and precipitation (Figs. 1a,c; blue circles) is smaller (<0.2) than for temperature and relative humidity (>0.2), indicating a weaker overall contribution of vertical velocity and precipitation to the empirical cloud model compared to relative humidity and surface temperature. We also find a saturation of cloudiness for precipitation values larger than $1 \text{ mm} (3 \text{ h})^{-1}$. Higher relative humidity translates into larger cloud fraction. The cloud-temperature relation is nonmonotonic and peaks at temperatures around 280K. The reduction of cloud coverage for temperatures >280 K is associated with the relatively low values of cloud cover in subtropical regions. For annual mean temperatures >300 K, one observes again an increase in cloudiness, associated with the onset of deep tropical convection. Note that the cubic fit does not capture the increase in clouds for high temperatures, which may lead to a slight underestimation of cloudiness in the ITCZ regions, the Indian Ocean, and western Pacific warm pool in our implemented scheme (Fig. 2).

The cloud scheme is implemented in LOVECLIM by calculating the vertically integrated cloud fraction at each horizontal grid point in the model, based on the polynomial fits derived from the ACE algorithm procedure, using the respective subdaily atmospheric fields x_i from LOVECLIM. The results (Fig. 2) for a preindustrial control simulation show that the new dynamic cloud scheme generally reproduces better overall agreement of cloud fractions with ISCCP fields in the middle to high latitudes and eastern equatorial Pacific than the standard version of LOVECLIM with the original active cloud scheme. Note, however, that remaining biases in tropical cloudiness result mostly from temperature, precipitation, and relative humidity biases in the model partly related to relatively weak vertical velocity fields in the tropics.

b. Anomaly coupling

Because of the coarse resolution of LOVECLIM, its T21 resolution is essentially blind to relatively narrow ENSO-related SST anomalies on the equator. We introduce tropical anomaly coupling to reduce this problem. Previous strategies altering ocean–atmosphere coupling have shown success in improving ENSO variability (Kirtman and Shukla 2002) and reducing mean



FIG. 1. (top)–(bottom) $C_1(x_1)$, $C_2(x_2)$, $C_3(x_3)$, and $C_4(x_4)$ (blue: lookup table) calculated using the ACE algorithm with ERA-40 state variables [vertical velocity at 400-hPa height (Pa s⁻¹), surface temperature (K), precipitation (m s⁻¹), and relative humidity] and the observed ISCCP cloud climatology data. Green lines represent cubic polynomials.

state biases in coupled models (Luo et al. 2005). The parameterization enhances the diabatic forcing within a specified patch in the tropical Pacific that intensifies SST anomalies. In other words, the surface temperature variability within this patch, as seen by the atmosphere, is intensified. The anomaly coupling parameterization is implemented using the following equation:

$$SST_{a}^{*}(\lambda, \varphi, t) = SST_{a}(\lambda, \varphi, t) + A[SST_{a}(\lambda, \varphi, t) - SST_{c}(\lambda, \varphi)] \exp\left[-\left(\frac{\lambda - P}{L_{1}}\right)^{2} - \left(\frac{\varphi}{L_{2}}\right)^{2}\right],$$

where SST_a^* is the perturbed atmosphere surface temperature, SST_a is the unperturbed atmosphere surface temperature (the value obtained by the atmosphere from the coupling routine), and SST_c is the climatological



FIG. 2. Mean total cloudiness for (a) long-term ISCCP satellite product; (b) LOVECLIM equilibrium simulation with the empirical ACE cloud scheme driven by model fields of vertical wind velocity at 400 hPa, precipitation, surface air temperature, and relative humidity; and (c) LOVECLIM equilibrium simulation with the standard active cloud scheme. Observed mean cloudiness is ~0.68, and simulated mean cloudiness (in both the new and standard diagnostic cloud schemes) is ~0.6. The rms error for the new and standard versions of LOVECLIM is 0.14 and 0.16, respectively. LOVECLIM equilibrium simulations represent constant preindustrial atmospheric forcing conditions.



FIG. 3. Schematic of the anomaly coupling parameterization. The parameter P specifies the center location of the Gaussian-shaped patch. The zonal and meridional *e*-folding length scales of the patch size are controlled by the parameters L_1 and L_2 , respectively.

atmosphere surface temperature corresponding to coupled model equilibrium (unforced) conditions; λ and φ are the longitudinal and latitudinal positions, respectively. SST_c is the daily climatological surface temperature calculated from a 20-yr reference of the equilibrium model conditions, prior to activation of the anomaly coupling. The shape of the anomaly patch is defined using a Gaussian function where the parameters P, L_1 , and L_2 define the zonal location on the equator and the zonal and meridional length scales, respectively. The amplitude of the coupling is controlled by an additional parameter A. Figure 3 shows a schematic of the anomaly coupling parameterization and parameters. The aim of this parameterization is to amplify the atmospheric response to tropical surface temperature variability and hence to increase the atmosphere-ocean coupling strength. We thereby circumvent the model's inability to simulate a realistic tropical response to surface temperature anomalies due to limited atmospheric resolution. The anomaly coupling amplifies only the surface temperature passed to the atmosphere component (ECBILT), so the direct effects of the parameterization are through enhanced variability of surface air temperature. Therefore, any substantial effects on ocean temperature are achieved through a dynamical ocean response, such as thermocline adjustment and/or Kelvin wave propagation related to ocean-atmospheric feedbacks. Throughout the rest of the text any reference to the model surface temperature pertains specifically to surface air temperature in the model's atmosphere component ECBILT.

It has been noted previously that flux adjustment methods in the tropics with large coupling amplitudes can lead to potential instabilities, resulting in bifurcations and multiple ENSO equilibria (Neelin and Dijkstra 1995). As a cross-check, we analyzed the model mean surface temperature and thermocline depth in the equatorial Pacific over a wide range of anomaly coupling parameter settings and found no instability issues for reasonable values of the coupling amplitude parameter A. We find that the model mean state and annual cycle of surface air temperature and upper-ocean temperature structure in the equatorial Pacific is somewhat sensitive to the anomaly coupling parameterization (as shown in Figs. 7-9 and discussed in the following sections). However, the model is stable for all values of A, with $\sim 0.1^{\circ}$ C variation in mean tropical Pacific surface temperature across the considered range in A (0.5–3.5). Similarly, the range in zonal mean thermocline depth of the equatorial Pacific (averaged from 120°E to 90°W) is less than \sim 3 m over the considered range in A. In other words, the anomaly coupling mainly affects tropical Pacific surface temperature variability and has little impact on the mean state. We find some rectification effects of the enhanced variability on the mean state of upper-ocean properties, but these effects lead to improvements in the model, such as reducing the warm bias in the eastern equatorial Pacific cold tongue and increasing the strength of the equatorial undercurrent (Figs. 7 and 8, discussed in following sections). Overall, the mean state is conserved for the range in coupling strength A considered here.

3. Ensemble design

We constructed two perturbed physics ensemble experiments to explore the sensitivity of tropical Pacific variability to anomaly coupling parameters A, P, L_1 , and L_2 . In addition to the anomaly coupling, the LOVECLIM version in both ensembles contains the modifications discussed in section 2 (i.e., the use of a linear balance equation and a diagnostic cloud scheme which uses the instantaneous fields of midlevel vertical velocity, precipitation, surface temperature, and relative humidity). The main ensemble consists of 49 members representing unique combinations of the anomaly coupling amplitude parameter (A: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5) and location parameter (P: 170° , 160° , 150° , 140°, 130°, 120°, and 110°W). The zonal and meridional length scale parameters L_1 and L_2 were optimized separately using a smaller preliminary ensemble. We separated the ensembles into two distinct optimizations in order to keep the ensemble sizes manageable, as dictated by computational constraints. In the ensemble presented here, the length scale parameters are held fixed at their optimal values $L_1 = 35^{\circ}$ (zonal width) and $L_2 = 10^{\circ}$ (meridional width). All ensemble members are initiated from a 2000-yr spinup simulation with anomaly coupling turned off. Each ensemble member is reequilibrated with the anomaly coupling turned on for an additional 2000 years. After this reequilibration stage, each ensemble member is run for an additional 500 years, saving monthly atmosphere and ocean fields that we use for analyzing the ENSO characteristics and performing model diagnostics. Atmospheric forcing conditions

are held fixed at preindustrial levels for the entire ensemble experiment (both spinup and anomaly coupling phases).

4. ENSO calibration

We perform a model calibration using observational ENSO statistics to determine the optimal combination of anomaly coupling parameters A and P within the ensemble described in section 3. The model parameters are calibrated with second moment statistics using the observed spectrum of monthly-mean surface temperature anomalies averaged over the Niño-3 region (5°S–5°N, 150°–90°W), based on the ECMWF Ocean Re-Analysis System 3 (ORA-S3) product (Balmaseda et al. 2008). Results remain generally the same for other SST products [e.g., Tropical Atmosphere Ocean (TAO) buoy array data].

The model's monthly temperature anomalies are calculated relative to the coupled model climatology of each ensemble member. The calibration technique emphasizes model-data agreement of ENSO statistical properties, specifically the variance of the Niño-3 monthly temperature anomalies at frequencies typically associated with ENSO variability. We calculate 10 power spectra for each ensemble member, representing distinct 50-yr time slices from the 500-yr model simulation with monthly output. We compare the mean of the 10 power spectra to 50 years of ORA-S3 reanalysis (1960–2009) (Fig. 4a). The optimal parameter settings are defined as the ensemble member with the minimum rms error in the spectrum compared to observed SSTs between the frequencies 0.1 and 1 yr^{-1} (or periods of 1 and 10 yr). In the case where multiple ensemble members exhibit very similar rms error, we also consider the location of the spectral peak and magnitude of the variance in order to highlight model-data agreement on ENSO time scales. Optimal parameter values for the calibrated LOVECLIM are $P = 120^{\circ}$ W and A =3.0 (red curve in Fig. 4a). The spectral results of the perturbed physics ensemble show that the representation of interannual variability in Niño-3 surface temperature is significantly improved in the calibrated version of LOVECLIM. The power spectra for the calibrated model and reanalysis show similar broad spectral peaks between 3 and 7 yr, indicating that LOVECLIM is capable of simulating the irregular nature of interannual El Niño-La Niña cycles (Figs. 4 and 5). We compare the spectral results of the calibrated simulation with 35 more comprehensive coupled atmosphere-ocean general circulation models (Fig. 4b), comprising the majority of the models (and international modeling groups) participating in CMIP5. The CMIP5 models represent the most up-todate and state-of-the-art coupled Earth system models.



FIG. 4. Power spectra (~10 degrees of freedom) of monthlymean surface temperature anomalies averaged over the Niño-3 region (5°S-5°N, 150°-90°W), plotted as the normalized variance on the y axis, as in Dijkstra (2006). (a) The observed spectrum (black curve) is derived from the ERA-40 and ORA-S3 data for the period 1960-2009. Gray curves show spectra for the individual equilibrium LOVECLIM ensemble members varying anomaly coupling strength and zonal patch location. The model's power spectra are calculated from 500-yr time series and represent the mean of 10 different 50-yr spectra for each ensemble member. The red curve denotes the ensemble member exhibiting the minimum rms error referenced to the observations between frequencies of 0.1 and 1. For reference, we also highlight the standard LOVECLIM model with no anomaly coupling and the standard diagnostic cloud scheme (blue curve). (b) Comparison between the observed Niño-3 spectrum (black curve), the calibrated LOVECLIM (red curve), and the range of spectra from 35 CMIP5 model simulations (gray curves). Observed and calibrated LOVECLIM spectra are plotted as in Fig. 5a, and CMIP5 models are analyzed corresponding to historic forcing years 1960-2009.



FIG. 5. Time series of monthly-mean surface temperature anomalies averaged over the Niño-3 region (5°S–5°N, 150°–90°W) for (a) the ERA-40 and ORA-S3 from 1960 to 2009, (b) the LOVECLIM model calibrated to the observed power spectrum (see Fig. 4), and (c) the out-of-box version of LOVECLIM. All time series are smoothed using a 5-month running mean. The shading represents El Niño (red) and La Niña (blue) events. The variance (skewness) of each smoothed time series is 0.64 (0.98) for (a), 0.83 (-2) for (b), and 0.12 (-0.61) for (c).

Figure 4b shows that the ENSO-like variability in the calibrated version of LOVECLIM rivals the performance of some of the CMIP5 models in simulating a realistic spectrum of monthly Niño-3 surface temperature anomalies compared to the observations between 1960 and 2009. Many of the CMIP5 models overestimate the SST variance and/or simulate unrealistically short ENSO cycles that are oftentimes too periodic. However, we note that the Niño-3 spectrum is only a single metric for analyzing ENSO in climate models, and many of the more comprehensive CMIP models outperform LOVECLIM in simulating metrics such as the mean state, cold tongue bias, seasonal cycle, and phase locking (e.g., Guilyardi et al. 2009b, 2012; Bellenger et al. 2013).

5. Discussion

The ENSO calibration highlights the improved LOVECLIM performance in simulating interannual tropical Pacific surface temperature variability. Key features of these results include 1) the power spectrum of monthly Niño-3 SST anomalies in the calibrated version of LOVECLIM generally agrees with observations, and 2) the calibrated model is comparable with more comprehensive CMIP5 models in terms of correctly capturing the variance and frequency characteristics of Niño-3 surface temperature variability. However, we also find an apparent bias in the skewness of the Niño-3 time series for the calibrated LOVECLIM (Fig. 5). The observed Niño-3 SST time series is positively skewed, meaning the warm anomalies associated with El Niño events are typically larger than the cold anomalies associated with La Niña. The calibrated version of LOVECLIM shows a negatively skewed time series (i.e., stronger La Niña compared to El Niño). This bias is a robust feature of the model and appears in all ensemble members, and the magnitude of the skewness bias generally increases with the variance. The positive skewness in the observed Niño-3 SST time series is primarily due to large El Niño events, whose growth can be accelerated as a result of westerly wind bursts (Jin et al. 2007) or nonlinear dynamical heating (Jin et al. 2003). We speculate that the simplified three-layer atmosphere model in LOVECLIM does not capture the necessary atmospheric dynamics to generate these large El Niño events. Past results have indicated that the lack of strong El Niño events can lead to zero skewness in a linear model (Thompson and Battisti 2001). Thus, the negative skewness may indicate the introduction of nonlinearities in the calibrated version of LOVECLIM, which are not present in the standard version (Fig. 5). The skewness of the calibrated LOVECLIM is approximately -0.6° C, and the mean skewness of the 35 CMIP5 models analyzed in Fig. 4b is ~ 0.06 , with a standard deviation of ~ 0.28 . Even with the negatively skewed Niño-3 time series, the calibrated version of LOVECLIM reflects a major model improvement through enhanced interannual variability of tropical Pacific surface temperatures compared to the standard model.

In addition to improved time series statistics, the calibrated model also shows improved patterns of surface temperature variability within the Niño-3 region compared to the standard version (Fig. 6). The standard model substantially underestimates the magnitude and zonal extent of equatorial Pacific temperature anomalies. While the zonal variability is improved in the calibrated model, the model overestimates the magnitude of the temperature variability, primarily in the Niño-3 region. Further, the meridional width of the modeled surface temperature anomalies is too large, but this bias is likely due to the coarsely resolved atmospheric model grid ($\sim 5^{\circ} \times 5^{\circ}$). Given these limitations, the calibrated LOVECLIM is comparable to CMIP3 (Guilyardi et al. 2009b) and CMIP5 models (Kim and Yu 2012) in the faithfulness of its simulation of the spatial patterns of surface temperature variability in the tropical Pacific, and many of those models share the same biases noted



FIG. 6. Standard deviations of monthly modeled and observed surface temperature for (a) the ORA-S3 (1960–2009), (b) the LOVECLIM model calibrated to the observed power spectrum (see Fig. 4), and (c) the standard version of LOVECLIM. The X in (b) denotes the center of the anomaly coupling patch.

here. However, owing to the fixed positioning of the anomaly coupling patch, this technique is likely not capable of capturing potential westward progression of temperature anomalies: for example, "central Pacific" flavors of El Niño (Ashok et al. 2007). The teleconnections and climate implications of central Pacific El Niños can be much different than eastern Pacific events, and recent evidence suggests that these events have become more frequent and more intense in recent years (Lee and McPhaden 2010). Because the eastern Pacific is the primary region of interest for Pacific SST variability, we focus on the Niño-3 region here for model–data comparison and calibration.

As discussed in the introduction, simulating a realistic mean state and seasonal cycle of tropical Pacific temperature are important factors for diagnosing a model's ENSO variability. We highlight the standard LOVECLIM's mean state of tropical Pacific surface temperature (Fig. 7), upperocean temperature and current structure (Fig. 8), and the seasonal cycle of surface temperature (Fig. 9) compared to reanalysis. We also analyze the sensitivity of the model mean state and seasonal cycle to the calibrated anomaly coupling. We find the standard version of LOVECLIM

exhibits some mean state biases typically shared with other coarse-resolution intermediate complexity models, such as a reduced zonal surface temperature gradient and a relatively weak equatorial undercurrent. However, the calibrated anomaly coupling partially corrects these biases (Figs. 7c and 8c). The subsurface ocean response is particularly interesting given that the direct effect of the anomaly coupling is seen only by the atmosphere, thus suggesting some indirect influence on upper-ocean properties through dynamical atmosphere-ocean feedbacks. The seasonal cycle in equatorial Pacific surface temperature is poorly simulated by LOVECLIM. Both the standard and calibrated models contain large biases. Both exhibit a biannual cycle in the eastern Pacific and do not capture the zonal asymmetry in temperature. The addition of anomaly coupling does not improve the representation of the annual cycle, though these biases are well known for other intermediate complexity models and even some more comprehensive atmosphere-ocean general circulation models (e.g., Timmermann et al. 2007).

To explore the LOVECLIM underlying ENSO dynamics and ocean–atmosphere feedbacks, we examine the cross-correlation structure between Niño-3 monthly



FIG. 7. Mean surface temperature for (a) the ORA-S3 (1960–2009) and (b) the calibrated version of LOVECLIM equilibrated to preindustrial atmospheric forcings; (c) difference between the calibrated and standard versions of LOVECLIM.

surface temperature anomalies and variation in depth of the 20°C isotherm averaged over the entire equatorial Pacific Ocean (5°S–5°N, 120°E–90°W). The 20°C isotherm depth is a good indicator of the upper-ocean heat content, so its cross-correlation with Niño-3 surface temperature provides insight into the model's ability to capture the recharge–discharge of the equatorial ocean heat content (Jin 1997; McPhaden et al. 2006). Comparisons of the lagged cross-correlation between Niño-3 surface temperature variations and variation of the 20°C isotherm are presented in Fig. 10. The result from the ORA-S3 reanalysis data for the period 1980–2009 generally agrees with previous observational analysis (Meinen and McPhaden 2000), showing a peak cross-correlation at roughly 7 month lag (equatorial heat content leading Niño-3 SST). When analyzing the more complete ORA-S3 record (1960–2009), the general shape of the observed lagged correlation curve is





FIG. 8. Mean ocean temperature (color contours) and zonal currents (black contours) for the equatorial Pacific (averaged between 2°S and 2°N) for (a) the ORA-S3 (1960–2009) and (b) the calibrated version of LOVECLIM equilibrated to preindustrial atmospheric forcings; (c) difference between the calibrated and standard versions of LOVECLIM. Black contour intervals are 8 cm s^{-1} in (a) and (b) and 0.5 cm s^{-1} in (c). The red lines in (c) represent the mean depth of the 20°C isotherm for the standard (solid) and calibrated (dashed) versions of LOVCLIM (note the difference is almost visually indistinguishable).

consistent with the latter portion of the record (1980–2009), though the magnitude of the peak crosscorrelation from ORA-S3 is considerably lower ($r \sim 0.35$) than for the 1980–2009 ORA-S3 record ($r \sim 0.5$) or the 1980–99 TAO buoy data ($r \sim 0.7$) (Meinen and McPhaden 2000). The main reason for this discrepancy is that, prior to 1976, ENSO variability was characterized by the westward propagating SST mode that does not invoke thermocline dynamics (Fedorov and Philander 2000). Only after 1976 did the thermocline recharge–discharge mode become more prevalent in ENSO dynamics, as expressed in the higher correlations in the TAO dataset and ORA-S3 captured during this period.

Figure 10 shows that both versions of LOVECLIM (calibrated and standard model) generally reproduce the observed lagged correlation between monthly Niño-3 surface temperature anomalies and the spatial average depth anomalies of the 20°C isotherm over the equatorial Pacific basin, analogous to the equatorial Pacific warm water volume. Discrepancies arise when comparing time series that are of consistent length with the observations (20 or 50 yr), which raises concerns about the robustness of the relatively short observational record when diagnosing ENSO performance in models (cf. Wittenberg 2009). The lagged correlation structure is generally equivalent between the standard and calibrated versions of LOVECLIM for multicentury time series (500 yr). Further, agreement between the model and observations (particularly for negative lags) indicates that the model is reliably and realistically simulating the recharge-discharge mechanism in both standard and calibrated versions. However, the close model-data agreement does not necessarily indicate improved ENSO-like variability since both calibrated and standard versions of the model show similar correlation structures.

One of the key elements of the ENSO cycle is the equatorial Kelvin wave, which is important in initiating the eastward expansion of water from the western Pacific warm pool. Coarse-resolution B-grid finite difference models, such as the CLIO3 ocean component in LOVECLIM, have been shown to robustly simulate realistic oceanic Kelvin waves (Ng and Hsieh 1994; Sriver et al. 2013). In analyzing the annual cycle in equatorial 20°C isotherm depths (not shown), we find that both calibrated and standard versions of LOVECLIM produce Kelvin waves with realistic phase speeds, consistent with previous results analyzing CMIP3 models (Timmermann et al. 2007). The magnitude of the zonal redistribution of upper-ocean heat content associated with these waves is amplified for the calibrated version of the model, and the relationship



FIG. 9. Longitude-time plots of the annual cycle of surface temperature anomalies in the equatorial Pacific relative to the long-term mean for (a) the ORA-S3 (1960–2009), (b) the calibrated version of LOVECLIM equilibrated to preindustrial atmospheric forcings, and (c) the difference between the calibrated and standard versions of LOVECLIM. LOVECLIM surface temperatures are from the atmosphere component model.

between upper-ocean heat content and surface temperature is illustrated using Hovmöller diagrams of a sequence of El Niño-La Niña cycles over a 15-yr period (Fig. 11). Figure 11 provides an illustrative example of the time-lagged relationship between eastern equatorial Pacific surface temperature and thermocline depth (Fig. 10) in advance of El Niño events. Anomalous positive ocean heat content accumulates in the central-western equatorial Pacific and is redistributed eastward through initiation of an oceanic Kelvin wave several months prior to El Niño onset. As stated previously, both versions of LOVECLIM agree with reanalysis in generally simulating lagged correlation structure between Niño-3 surface temperature and upper-ocean heat content, with positive ocean heat content anomalies leading positive Niño-3 surface temperature anomalies by \sim 7 months. The calibrated version of LOVECLIM substantially amplifies the magnitude of this mechanism, thus contributing to more realistic ENSO-like variability as quantified by Niño-3 surface temperature variability.

The positive Bjerknes feedback and negative heat flux feedback are important metrics for diagnosing ENSO in models. These feedbacks can be quantified through linear regressions of Niño-3 surface temperature anomalies and Niño-4 zonal wind anomalies (Bjerknes

feedback) or Niño-3 surface heat flux anomalies (heat flux feedback). The slopes of these regressions define the magnitude of the feedbacks (μ : Bjerknes; α : heat flux). Recent model studies and intercomparisons have shown that these feedbacks can be very important in assessing ENSO performance in climate models (Guilyardi et al. 2009a; Lloyd et al. 2009, 2011). We diagnose these feedbacks for the standard and calibrated versions of LOVECLIM in Fig. 12, which shows scatterplots of monthly Niño-3 surface temperature anomalies and Niño-4 wind zonal wind stress anomalies (Bjerknes feedback) and Niño-3 heat flux anomalies (heat flux feedback). We find partially compensating influences of these feedbacks in the calibrated version of LOVECLIM in that the magnitude of the negative heat flux feedback is reduced along with the magnitude of the positive Bjerknes feedback. Further, the calibrated version of LOVECLIM exhibits some nonlinearity between Niño-3 surface temperature anomalies and Niño-3 heat flux anomalies. The nature of these effects is currently being investigated in a larger perturbed physics ensemble and is beyond the scope of this paper. Though the magnitude of the Bjerknes feedback is reduced in the calibrated model, the correlation between Niño-3 surface temperature anomalies and Niño-4 zonal wind stress anomalies is substantially improved. This is further



FIG. 10. Lagged cross-correlation between monthly-mean surface temperature anomalies averaged over the Niño-3 region $(5^{\circ}S-5^{\circ}N, 150^{\circ}-90^{\circ}W)$ and monthly-mean anomalies of the 20°C isotherm depth averaged over the equatorial Pacific $(5^{\circ}S-5^{\circ}N, 120^{\circ}E-90^{\circ}W)$. The black curves show the observed relationship derived from the ORA-S3 during the periods 1960–2009 (solid black) and 1980–2009 (dashed black). Red (blue) curve represent the calibrated (standard) version of the LOVECLIM model. LOVECLIM surface temperatures are from the atmosphere component model, and correlations are calculated using 500-yr integrations (consistent with Fig. 4). Negative lags indicate that equatorial Pacific thermocline depth anomalies are leading Niño-3 surface temperature anomalies.

illustrated by the spatial structure of correlation between Niño-3 surface temperature anomalies and zonal surface wind stress anomalies (Fig. 13), which shows an increase in correlation in the central/western tropical Pacific more consistent with diagnoses of reanalysis data.

The increase in the heat flux feedback and reduction in the Bjerknes feedback for the calibrated LOVECLIM (Fig. 13) is indicative of a more general relationship between these feedbacks and the amplitude of Niño-3 surface temperature variability within the entire ensemble (Fig. 14). We find the model exhibits a negative linear relationship between the Bjerknes feedback and ENSO amplitude and a positive linear relationship between the heat flux feedback and ENSO amplitude, across the entire ensemble. Enhancing the Niño-3 surface temperature variability is associated with a reduction in the magnitude of the positive Bjerknes feedback, but the spatial correlation structure between Niño-3 surface temperature and zonal surface wind stress is improved. These relationships between feedbacks and ENSO amplitude are generally consistent with previous results from model intercomparisons (e.g., Lloyd et al. 2009), except model intercomparisons analyze variations due to different model structures (CMIP3), whereas here we are analyzing parametric variations within the same model. Disentangling the effect of structural versus parametric uncertainties is difficult and beyond the scope of this paper. However, the insensitivity of the Niño-3 surface temperature

variability to the Bjerknes feedback in the LOVECLIM ensemble points to relatively weak ocean-atmosphere coupling. These results suggest that the improved ENSO-like variability is primarily an atmospheric response in the calibrated model and not a coupled oceanatmosphere phenomenon (Clement et al. 2011). This point is reinforced by the similarities in the laggedcorrelation structure between Niño-3 surface temperature and upper-ocean heat content (Fig. 10) for the calibrated and standard versions of the model. While the correlation structure for both versions agrees closely with observations, the ocean recharge-discharge mechanism in the model is relatively insensitive to the addition of anomaly coupling. While the main focus of the current paper is to provide details and results of an ENSO calibration experiment using a flexible intermediate climate model, the findings presented here may provide insights that can guide the development of new perturbed physics ensembles sampling both parametric and structural uncertainties for diagnosing mechanisms important for ENSO.

6. Caveats

Our methodology includes several simplifying assumptions. One caveat is that the anomaly coupling amplifies the local surface temperature (in the applied patch region) as seen only by the atmosphere and not by the ocean. The immediate effect on the local ocean SST is to damp the anomaly through surface flux responses to restore equilibrium at the air-sea interface. Thus, any sustained subsurface ocean response is achieved via enhanced dynamical feedbacks induced by the atmosphere model. As a result, the major oceanic feedbacks on eastern equatorial Pacific SST in the ocean modelsuch as thermocline depth, upwelling, and zonal advective feedbacks-are largely driven by atmospheric processes and dynamical ocean-atmosphere feedbacks, including local and remote wind forcing, which are influenced by the anomaly coupling.

An additional caveat relates to uncertainties in our spectral and time series analyses. In the results presented in section 4, we compare observed temperature records from a 50-yr period (1960–2009) with the mean spectrum of ten 50-yr time slices of model output corresponding to equilibrium preindustrial conditions. We chose to use 50-yr time slices because the length is consistent with our observation-based product. However, we also consider multiple time slices in our calibration method because it provides a more robust ENSO metric in the model. In other words, a single 50-yr time series in not of sufficient length to obtain a robust model representation of ENSO behavior, given internal



FIG. 11. Longitude–time plots of monthly anomalies of (a) surface air temperature and (b) anomalies of the 20°C isotherm depth, for 15 years of model output from the calibrated version of LOVECLIM. The figures highlight two distinct El Niño–like events occurring in years 3 and 9 of the model simulation and illustrate the lagged relationship between Niño-3 surface temperature anomalies and the thermocline adjustment in the equatorial Pacific.

variability within the model (e.g., Wittenberg 2009; Ault et al. 2013) and interdecadal/intercentennial variability of ENSO behavior (e.g., Cane 2005; Mann et al. 2005). The sensitivity of the Niño-3 spectrum used in calibrating the model varies considerably between 50-yr time slices (Fig. 15). While the location of the spectral peak is robust, the variance is sensitive to the choice of the averaging interval within the run. Thus, the data-model calibration may result in a different optimal combination of anomaly coupling parameters when analyzing different 50-yr intervals. We consider multiple 50-yr intervals in calibrating the model, but we consider only a single 50-yr interval of observations, and the robustness of this record over longer intervals is not clear. The methodology presented here does not necessarily assume that the ENSO statistics derived from ocean reanalysis data over the past 50 years are indicative of millennial-scale ENSO behavior.



FIG. 12. (left) Scatterplots of monthly Niño-3 heat flux anomalies and monthly Niño-3 surface air temperature anomalies for the (top) standard and (bottom) calibrated versions of LOVECLIM (based on 500 years of equilibrated model output). The slope of the linear regression defines the negative heat flux feedback (α). (right) Scatterplots of monthly Niño-4 zonal wind stress anomalies and monthly Niño-3 surface air temperature anomalies for the (top) standard and (bottom) calibrated versions of LOVECLIM. The slope of the linear regression defines the positive Bjerknes feedback (μ). Values of the feedbacks (regression slopes) and correlations (r) are listed on each plot.

The calibration methodology and parameter values are selected primarily for the purposes of the analysis shown here, and the main goal of this paper is to highlight the improved representation of ENSO-like variability in a reduced complexity climate model. However, the parameter optimization may become physically meaningful in a formal data–model assimilation experiment, in which case a careful consideration of spectral uncertainties would be necessary. These uncertainties could be reduced by 1) using a longer observational time series for calibration, 2) refining the calibration technique to consider spectra from multiple averaging periods during the data assimilation process through the use of a probabilistic representation of the observational constraints, and/ or 3) using transient forcing conditions that are consistent between the model and observations.

The negative skewness in Niño-3 surface temperature in the calibrated version LOVECLIM provides an additional caveat. It is a robust feature of the anomaly coupling ensemble presented here, and the bias increases with ENSO amplitude. Reducing this bias is important for analyzing ENSO behavior in the context of climate change, and we are exploring methods to minimize (or perhaps even reverse) the skewness in larger perturbed physics ensembles.



FIG. 13. Correlation between monthly zonal wind stress anomalies and monthly surface air temperature anomalies, averaged between 5°S and 5°N, for ERA-40 from 1961 to 2000 (dashed black curve) and the calibrated (red curve) and standard (blue curve) versions of LOVECLIM.

7. Conclusions

We present a modified version of the LOVECLIM climate model that improves the representation of tropical Pacific coupled ocean–atmosphere dynamics and, accordingly, the performance of the resulting interannual variability in tropical Pacific surface temperature. These modifications include a new empirical diagnostic cloud scheme and an anomaly coupling technique that amplifies diabatic atmospheric forcing at the surface in the equatorial tropical Pacific. We find that the modifications improve the representation of the large-scale temperature

patterns and variability in the tropical Pacific. When the anomaly coupling is calibrated to observations, the model generally reproduces the characteristics of the observed spectrum of Niño-3 surface temperature variability (frequency range and variance). Furthermore, sensitivity analysis of the anomaly coupling parameterizations provides some insights to the model's representation of multiple ocean-atmosphere mechanisms important for understanding the underlying ENSO physics, such as the recharge-discharge mechanism, the positive Bjerknes feedback, and the negative heat flux feedback. Overall, the calibrated LOVECLIM robustly reproduces some observed ENSO characteristics. However, it also exhibits weak ocean-atmosphere coupling, and, as a result, the ENSO-like variability is largely an atmospheric phenomenon. The calibrated model compares well with more comprehensive state-of-the-art CMIP5 models in simulating the observed Niño-3 spectrum of surface temperature anomalies, while it still exhibits biases in Niño-3 skewness and limitations in simulating a realistic seasonal cycle of tropical Pacific surface temperature. Specifically, the simulated Niño-3 surface temperature time series is negatively skewed, while the observed time series is positively skewed, and the magnitude is twice that of the observations. Further, the simulated annual cycle of tropical surface temperature does not capture zonal asymmetries and incorrectly exhibits a biannual cycle in the central-to-eastern Pacific regions. Given the reduced complexity and tractability of LOVECLIM, the results shown here highlight the usefulness of the model for research efforts focusing on assimilation of tropical



FIG. 14. Scatterplots of the standard deviations of monthly Niño-3 surface air temperature anomalies and (a) the Bjerknes feedback (μ) and (b) heat flux feedback (α) for the entire LOVECLIM anomaly coupling ensemble. Each point in (a) and (b) represents a different ensemble member corresponding to a unique combination of anomaly coupling parameters.



FIG. 15. Power spectra of monthly-mean surface temperature anomalies averaged over the Niño-3 region for the calibrated version of LOVECLIM. The black curve represents the observational product using the ORA-S3 (1960–2009), as shown in Fig. 4a. The gray shading highlights the range of the spectra calculated from 10 different 50-yr intervals of the calibrated LOVECLIM model. The red curve denotes the mean of the 10 different spectra (consistent with the calibration shown in Fig. 4).

Pacific paleo-information, parameter estimation, and uncertainty quantification.

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