

UNDERSTANDING EL NIÑO IN OCEAN–ATMOSPHERE GENERAL CIRCULATION MODELS

Progress and Challenges

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New community strategies to improve understanding and modeling of El Niño in state-of-the-art climate models provide opportunities for more accurate tropical climate predictions.

The term *El Niño* was originally used to denote the annual occurrence of a warm ocean current that flows southward along the west coast of Peru and Ecuador around Christmas. The term is now used to

refer to the basin-scale warming in the tropical Pacific Ocean that takes place at intervals of 2–7 yr and alternates with an opposite cold phase, called *La Niña*. The atmospheric manifestation of El Niño is the Southern Oscillation—a large-scale tropical east–west seesaw in southern Pacific sea level surface pressure. Hence, the phenomenon is now often called El Niño–Southern Oscillation (ENSO). Although ENSO originates in the tropical Pacific, it affects global climate and weather events such as drought/flooding and tropical storms. Therefore, understanding and predicting ENSO are crucial to both the scientific community and the public (McPhaden et al. 2006).

The theoretical explanations of ENSO can be loosely grouped into two frameworks (Wang and Picaut 2004). In one framework, ENSO is a self-sustained and naturally oscillatory mode of the coupled ocean–atmosphere system. In the second, ENSO is a damped mode externally sustained by atmospheric random “noise” forcing. There are arguments to support both perspectives, and there are studies that suggest that the system may alternate between multidecadal epochs of more damped

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The abstract for this article can be found in this issue, following the table of contents.

DOI:10.1175/2008BAMS2387.1

In final form 23 July 2008
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versus more freely oscillating dynamics (Fedorov and Philander 2000). In addition, El Niño involves interactions extending through different time scales with various climate phenomena, such as the seasonal cycle, intraseasonal oscillations, or decadal oscillations. For example, ENSO is more sensitive to wind perturbations in spring and autumn but less so in summer and winter (Burgers et al. 2005). Despite past efforts at reconciling early coarse-grid coupled model simulations of ENSO phenomena with theory and observations (Neelin 1991), as well as a number of recent theoretical, observational, and modeling efforts to more fully understand ENSO, many intertwined issues regarding its dynamics, impacts, and predictability remain unresolved.

We here report on advances made in recent years in modeling ENSO in coupled general circulation models (CGCMs), the challenges that lie ahead, and the related current scientific debate. The material presented draws on chapters 8 and 10 of the fourth

assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC; Meehl et al. 2007b), as well as on community discussions initiated during the ENSO in IPCC AR4 meeting held in May 2006 in Paris, France (http://ncas-climate.nerc.ac.uk/~ericg/Projects/ipcc_ens0_06.html), and continued at the Third Working Group on Numerical Experimentation (WGNE) Workshop on Systematic Errors in Climate and Numerical Weather Prediction Models held in San Francisco, California, in February 2007 (<http://www.pcmdi.llnl.gov/wgne2007>).

CURRENT MODEL PERFORMANCE. During the last decades, there has been steady progress in the simulation and seasonal prediction of ENSO and its global impacts using CGCMs (Delecluse et al. 1998; Latif et al. 2001; Davey et al. 2001; AchutaRao and Sperber 2002; Randall et al. 2007). More recently, the parameterized physics have become more comprehensive, the horizontal and vertical

TROPICAL PACIFIC MEAN STATE AND ANNUAL CYCLE PERFORMANCE IN CGCMS

Simulating the time-mean properties in the tropics has continually been a challenge for coupled GCMs. Though most models can internally generate the fundamental mechanisms that drive El Niño properties, most models simulate a mean zonal equatorial wind stress that is too strong and that has an annual amplitude that is also too strong (Fig. 1; see also Guilyardi 2006; Lin 2007a). This has profound effects on ENSO behavior in that it limits the regimes in which interannual anomalies can develop. Indeed, several studies have shown that a large amplitude of the seasonal cycle usually implies a weak El Niño, and vice versa (Fedorov and Philander 2001; Guilyardi 2006). Similarly, the meridional extent of the wind variability, of importance for ENSO phase change, is too confined near the equator (Zelle et al. 2005; Capotondi et al. 2006; Capotondi 2008). The “double Intertropical Convergence Zone (ITCZ)” problem, in which a symmetrization of the circulation across the equator leads to a spurious Southern Hemisphere ITCZ and is associated with excessive precipitation over much of the tropics, remains a major source of model error in simulating the annual cycle in the tropics (Lin 2007a), and it can ultimately impact the fidelity of the simulated El Niño (Guilyardi et al. 2003; Sun et al. 2009). Similarly, there are still large differences in how the models reproduce the mean state of the tropical ocean, including the mean thermocline depth and slope along the equator (Fig. 2) and the structure of the

equatorial currents (Brown and Fedorov 2008). Along the equator in the Pacific, the models have difficulty capturing the correct intensity and spatial structure of the East Pacific cold tongue. Often, the simulated cold tongue is too equatorially confined, extends too far to the west and is too cold (see Fig. 4 of Reichler and Kim 2008). These recurrent biases, already present in CMIPI 15 yr ago, arise from numerous fac-

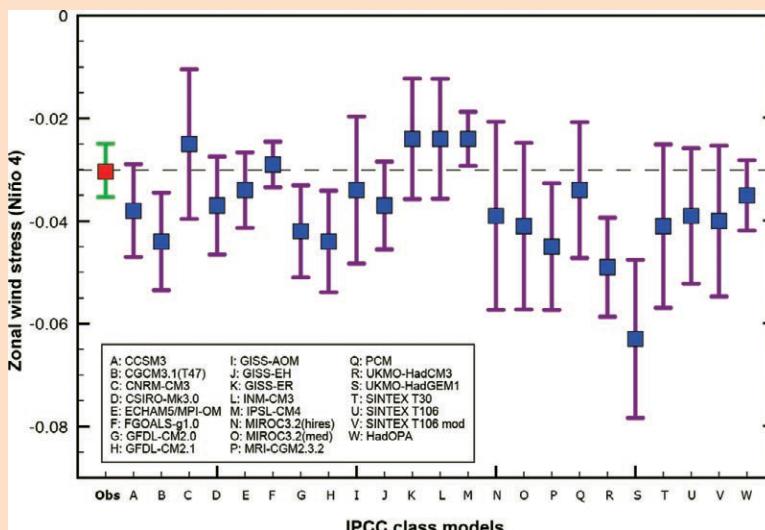


FIG. 1. Mean zonal wind stress (squares) and annual cycle amplitude (bars) in the central-western Pacific (Niño-4 region; see Fig. 4) for the 20th-century simulations of the IPCC AR4. (left) Observations are taken from the 40-yr European Centre for Medium-Range Weather Forecasts (ECWMF) Re-Anlysis (ERA40) [1950–2000 average is -0.03 N m^{-2}]. Units are N m^{-2} .

resolutions have increased (Guilyardi et al. 2004; Roberts et al. 2009), and the application of ocean observations in initializing seasonal forecasts has become more sophisticated (Alves et al. 2004). These improvements in model formulation have led to a better representation of the spatial pattern of the sea surface temperature (SST) anomalies in the eastern Pacific and of ENSO's periodicity (AchutaRao and Sperber 2006). Compared to previous generation models, some of the third coupled model intercomparison project (CMIP3) models used for the fourth assessment report (AR4) of the IPCC (Randall et al. 2007; Meehl et al. 2007a) can now simulate not only the mean state and the annual cycle with some degree of fidelity but also the tropical interannual variability, without the use of the flux corrections—an artificial adjustment to correct model biases and used in earlier generations of CGCMs. Indeed, many CGCMs now exhibit a behavior that is qualitatively similar to that of the real-world ENSO, which is a

considerable achievement given the complexity of the interactions involved.

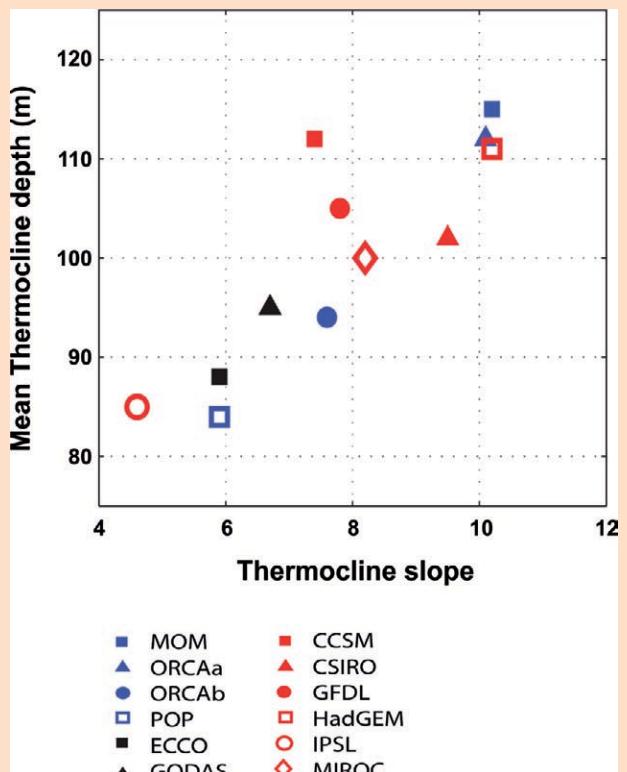
Despite this progress, recent multimodel analyses show that serious systematic errors in the simulated background climate (time mean and annual cycle; see the sidebar “Tropical Pacific mean state and annual cycle performance in CGCMs” below for more information) as well as in the simulated natural variability persist (van Oldenborgh et al. 2005; Guilyardi 2006; Capotondi et al. 2006; Wittenberg et al. 2006). Several studies pointed out that these coupled model errors can often be traced to the atmosphere component (Braconnot et al. 2007; L’Ecuyer and Stephens 2007; Sun et al. 2009).

Coupled GCMs produce a variety of El Niño variability time scales (Fig. 3): model spectra range from very regular near-biennial oscillations to spectra that are close to the observed 2–7 yr. The observed seasonal phase locking—El Niño and La Niña anomalies tend to peak in boreal winter and are weakest

tors including overly strong trade winds, leading to increased cooling via oceanic upwelling, mixing, and latent heat flux to the atmosphere; a diffuse thermocline structure, leading to improper sensitivity of SST to anomalous upwelling and vertical mixing; insufficient surface and penetrating solar radiation, and weak ocean vertical mixing in the subtropics, leading to subsurface temperature errors along the equator; and weak tropical instability waves, resulting in too little meridional spreading of SST anomalies during cold events (Meehl et al. 2001; Luo et al. 2005; Wittenberg et al. 2006; Lin 2007a). There are also errors in the tropical Pacific seasonal cycle, both in SST and wind: many models exhibit an overly strong seasonal cycle in the east Pacific (Fig. 1) and/or a spurious semiannual cycle, possibly tied to the lack of sufficient meridional asymmetry in the background state (Li and Philander 1996; Guilyardi 2006; Timmermann et al. 2007) and/or errors in the water vapor feedbacks (Wu et al. 2008). The lack of marine stratocumulus clouds in the eastern part of the tropical Pacific is still a major issue in CGCMs (Lin 2007a) and, associated with a too weak coastal upwelling along the coast of Peru and Chili, leads to a

warm bias in these regions. Nevertheless, the CMIP3 models show a clear improvement over previous generation models, as shown in AchutaRao and Sperber (2006) and Reichler and Kim (2008).

FIG. 2. Mean depth of the equatorial thermocline and mean thermocline slope along the equator as simulated in a number of ocean-only models (blue), data assimilation models (black), and coupled models (red). The thermocline slope is defined as the normalized difference between thermocline depth at 180° and 100°W, where an appropriate isopycnal surface was chosen for each individual model. The thermocline depth corresponds to maximum vertical density gradient along the equator. Note the large differences in the mean thermocline depth and, especially, thermocline slope in the models. After Brown and Fedorov (2008).



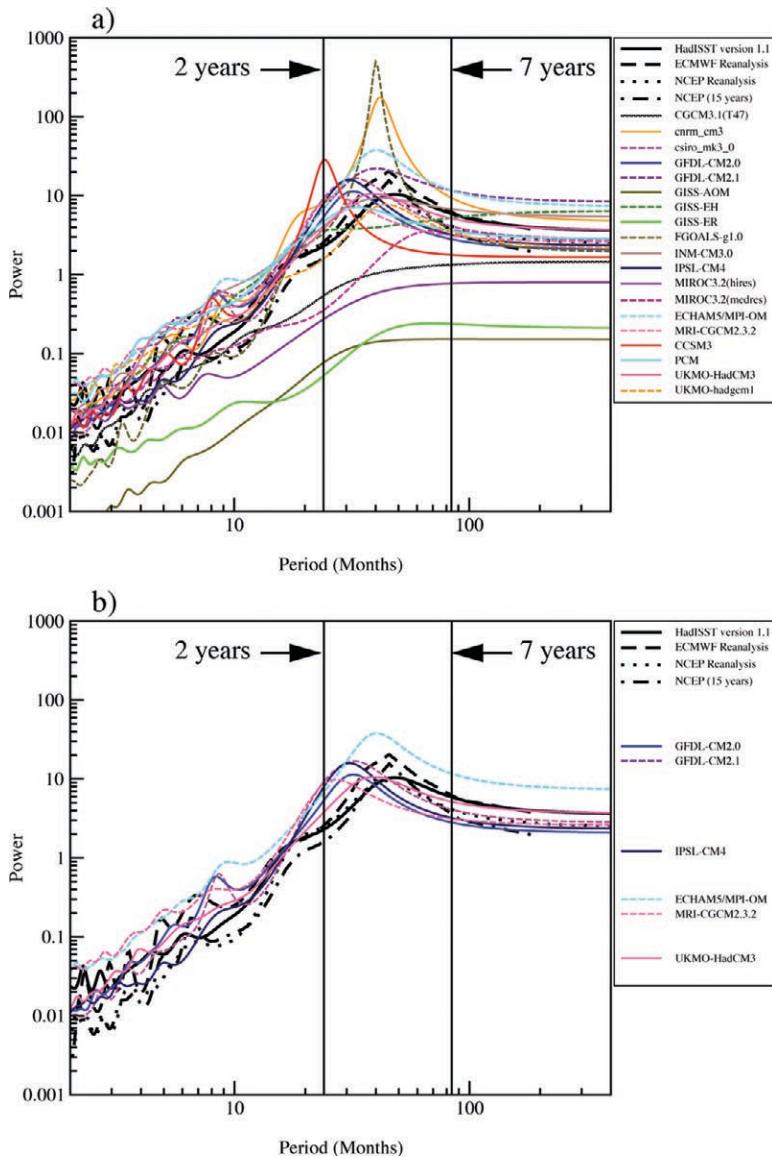


FIG. 3. Niño-3 SST anomaly spectra for IPCC AR4 models in preindustrial conditions. (a) Original figure from AchutaRao and Sperber (2006); (b) “eye-ball” selection of six closest to observed (note that MRI is the only flux-adjusted of the six).

in boreal spring—is often not captured by models, which either show little seasonal modulation or a phase locking to the wrong part of the annual cycle, although some models do show some tendency to have ENSO peaking in boreal winter (not shown). All of these biases combine to generate errors in ENSO amplitude, period, irregularity, skewness, or spatial patterns (Fig. 4).

Even though CGCMs have common biases, they still exhibit a diversity of El Niño behavior that is well beyond the observed diversity of events. For instance, the modeled amplitude of El Niño ranges from less than half to more than double the ob-

served amplitude (van Oldenborgh et al. 2005; AchutaRao and Sperber 2006; Guilyardi 2006; Fig. 5). The complex interactions of the main biases described above (and with a number of likely others as discussed below) together with model structural diversity still make it difficult to clearly identify the origin of deficiencies in simulated ENSO. Nevertheless, it is likely that progress can be made. CGCMs do appear now to exhibit many of the key processes and interactions thought to control ENSO in the real world.

ENSO FEEDBACKS. Theory has established that ENSO results from the interaction of a number of feedbacks, either amplifying or damping the associated interannual anomalies (Wang and Picaut 2004). ENSO involves the positive ocean-atmosphere feedback of Bjerknes (1969) that culminates with warm or cold SST anomalies in the equatorial eastern and central Pacific. Once an event is under way, negative feedbacks are also required to terminate the growth of warm or cold SST anomalies. Theoretical work on ENSO during the past decades has proposed four major negative feedbacks: wave reflection at the ocean western boundary (Suarez and Schopf 1988; Battisti and Hirst 1989), a discharge process resulting from Sverdrup transport (Jin 1997), a western Pacific wind-forced Kelvin wave of opposite sign (Weisberg

and Wang 1997), and anomalous zonal advection (Picaut et al. 1997). These negative feedbacks may work in varying combinations to terminate El Niño or La Niña (Wang 2001).

Starting from the linearized SST equation, Jin et al. (2006) derived a coupled stability index (referred to the BJ index) that details ocean-atmosphere feedbacks. They identified five different feedbacks: the mean advection and upwelling feedback (always negative), the thermal damping rate (resulting from surface heat fluxes and also negative), the zonal advection feedback (positive), the Ekman pumping feedback (positive), and the thermocline feedback

(positive) (for details, see Burgers et al. 2005; Jin et al. 2006). Hence, El Niño and La Niña will develop only if the sum of these feedbacks is positive or if the system is constantly forced by external perturbations. To the extent that this theoretical framework also applies to complex models, evaluating these feedbacks in CGCMs may help to illuminate the sources of errors. For instance, most models underestimate the thermocline feedback, that is, the effect of thermocline depth variations on SST (van Oldenborgh et al. 2005), as well as the air–sea

coupling strength (involved in the Bjerknes feedback), which measures the wind response to SST anomalies (Guilyardi 2006) and is a main contributor to the last three positive feedbacks of the BJ index. This is compensated for by too little thermal damping, mainly resulting from reduced cloud-shading feedback (Philip and van Oldenborgh 2006; Sun et al. 2009).

NONLINEARITIES AND THE ROLE OF TROPICAL MULTISCALE INTERACTIONS.

ENSO cannot be viewed in isolation of other space and time scales in the tropical Pacific. A body of recent studies strongly suggests that El Niño also interacts with higher-frequency processes (like intraseasonal oscillations; Kessler 2002; Fedorov 2002; Fedorov et al. 2003; Lengaigne et al. 2004a,b) and with the mean state and seasonal cycle of the tropical Pacific (Jin et al. 1994; Tziperman et al. 1994, 1997; Guilyardi 2006). CGCMs have a number of biases in these other space and time scales that can impede on the fidelity of the modeled ENSO (see Lin et al. 2006). Nonlinear processes are required to transfer energy between fluctuations at different space and time scales. The main nonlinear processes relevant to ENSO and highlighted by the above studies include atmospheric

convection, evaporation and cloud feedbacks, wind response to SST anomalies, zonal advection, and thermocline–surface coupling. Nonlinearity can also arise from the small-scale coupling between the ocean and the atmosphere, like tropical instability waves (TIW) in the east Pacific (Pezzi et al. 2004; Jochum and Murtugudde 2006; An 2008a; Norton et al. 2009). In models with high enough ocean resolution to permit such waves (and other small ocean structures, like equatorial and eastern boundary upwelling or western boundary currents) there is evidence that the resolution of the atmosphere numerical grid also

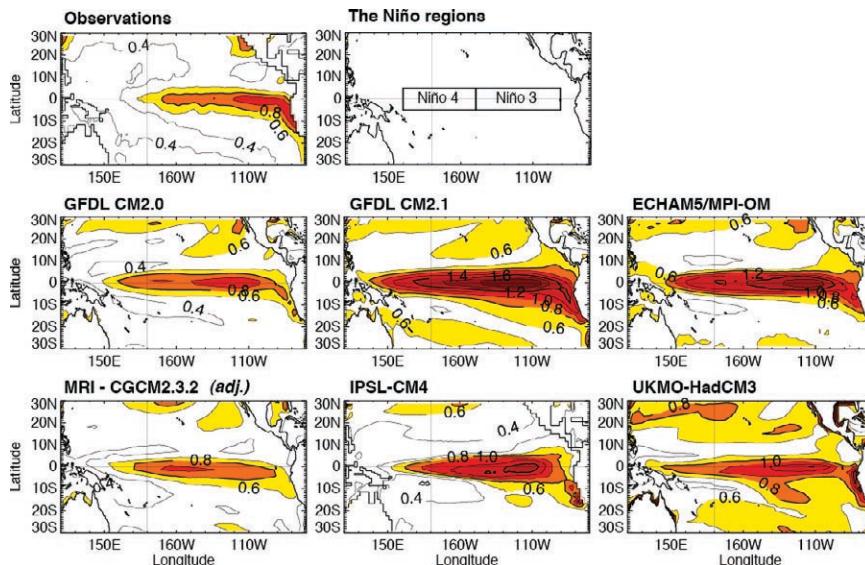


FIG. 4. SST std dev ($^{\circ}\text{C}$) for 100 yr of monthly data for models in Fig. 3b. Observations are taken from HadISST1.1 (1900–99). The location of the Niño regions discussed in the text is also shown.

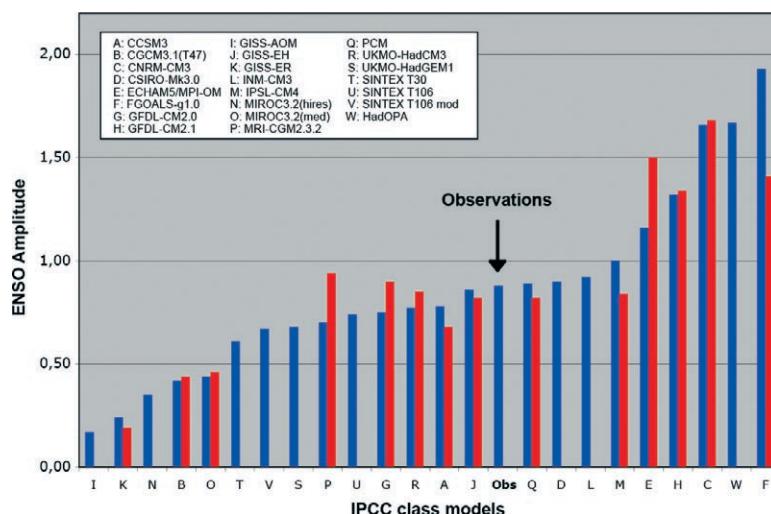


FIG. 5. ENSO amplitude in 23 coupled CGCMs, including those used for the IPCC AR4, as measured by the Niño-3 SST anomaly std dev in preindustrial simulations (blue bars) and equilibrated $2 \times \text{CO}_2$ scenarios (red bars).

needs to be increased to resolve the coupling of these small ocean features, which have sizes typically less than 100 km (i.e., 1°). This may partly explain the improved simulation of ENSO when the atmosphere numerical grid reaches this resolution (Guilyardi et al. 2004; Roberts et al. 2009).

Nonlinear interactions have further been proposed to explain the observed positive skewness of ENSO, that is, the fact the El Niño events have a larger amplitude than La Niña situations (Burgers and Stephenson 1999; Hannachi et al. 2003; An and Jin 2004; Monahan and Dai 2004), a property that can also evolve at decadal time scales (An 2008b). Several studies have looked into reproducing the observed skewness in simple ENSO models (Lin and Derome 2004; An et al. 2005a,b; Philip and van Oldenborgh 2009) and analyzing it in CGCMs (Hannachi et al. 2003; van Oldenborgh et al. 2005; Yeh and Kirtman 2007). Unlike observations, most GCMs exhibit a linear ENSO, with SST skewness near zero in the tropical Pacific (Hannachi et al. 2001; van Oldenborgh et al. 2005). This could conceivably render them less sensitive than the real world to changes in climate, even though other studies attribute the positive skewness of ENSO to sources other than nonlinearity such as the superposition of ENSO, decadal variations, or global warming trends (Lau and Weng 1999).

ATMOSPHERE MODEL BIASES VERSUS OCEAN MODEL BIASES. A common theme emerging from CGCM studies is the role of atmospheric dynamics and feedbacks in determining model El Niño characteristics. Mechanistic models tend to parameterize the atmospheric component of El Niño in terms of simple concepts, such as a constant value for the coupling strength or for the surface heat flux damping of SST anomalies. Yet, studies such as Schneider (2002), Guilyardi et al. (2004), and Toniazzo et al. (2008) have revealed a strong diversity of behavior in models in which either atmospheric models or even just the parameters in a single atmospheric model are varied. The ocean GCMs typically used in IPCC-class CGCMs also play a role in ENSO systematic errors (e.g., the representation of turbulent mixing remains a major challenge and strongly influences thermocline properties) but appear to play a lesser role than atmospheric GCMs (Guilyardi et al. 2004). Nevertheless, simulations similar to those reported in Toniazzo et al. (2008), but in which ocean rather than atmosphere parameters are varied in the HadCM3 model, do show variations in ENSO behavior.

Whether further improvements in ENSO simulation with CGCMs depends more on improving the atmospheric or the oceanic component of CGCMs will be answered over time. Properties of atmospheric GCMs appear to be critical, perhaps because their sensitivity, complexity, and nonlinearity can produce larger biases that impose limitations on ENSO properties and feedbacks. For example, Lin (2007a) has shown that several shortcomings of the coupled CMIP3 models stemmed from the atmosphere component of these models. In view of the high sensitivity of CGCMs to the atmospheric convection scheme (Kim et al. 2008; Neale et al. 2008, Guilyardi et al. 2009, manuscript submitted to *J. Climate*), more research is needed on the role of thermodynamical processes and feedbacks. Bony and Dufresne (2005) also analyzed the cloud radiative feedbacks in convection/subsidence dynamical regimes in the CMIP3 models and concluded that the simulation of marine boundary layer clouds is at the heart of tropical cloud feedback uncertainties in current CGCMs. These marine boundary layer clouds occur in the eastern tropical Pacific, a key region for El Niño amplification, and biases in their representation can also contribute to the simulated ENSO diversity.

ENSO IN A CHANGING CLIMATE. Most (but not all) IPCC AR4 models are qualitatively consistent in their projections of *mean* changes over the tropical Pacific. The SST warms more along the equator than off the equator, and a reduced east–west SST gradient (Fig. 6) is associated with a weakened Walker circulation and reduced trade winds (Hansen et al. 2006; Fedorov et al. 2006; Vecchi et al. 2006, 2008). Such changes in the mean state can influence the ENSO-related processes and feedbacks and have the potential to modify ENSO properties. For example, studies show that a more stable ENSO is less sensitive to changes in the background state than when it is closer to instability (Zelle et al. 2005). Atmosphere deep-convection triggering is also highly dependent on the mean SST distribution, and associated heat flux feedbacks may change. Nevertheless, van Oldenborgh et al. (2005) noted that if only the six “best” models for ENSO are considered, the tendency for a reduced mean east–west gradient is much less obvious than if all models are considered.

However, and as seen from Fig. 6 (Fig. 10.16 of the IPCC AR4 report), which displays the ratio of ENSO variability between the current climate and the last 50 yr of the SRES A2 experiments (2051–2100) as a function of the background change, models are inconsistent with respect to their projections of change

in ENSO amplitude (see also van Oldenborgh et al. 2005; Merryfield 2006; Guilyardi 2006), even in very high CO₂ scenarios (Fig. 5). While some models show an increase in ENSO variability in response to greenhouse gas increases, others do not exhibit any detectable change, and still others show a decrease in variability.

Discerning whether any future changes in ENSO amplitude are due to external forcing or are simply due to internal longer-term variation is complicated by significant decadal fluctuations both in observations and in long control integrations (Knutson et al. 1997; AchutaRao and Sperber 2002; Yukimoto and Kitamura 2003; Yeh et al. 2004; Yeh and Kirtman 2004; An et al. 2005; Meehl et al. 2006; Lin 2007b). Nevertheless, changes of ENSO variability, where they can be detected above these large natural variations, are highly model dependent, even if extreme scenarios are analyzed ($4 \times \text{CO}_2$). Hence, even though all models show continued ENSO variability in the future no matter what the change of average background conditions, there is no consistent indication at this time of discernible changes in amplitude or frequency for the twenty-first century (Meehl et al. 2007b). Similarly, large model differences in the skewness of the variability limits the assessment of the future relative strength of El Niño and La Niña events (van Oldenborgh et al. 2005). Because ENSO is the dominant mode of climate variability at interannual time scales, the lack of consistency in the model predictions of the response of ENSO to global warming currently limits our confidence in using these predictions to address adaptive societal concerns, such as regional impacts or extremes (Joseph and Nigam 2006; Power et al. 2006). Nevertheless, paleoevidence that ENSO may have been quite different in the past (e.g., Tudhope et al. 2001; Cobb et al. 2003) indicates the risk that ENSO and the associated teleconnections [see, e.g., Meehl and Teng (2007) on the shift of ENSO teleconnections in North America] might be quite different in the future, a fact also available to those assessing mitigation options.

A better understanding of the sensitivity of ENSO to changes in processes and feedbacks will help explain these differences, possibly leading to more confident projections. For instance, the disagreement among the various IPCC AR4 models regarding future changes in ENSO does not rule out that a subset of models can show a common ENSO response to climate change. Guilyardi (2006) showed that among those models that best reproduced the diversity of the observed ENSO, there was a significant trend toward increased El Niño amplitude in high-CO₂ scenarios.

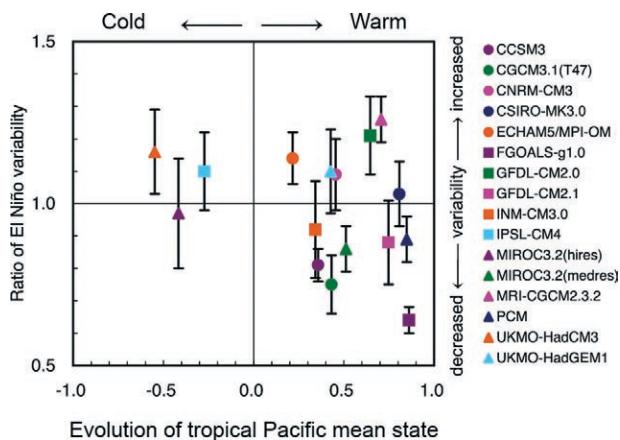


FIG. 6. Mean state change in average tropical Pacific SSTs and change in El Niño variability simulated by AOGCMs (adapted from Meehl et al. 2007b). The mean state change (horizontal axis) is computed over the area 10°S to 10°N, 120°E to 80°W (reproduced from Yamaguchi and Noda 2006). The change in El Niño variability (vertical axis) is denoted by the ratio of the ENSO amplitude between the current climate and the last 50 yr of the SRES A2 experiments (2051–2100), except for FGOALS-g1.0 and MIROC3.2(hires), for which the SRES A1B was used, and UKMO-HadGEM1, for which the 1% yr⁻¹ CO₂ increase climate change experiment was used, in the region 30°S to 30°N, 30°E to 60°W (reproduced from van Oldenborgh et al. 2005). Error bars indicate the 95% confidence interval.

Hence, to improve decadal-to-centennial projections, process and feedback diagnostics are needed to limit the subset of models to those that are more consistent with the real world. Even if models do not predict significant changes in El Niño statistics in the future (e.g., either amplitude or frequency), the relative balance of feedbacks and teleconnections (and the associated impacts) during ENSO could evolve (Philip and van Oldenborgh 2006), perhaps altering ENSO predictability.

The characteristics of ENSO in past climates, as provided by paleoclimate records and coupled model simulations, can also help constrain models for future climate changes [see Chen et al. (2004), Zheng et al. (2008), and Brown et al. (2007), who address the mid-Holocene ENSO weakening as a test of a coupled model]. For instance, recently obtained temperature records (derived from tropical deep-sea cores) suggest that in the early Pliocene, approximately 3–5 million years ago, the tropics were characterized by a persistent warm state similar to the peak of El Niño (Fedorov et al. 2006). During this time interval, and possibly before, the proxy data may be interpreted as showing a significantly reduced or virtually non-existent zonal SST gradient along the equator with

therefore no possibility for ENSO development. The climate of the early Pliocene can be considered as a partial analog to the contemporary global warming, because external factors that control climate were similar to what they are today. The current generation of climate models do not simulate a persistent warm state even when forced with concentrations of carbon dioxide an order of magnitude larger than the current values (e.g., Haywood et al. 2007). If the paleodata available at present are indeed representative of such a state, then problems in the ability of models to simulate perennial warm conditions could indicate deficiencies in the models. More study is needed on both the modeling and observational aspects.

Finally, there are additional new questions on the horizon as full Earth system models mature: How might ENSO's impact on fires, dust, ecosystems, agriculture, and fisheries change in the future? How might evolving ocean chlorophyll concentrations affect oceanic solar penetration (Timmerman and Jin 2002; Lengaigne et al. 2007), the equatorial thermocline, and SST through the ENSO cycle and in response to climate change? Might the ENSO-CO₂ cycle help to constrain global carbon-cycle feedbacks? Making progress on these issues first requires a better understanding of the physical and dynamical properties of ENSO in CGCMs.

WHAT OBSERVATIONS DO ENSO MODELERS NEED? Until the observed relationships describing the ENSO feedbacks are better constrained, modelers will continue to struggle to get the right balance of processes for ENSO. This points to a key need of the modeling community: a sustained, multidecadal global climate observing system for both the upper ocean and lower atmosphere, with attention given to maintaining continuity and diversity of observations. The key variables that must be constrained include the SST, precipitation and atmospheric convection, surface fluxes (wind stress, air-sea heat flux), subsurface thermal and haline structure of the upper ocean, and upper ocean currents. A sample of some leading ENSO-relevant observational products is given in Wittenberg et al. (2006). In addition, observations of chemical and biological variables will be required as Earth system models mature.

Investment in the future observing system is essential for continued progress in modeling for coming decades. However, to address the deficiencies of today's models, we cannot afford to wait for future observations. To sample the real-world natural variability of ENSO and its response to slow changes in

climate, it is also essential to 1) continually reanalyze existing observations using state-of-the-art atmospheric, oceanic, and coupled models, to ensure that the best observational guidance is available to modelers in a convenient form; 2) recover missing historical observations, as in the Global Oceanographic Data Archaeology and Rescue Project (GODAR; www.nodc.noaa.gov/General/NODC-dataexch/NODC-godar.html); and 3) develop merged paleoclimate records, based on corals and other proxies, which have been verified against the historical record and extended as far as possible into the deep past. For all of these efforts, it is essential to produce not only the best estimate of the observed quantity but also a realistic representation of the associated uncertainty.

Process-oriented, regional-scale observational field campaigns (such as SPICE; www.ird.nc/UR65/SPICE/, or VOCALS; www.eol.ucar.edu/projects/vocals/) are needed because they will undoubtedly fuel model improvements in the long term. But the lack of historical long-term, sustained, basin-scale, high-quality observations [in contrast to today's Tropical Atmosphere Ocean Triangle Trans-Ocean Buoy Network (TAO/TRITON) Project (www.pmel.noaa.gov/toa/); McPhaden et al. (1998) and Research Moored Array for African-Asian-Australian Monsoon (RAMA) moorings (McPhaden et al. 2009), Argo automatic floats (www.argo.ucsd.edu), Jason altimetry (<http://topex-www.jpl.nasa.gov/>), and the A-Train constellation of satellites (Stephens et al. 2002)] to constrain models is perhaps the biggest impediment to winnowing the wide variety of ENSO simulations among today's CGCMs.

THE CASE FOR NEW ENSO MODELING STRATEGIES. How good do ENSO models need to be? Indeed, the question that scientists face in making climate projections or predictions is one of model credibility (see, e.g., Räisänen 2007). In many prediction problems, seasonal climate forecasting of El Niño being a prime example, it is possible to verify predictions after the fact. This becomes practically very difficult in the case of the ENSO response to climate change, as the signal-to-noise ratio is very small because of strong interannual (and decadal) variability. Nor can scientists and policymakers wait until the climate change has already occurred for verification scores. Thus, an "expert assessment" is usually required, based on a model's ability to reproduce aspects of present-day and/or past conditions. New modeling strategies to provide such assessments can now be envisioned, thanks to the rise of multimodel ensembles and the use of seasonal forecast techniques.

A multimodel ensemble allows both an assessment of the consistency of the predictions of different models and an overall (probabilistic) forecast to be made, taking into account the spread of the model predictions. Multimodel ensembles of seasonal forecasts or projections almost always outperform the best models' skill (Palmer et al. 2004; Rahmstorf et al. 2007). A major factor in this is that the multimodel ensemble samples some of the model formulation uncertainty, which as described above is quite large for ENSO. When it comes to predicting the evolution of ENSO for a specific year, this "averaging out" of model error can be quite effective, perhaps because the impact of a particular model's errors is in many situations equally likely to lead to an over- or underestimate of the actual SST. For statements on the expected future increase/decrease of ENSO variability, however, there seems no reason to trust the "average" answer as being close to the truth. Indeed, given the evident sensitivity of the results and the imperfections of even the best models, we cannot be confident that the outcome will even lie within the range predicted by today's models. Coordinated multimodel experiments [using several CGCMs as for the CMIP3 database or the same model with varying parameters as in Toniazzo et al. (2008)] do however allow the exploration of common sensitivities—or lack thereof. For this reason, maintaining a diversity of models (both within the IPCC class and through the complexity hierarchy of toy models, intermediate models, and hybrid statistical/dynamical models) is very important.

Seasonal forecasts can also provide a powerful test for IPCC-class CGCMs (Palmer et al. 2008). The classical analysis of ENSO in IPCC integrations (either basic statistics or more advanced evaluation of feedbacks) usually concentrates on the long (at least multidecadal) time series statistics needed to compute robust signals. Yet, this strategy cannot fully explain how the model's errors (in the mean state but also in the feedbacks) were generated in the first place. This is an issue because the initial model errors result in a balance (a new mean state and annual cycle) that then becomes difficult to link to particular model deficiencies (such as arising from model parameterizations). Hence, there is a need for an experimental framework that would focus on the initial adjustment of these models. Such a framework can be provided by the seasonal forecast approach.

We here encourage the use of such an approach to initialize the ocean and atmosphere state of a coupled model as close as possible to the observed state and launch "forecasts" of several months (up to a year) at regular intervals during the recent

"well-observed" decades. These simulations can provide rich diagnostic possibilities, to see how (and sometimes why) coupled errors develop in the tropics, in the context of detailed observations. For instance, they provide a good configuration to look at cloud–convection–radiation–SST interactions, in conditions specific to a given year, allowing detailed comparison with observations such as satellite data. In an era in which model errors are very large, then comparison of any short-term integration with an observed "climatology" would show the large errors adequately, regardless of which years were chosen for comparison. However, as short-term coupled model errors become comparable to observed interannual variability, proper referencing of the model integrations to specific observed years becomes important to make further progress.

By carefully analyzing the models' departure from the observed state, one should be able to more precisely identify the parameterization(s) responsible for any drift. For example, if a forecast is launched before an observed El Niño event and the model fails to reproduce the event, a careful analysis might show that the surface heat flux damping feedbacks were too strong in the model to allow the event to develop, or if the event has a too weak amplitude, that the wind response to the SST anomaly was too confined near the equator or that the ocean dissipation was too strong to sustain intraseasonal signals (Woolnough et al. 2007).

Such simulations are computationally cheap to perform and allow more possibilities for testing than do multicentury simulations. For instance, an experiment using 6-month hindcasts with two starts per year, looking at five different situations (e.g., 1993/1995/1997/1999/2001) and using five-member ensembles requires only 25 yr of integration. A more comprehensive assessment of the seasonal forecast skill of a climate model can be made via participation in the Climate-system Historical Forecast Project (CHFP; www.clivar.org/organization/wgsip/chfp/chfp.php) organized by the CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP) for the World Climate Research Program (WCRP).

There are still several questions in the setup of these simulations that will need to be addressed, like initialization or drift interpretation. A simple initialization has to be proposed for the IPCC groups that do not have an ocean data assimilation system in place. One possibility is to "nudge" a coupled simulation with observed wind stress and/or SST (Keenlyside et al. 2005; Luo et al. 2008). Recent work has shown that just nudging the wind stress in a coupled model allows a good representation of the interannual SST

Nino-3.4 SST index
(band-pass filter: 17.5 mths - 7.3 yrs)

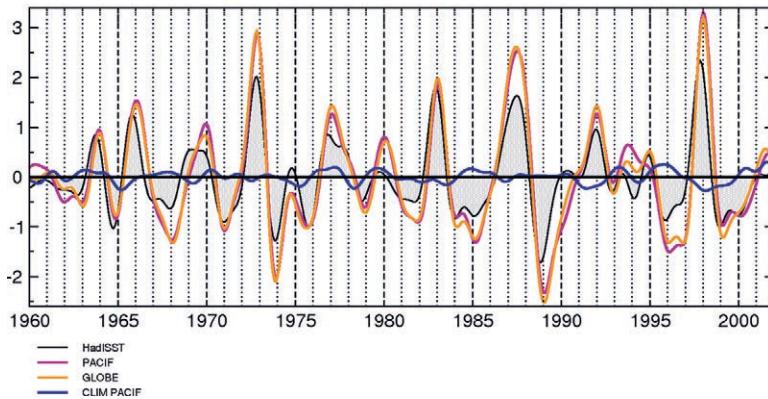


FIG. 7. Evolution of the Niño-3.4 (170°W–110°W, 5°N–5°S) interannual SST anomaly for the HadISST1.1 observations (black), a simulation in which the tropical ERA-40 wind stress has been nudged into the CNRM-CM3 IPCC coupled model (pink), a similar simulation with a global nudging of the wind stress (orange) and a simulation with imposed ERA-40 climatology (blue). After Joly and Voltaire (2009).

(Fig. 7; Joly et al. 2009). Nevertheless, even if a model could produce a completely accurate prediction of ENSO (within the constraints of chaotic error growth), this is not a sufficient condition for a model to accurately simulate ENSO under climate change. Even if the processes and feedbacks that occur on seasonal time scales do not necessarily form the complete set of climate change processes and feedbacks, improving them in models will reap many benefits.

DEVisING A SUITE OF ENSO METRICS AND DIAGNOSTICS. It is important to assess ENSO characteristics in terms of theoretical/mechanistic understanding of the phenomena, not just looking at local statistics (e.g., Niño-3 SST anomalies)¹, which may have the correct value for the wrong reasons (i.e., as a result of bias compensation). Moreover, multimodel analyses should rely on common diagnostics. The definition of a set of “metrics” to assess a phenomenon can have great value to the wider community engaged in model development and/or analysis. Metrics are now under discussion in preparation for future CMIPs (Gleckler et al. 2008), and the CLIVAR Pacific Panel (www.clivar.org/organization/pacific/pacific.php) is charged with devising metrics for ENSO and for the wider tropical Pacific climate. Here we use the term “metric” as a measure of the “distance” of the model to some observational reference, usually computed as a single scalar

¹ The Niño-3 region spans 5°S–5°N and 150°–90°W in the East Pacific; see Fig. 4.

value (Gleckler et al. 2008) while other more complex or qualitative analyses where observations do not provide an easy reference are called “diagnostics.” The intent is not to reduce evaluation of models to single numbers, except in the specific example of producing likelihood weights in probabilistic prediction [in which case such metrics should test all the relevant physical process involved in the prediction problem, e.g., Collins (2005, 2007)]. Rather, a suite of metrics and diagnostics, which addresses a range of physical processes and impacts of interest to various experts and stakeholders, should be applied.

A first step is to distinguish the metrics from the diagnostics. Metrics require a set of well-observed references and should be concise, physically informative, societally relevant, and easy to understand, compute, and compare. A few examples are given in the “Examples of ENSO-related metrics” sidebar. When summarized by a single scalar, the metrics are amenable to intermodel Taylor (2001) diagrams. The more sophisticated theory-based diagnostics are less easily constrained by observations. Nevertheless, by helping to bridge the gap between our theoretical understanding of ENSO and its representation in CGCMs (Fedorov et al. 2003; Held 2005), this second category holds the most promise in helping scientists to understand the modeled errors in CGCMs, as already demonstrated by several recent studies (Mechoso et al. 2003; Capotondi et al. 2006; Philip and van Oldenborgh 2006; Jin et al. 2006; Fedorov 2007; Dewitte et al. 2007; Brown and Fedorov 2008).

Among the key metrics to measure and constrain with observations are the feedbacks between the ocean and atmosphere, which give rise to ENSO and help govern its behavior. A list of leading concepts from ENSO theory that have guided recent studies could include the wind response to SST anomalies, thermocline and zonal advection feedbacks, wind-coupling strength and pattern, surface heat flux damping, oceanic adjustment delay time, and stochastic forcing. For instance, the coupling strength, which measures the intensity of the Bjerknes (1969) feedback, can be quantified using a linear regression of the wind stress anomaly field onto the Niño-3 SST anomaly index (Guilyardi 2006). Similarly, the damping of SST anomalies by surface heat fluxes can

be assessed by regressing the net heat flux onto the Niño-3 SST anomaly index or, alternatively, onto the colocated SST anomaly (Lin 2007a; Sun et al. 2006, 2009). These can further be assembled in the common framework of the BJ index, which measures the amplification/damping rate of ENSO (Jin et al. 2006). The efficiency of the energy transfer from the winds to the thermocline is another important parameter that can affect the properties of ENSO.

There are two key challenges in devising the right blend of metrics and diagnostics. First, the theoretical understanding of all aspects of ENSO evolution is still incomplete—ENSO is a multimechanism phenomenon and different mechanisms may work in varying combinations to produce and terminate a particular El Niño event (Wang 2001). Second, the difficulty of constraining all the relevant feedbacks with observations, due to the brief, nonstationary, and partial observations of the real world, still exists, despite considerable recent achievements in observational programs. For example, there is large uncertainty among satellite data, in situ measurements, and reanalysis products for feedbacks as basic to ENSO as the ocean–atmosphere coupling strength (Wittenberg 2004) or the cloud radiative feedbacks (Cronin et al. 2006). Nor is it clear how long we must run models and observe nature to get robust statistics for comparison (due to large decadal variations as discussed above), or what metrics are most robust. Hence, an evaluation of the

uncertainties in these metrics and diagnostics has to be included, to prevent assigning large weights to small differences in the performance of models. Nevertheless, given the large errors still exhibited by most current CGCMs, process- and feedback-based metrics and diagnostics do provide an objective way to downweight the results from obviously unrealistic models, and they could help focus modeling effort in improving the realism of ENSO while maintaining a healthy model diversity.

As CGCM developers and users, we envision the ENSO metrics and diagnostics to be presented on a CLIVAR Web site, including pathways to recommended observational datasets [in an easy-to-use gridded format like OPeNDAP (<http://opendap.org>) and following community agreed-upon metadata standards like NetCDF (www.unidata.ucar.edu/software/netcdf) and those developed for the next IPCC, e.g., <http://metaforclimate.eu> or www.earthsystemcurator.org/] and a repository of scripts to generate the diagnostics for the observations and model data as well as “distance” metrics between those diagnostics.

CONCLUSIONS. The IPCC AR4 projections offer a wide range of possibilities regarding what will happen to ENSO in the future. However, there is neither an indication of a complete disappearance of ENSO variability over the next century nor an explosion of

EXAMPLES OF ENSO-RELATED METRICS

The following are a few examples of ENSO metrics:

- Mean and seasonal spatial root-mean-square errors, computed in specific regions (e.g., in the entire tropics, east Pacific, warm pool, equatorial wave guide, etc.) and for key fields: SST, precipitation, wind stress, cloudiness, etc. (see Gleckler et al. 2008).
- For the classical ENSO-related SST time series, averaged in specific regions (Niño-3, Niño-4, . . . the corresponding metrics (in order of increasing sophistication) can be
 - climatological annual mean (a single scalar);
 - climatological annual cycle (12 months), leading to the climatological standard deviation;
 - time series statistics of anomaly standard deviation, skewness, phase locking, and autocorrelation;
 - wavelet decomposition leading to time-mean spectrum and ENSO modulation; and
 - correlation with other time series (e.g., Niño-4 zonal wind stress).
- Warm water volume, which measures the state of the heat recharge in the equatorial Pacific (see Meinem and McPhaden 2001; www.pmel.noaa.gov/tao/elnino/www/).
- Trans-Niño index, lag correlated with Niño-3 SST anomalies, which provides information about the type of El Niño event (Trenberth and Stepaniak 2001).
- Intraseasonal activity as proposed by the MJO CLIVAR Working Group (http://climate.snu.ac.kr/mjo_metrics/index.htm).

The definition of a more complete set of metrics is under way in the CLIVAR Pacific Panel.

large ENSO events. Most of the CMIP3 models can now produce a reasonable climatology and ENSO without flux adjustments, enhancing their physical credibility for simulating ENSO and its response to climate changes. The credibility of these models could be further enhanced by improving the simulations of twentieth-century ENSO statistics and by subjecting the models both to seasonal forecast and paleoclimate tests to assess their ENSO sensitivities. To constrain the physics and behavior of ENSO models, the climate community must

- improve the quality and utility of historical and paleoclimate records;
- maintain the present ENSO observing system into the future;
- continue to freely exchange model output using common formats so that intercomparison studies can be easily performed;
- isolate the main sources of error for the models, guided by theory, observations, and rigorous evaluation of the models, including tests in seasonal forecast mode;
- better understand the physical processes involved in the response of ENSO to climate change and link those to the main sources of model error; and
- better represent unresolved processes and coupled feedbacks.

Defining a set of metrics will help scientists assess the quality of ENSO simulations and easily intercompare different models in a way that integrates both observations and theory. This will also allow non-ENSO specialists and the wider impacts community using CGCM outputs to better evaluate the ENSO processes and feedbacks relevant for their own particular study. Finally, this definition should also help decide how to best invest limited computer and model-development resources. As the models are improved, there is hope for better ENSO simulations and more reliable seasonal forecasts and climate projections.

ACKNOWLEDGMENTS. Fruitful discussions with Julia Slingo, Axel Timmermann, Peter Gleckler, Ben Kirtman, Magdalena Balmaseda, Fei-Fei Jin, and the participants of the ENSO in IPCC meeting held in 2006 in Paris are acknowledged. Ken Sperber provided the initial version of Fig. 3. This work was partly funded by the European Community ENSEMBLES (COCE-CT-2003-505539) and DYNAMITE (003903-GOCE) projects under the Sixth Framework Programme and by the CNRS PICS CORDIAL. EG is indebted to SOEST/University of Hawaii at Manoa

for providing support for a research sabbatical during the course of this study. AVF is indebted for funding support from NSF, DOE Office of Science, the David and Lucile Packard Foundation, and CNRS. MC was supported by the U.K. Department of the Environment, Food and Rural Affairs under Contract PECD/7/12/37. AC was supported by NOAA through a CMIP grant. CW is supported by a grant from NOAA/Climate Program Office and by the base funding of NOAA/AOML. We also thank Jerry Meehl and two anonymous reviewers for constructive comments that significantly helped to improve the initial manuscript.

REFERENCES

- AchutaRao, K., and K. Sperber, 2002: Simulation of the El Niño Southern Oscillation: Results from the coupled model intercomparison project. *Climate Dyn.*, **19**, 191–209.
- , and —, 2006: ENSO simulations in coupled ocean–atmosphere models: Are the current models better? *Climate Dyn.*, **27**, 1–16.
- Alves, O., M. Alonso Balmaseda, D. Anderson, and T. Stockdale, 2004: Sensitivity of dynamical seasonal forecasts to ocean initial conditions. *Quart. J. Roy. Meteor. Soc.*, **130**, 647–667.
- An, S. I., 2008a: Interannual variations of the tropical ocean instability wave and ENSO. *J. Climate*, **21**, 3680–3686.
- , 2008b: A review on interdecadal changes in the nonlinearity of ENSO. *Theor. Appl. Climatol.*, in press.
- , and F.-F. Jin, 2004: Nonlinearity and asymmetry of ENSO. *J. Climate*, **17**, 2399–2412.
- , Y. G. Ham, J. S. Kug, F. F. Jin, and I. S. Kang, 2005a: El Niño–La Niña asymmetry in the coupled model intercomparison project simulations. *J. Climate*, **18**, 2617–2627.
- , W. W. Hsieh, and F. F. Jin, 2005b: A nonlinear analysis of the ENSO cycle and its interdecadal changes. *J. Climate*, **18**, 3229–3239.
- Battisti, D. S., and A. C. Hirst, 1989: Interannual variability in the tropical atmosphere–ocean model: Influence of the basic state, ocean geometry, and nonlinearity. *J. Atmos. Sci.*, **45**, 1687–1712.
- Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163–172.
- Bony, S., and J. L. Dufresne, 2005: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.*, **32**, L20806, doi:10.1029/2005GL023851.
- Braconnot, P., F. Hourdin, S. Bony, J. Dufresne, J. Grandpeix, and O. Marti, 2007: Impact of different convective cloud schemes on the simulation of the

- tropical seasonal cycle in a coupled ocean–atmosphere model. *Climate Dyn.*, **29**, 501–520.
- Brown, J. N., and A. V. Fedorov, 2008: Mean energy balance in the tropical Pacific ocean. *J. Mar. Res.*, **66**, 1–23.
- , M. Collins, A. W. Tudhope, and T. Toniazzo, 2007: Modeling mid-Holocene tropical climate and ENSO variability: Towards constraining predictions of future climate change with palaeo-data. *Climate Dyn.*, **30**, 19–36.
- Burgers, G., and D. B. Stephenson, 1999: The normality of El Niño. *Geophys. Res. Lett.*, **26**, 1027–1030.
- , F.-F. Jin, and G. J. van Oldenborgh, 2005: The simplest ENSO recharge oscillator. *Geophys. Res. Lett.*, **32**, L13706, doi:10.1029/2005GL022951.
- Capotondi, A., 2008: Can the mean structure of the tropical pycnocline affect ENSO period in coupled climate models? *Ocean Modell.*, **20**, 157–169.
- , A. Wittenberg, and S. Masina, 2006: Spatial and temporal structure of tropical Pacific interannual variability in 20th-century coupled simulations. *Ocean Modell.*, **15**, 274.
- Chen, D., M. A. Cane, A. Kaplan, S. E. Zebiak, and D. Huang, 2004: Predictability of El Niño over the past 148 years. *Nature*, **428**, 733–736.
- Cobb, K. M., C. D. Charles, H. Cheng, and R. L. Edwards, 2003: El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, **424**, 271–276.
- Collins, M., 2005: El Niño– or La Niña–like climate change? *Climate Dyn.*, **24**, 89–104.
- , Ed., 2007: Ensembles and probabilities: A new era in the prediction of climate change. *Philos. Trans. Roy. Soc. London*, **365A**, 1957–1970.
- Cronin, M. F., N. A. Bond, C. W. Fairall, and R. A. Weller, 2006: Surface cloud forcing in the East Pacific stratus deck/cold tongue/ITCZ complex. *J. Climate*, **19**, 392–409.
- Davey, M., and Coauthors, 2001: STOIC: A study of coupled model climatology and variability in tropical ocean regions. *Climate Dyn.*, **18**, 403–420.
- Delecluse, P., M. Davey, Y. Kitamura, S. G. H. Philander, M. Suarez, and L. Bengtsson, 1998: TOGA review paper: Coupled general circulation modeling of the tropical Pacific. *J. Geophys. Res.*, **103**, 14 357–14 373.
- Dewitte, B., C. Cibot, C. Périgaud, S.-I. An, and L. Terray, 2007: Interaction between near-annual and ENSO modes in a CGCM simulation: Role of equatorial background mean state. *J. Climate*, **20**, 1035–1052.
- Fedorov, A. V., 2002: The response of the coupled tropical ocean–atmosphere to westerly wind bursts. *Quart. J. Roy. Meteor. Soc.*, **128**, 1–23.
- , 2007: Estimating net energy dissipation rates in the tropical ocean: Diabatic effects on ENSO dynamics. *J. Climate*, **20**, 1099–1108.
- , and S. G. Philander, 2000: Is El Niño changing? *Science*, **288**, 1997–2002.
- , and —, 2001: A stability analysis of tropical ocean–atmosphere interactions: Bridging measurements and theory for El Niño. *J. Climate*, **14**, 3086–3101.
- , S. L. Harper, S. G. Philander, B. Winter, and A. Wittenberg, 2003: How predictable is El Niño? *Bull. Amer. Meteor. Soc.*, **84**, 911–919.
- , P. S. Dekens, M. McCarthy, A. C. Ravelo, P. B. deMenocal, and M. Barreiro, 2006: The Pliocene Paradox (mechanisms for a permanent El Niño). *Science*, **312**, 1485–1489.
- Gleckler, P. J., K. E. Taylor, and C. Dutriaux, 2008: Performance metrics for climate models. *J. Geophys. Res.*, **113**, D06104, doi:10.1029/2007JD008972.
- Guilyardi, E., 2006: El Niño–mean state–seasonal cycle interactions in a multi-model ensemble. *Climate Dyn.*, **26**, 329–348.
- , P. Delecluse, S. Gualdi, and A. Navarra, 2003: Mechanisms for ENSO phase change in a coupled GCM. *J. Climate*, **16**, 1141–1158.
- , and Coauthors, 2004: Representing El Niño in coupled ocean–atmosphere GCMs: The dominant role of the atmospheric component. *J. Climate*, **17**, 4623–4629.
- Hannachi, A., D. B. Stephenson, and K. R. Sperber, 2003: Probability-based methods for quantifying nonlinearity in the ENSO. *Climate Dyn.*, **20**, 241–256.
- Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. M. Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci.*, **103**, 14 288.
- Haywood, A. M., P. J. Valdes, and V. L. Peck, 2007: A permanent El Niño–like state during the Pliocene? *Paleoceanography*, **22**, PA1213, doi:10.1029/2006PA001323.
- Held, I. M., 2005: The gap between simulation and understanding in climate modeling. *Bull. Amer. Meteor. Soc.*, **86**, 1609–1614.
- Jin, F.-F., 1997: An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.*, **54**, 811–829.
- , J. D. Neelin, and M. Ghil, 1994: El Niño on the devil’s staircase: Annual subharmonic steps to chaos. *Science*, **264**, 70–72.
- , S. T. Kim, and L. Bejarano, 2006: A coupled-stability index for ENSO. *Geophys. Res. Lett.*, **33**, L23708, doi:10.1029/2006GL027221.
- Jochum, M., and R. Murtugudde, 2006: Temperature advection by tropical instability waves. *J. Phys. Oceanogr.*, **36**, 592–605.

- Joly, M., and A. Voldoire, 2009: Influence of ENSO on the West African monsoon: temporal aspects and atmospheric processes. *Climate Dyn.*, in press
- Joseph, R., and S. Nigam, 2006: ENSO evolution and teleconnections in IPCC's 20th-century climate simulations: Realistic representation? *J. Climate*, **19**, 4360–4377.
- Keenlyside, N. S., M. Latif, M. Botzet, J. Jungclaus, and U. Schulzweida, 2005: A coupled method for initializing El Niño–Southern Oscillation forecasts using sea surface temperature. *Tellus*, **57A**, 340–356.
- Kessler, W. S., 2002: Is ENSO a cycle or a series of events? *Geophys. Res. Lett.*, **29**, 2125, doi:10.1029/2002GL015924.
- Kim, D., J.-S. Kug, I. -S. Kang, F.-F. Jin, and A. T. Wittenberg, 2008: Tropical Pacific impacts of convective momentum transport in the SNU coupled GCM. *Climate Dyn.*, **31**, 213–226, doi:10.1007/s00382-007-0348-4.
- Knutson, T., S. Manabe, and D.-F. Gu, 1997: Simulated ENSO in a global coupled ocean–atmosphere model: Multidecadal amplitude modulation and CO₂ sensitivity. *J. Climate*, **10**, 138–161.
- Latif, M., and Coauthors, 2001: ENSIP: The El Niño simulation intercomparison project. *Climate Dyn.*, **18**, 225–76.
- Lau, K. M., and H. Weng, 1999: Interannual, decadal–interdecadal, and global warming signals in sea surface temperature during 1955–97. *J. Climate*, **12**, 1257–1267.
- L'Ecuyer, T. S., and G. L. Stephens, 2007: The tropical atmospheric energy budget from the TRMM perspective. Part II: Evaluating GCM representations of the sensitivity of regional energy and water cycles to the 1998–99 ENSO cycle. *J. Climate*, **20**, 4548–4571.
- Lengaigne, M., E. Guilyardi, J.-P. Boulanger, C. Menkes, P. Inness, P. Delecluse, and J. M. Slingo, 2004a: Triggering of El Niño by westerly wind events in a coupled general circulation model. *Climate Dyn.*, **23**, 601–620.
- , J. P. Boulanger, C. Menkes, P. Delecluse, and J. Slingo, 2004b: Westerly wind events in the tropical Pacific and their influence on the coupled ocean–atmosphere system: A review. *Earth's Climate: The Ocean–Atmosphere Interaction*, C. Wang, S.-P. Xie, and J. A. Carton, Eds., Amer. Geophys. Union, 49–69.
- , C. Menkes, O. Aumont, T. Gorgues, L. Bopp, J.-M. André, and G. Madec, 2007: Influence of the oceanic biology on the tropical Pacific climate in a coupled general circulation model. *Climate Dyn.*, **28**, 503–516.
- Li, T., and G. Philander, 1996: On the annual cycle in the eastern equatorial Pacific. *J. Climate*, **9**, 2986–2998.
- Lin, H., and J. Derome, 2004: Nonlinearity of the extratropical response to tropical forcing. *J. Climate*, **17**, 2597–2608.
- Lin, J. L., 2007a: The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean–atmosphere feedback analysis. *J. Climate*, **20**, 4497–4525.
- , 2007b: Interdecadal variability of ENSO in 21 IPCC AR4 coupled GCMs. *Geophys. Res. Lett.*, **34**, L12702, doi:10.1029/2006GL028937.
- , and Coauthors, 2006: Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals. *J. Climate*, **19**, 2665–2690.
- Luo, J. J., S. Masson, E. Roeckner, G. Madec, and T. Yamagata, 2005: Reducing climatology bias in an ocean–atmosphere CGCM with improved coupling physics. *J. Climate*, **18**, 2344–2360.
- , S. Masson, S. K. Behera, and T. Yamagata, 2008: Extended ENSO predictions using a fully coupled ocean–atmosphere model. *J. Climate*, **21**, 84–93.
- McPhaden, M. J., and Coauthors, 1998: The Tropical Ocean–Global Atmosphere (TOGA) observing system: A decade of progress. *J. Geophys. Res.*, **103**, 14 169–14 240.
- , S. E. Zebiak, and M. H. Glantz, 2006: ENSO as an integrating concept in earth science. *Science*, **314**, 1739–1745.
- , and Coauthors, 2009: RAMA: Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Amer. Meteor. Soc.*, in press.
- Mechoso, C. R., J. D. Neelin, and J.-Y. Yu, 2003: Testing simple models of ENSO. *J. Atmos. Sci.*, **60**, 305–318.
- Meehl, G. A., and H. Teng, 2007: Multi-model changes in teleconnections over North America in a future warmer climate. *Climate Dyn.*, **29**, 779–790, doi:10.1007/s00382-007-0268-3.
- , P. R. Gent, J. M. Arblaster, B. L. Otto-Bliesner, E. C. Brady, and A. Craig, 2001: Factors that affect the amplitude of El Niño in global coupled climate models. *Climate Dyn.*, **17**, 515.
- , H. Teng, and G. W. Branstator, 2006: Future changes of El Niño in two global coupled climate models. *Climate Dyn.*, **26**, 549–566.
- , C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007a: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.*, **88**, 1383–1394.
- , and Coauthors, 2007b: Global climate projections. *Climate Change 2007: The Physical Science Basis*, S.

- D. Solomon et al., Eds., Cambridge University Press, 747–845.
- , C. Tebaldi, H. Teng, and T. Peterson, 2007c: Current and future U.S. weather extremes and El Niño. *Geophys. Res. Lett.*, **34**, L20704, doi:10.1029/2007GL031027.
- Meinen, C. S., and M. J. McPhaden, 2001: Interannual variability in warm water volume transports in the equatorial Pacific during 1993–99. *J. Phys. Oceanogr.*, **31**, 1324–1345.
- Merryfield, W. J., 2006: Changes to ENSO under CO₂ doubling in the IPCC AR4 coupled climate models. *J. Climate*, **19**, 4009–4027.
- Monahan, A. H., and A. Dai, 2004: The spatial and temporal structure of ENSO nonlinearity. *J. Climate*, **17**, 3026–3036.
- Neale, R. B., J. H. Richter, and M. Jochum, 2008: The impact of convection on ENSO: From a delayed oscillator to a series of events. *J. Climate*, **21**, 5904–5924.
- Neelin, J. D., 1991: The slow sea surface temperature mode and the fast-wave limit: Analytic theory for tropical interannual oscillations and experiments in a hybrid coupled model. *J. Atmos. Sci.*, **48**, 584–606.
- Norton, W. A., and Coauthors, 2009: HiGEM: The new U.K. high-resolution global environment model—Model description and basic analysis. *J. Climate*, in press.
- Palmer, T. N., and Coauthors, 2004: Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER). *Bull. Amer. Meteor. Soc.*, **85**, 853–872.
- , and Coauthors, 2008: Toward seamless prediction: Calibration of climate change projections using seasonal forecasts. *Bull. Amer. Meteor. Soc.*, **89**, 459–470.
- Pezzi, L. P., J. Vialard, K. J. Richards, C. Mekes, and D. Anderson, 2004: Influence of ocean–atmosphere coupling on the properties of tropical instability waves. *Geophys. Res. Lett.*, **31**, L16306, doi:10.1029/2004GL019995.
- Philip, S., and G. J. van Oldenborgh, 2006: Shifts in ENSO coupling processes under global warming. *Geophys. Res. Lett.*, **33**, L11704, doi:10.1029/2006GL026196.
- , and —, 2009: Significant atmospheric nonlinearities in the ENSO cycle. *J. Climate*, in press.
- Picaut, J., F. Masia, and Y. du Penhoat, 1997: An advective-reflective conceptual model for the oscillatory nature of the ENSO. *Science*, **277**, 663–666.
- Power, S., M. Haylock, R. Colman, and X. Wang, 2006: The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. *J. Climate*, **19**, 4755–4771.
- Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville, 2007: Recent climate observations compared to projections. *Science*, **316**, 709–711.
- Räisänen, J., 2007: How reliable are climate models? *Tellus*, **59A**, 2–29.
- Randall, D. A., and Coauthors, 2007: Climate models and their evaluation. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 589–662.
- Reichler, T., and J. Kim, 2008: How well do coupled models simulate today’s climate? *Bull. Amer. Meteor. Soc.*, **89**, 303–311.
- Roberts, M. J., and Coauthors, 2009: Impact of resolution on the tropical Pacific circulation in a matrix of coupled models. *J. Climate*, in press.
- Schneider, E. K., 2002: Understanding differences between the equatorial Pacific as simulated by two coupled GCMs. *J. Climate*, **15**, 449–469.
- Stephens, G. L., and Coauthors, 2002: The cloudsat mission and the A-train. *Bull. Amer. Meteor. Soc.*, **83**, 1771–1790.
- Suarez, M. J., and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.*, **45**, 3283–3287.
- Sun, D., and Coauthors, 2006: Radiative and dynamical feedbacks over the equatorial cold tongue: Results from nine atmospheric GCMs. *J. Climate*, **19**, 4059–4074.
- , Y. Yu, and T. Zhang, 2009: Tropical water vapor and cloud feedbacks in climate models: A further assessment using coupled simulations. *J. Climate*, in press.
- Taylor, K. E., 2001: Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, **106**, 7183–7192.
- Timmermann, A., and F. Jin, 2002: Phytoplankton influences on tropical climate. *Geophys. Res. Lett.*, **29**, 2104, doi:10.1029/2002GL015434.
- , and Coauthors, 2007: The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *J. Climate*, **20**, 4899–4919.
- Toniazzo, T., M. Collins, and J. Brown, 2008: The variation of ENSO characteristics associated with atmospheric parameter perturbations in a coupled model. *Climate Dyn.*, **30**, 643–656.
- Trenberth, K. E., and D. P. Stepaniak, 2001: Indices of El Niño evolution. *J. Climate*, **14**, 1697–1701.
- Tudhope, A., and Coauthors, 2001: Variability in the El Niño–Southern Oscillation through a glacial–interglacial cycle. *Science*, **291**, 1511–1517.
- Tziperman, E., L. Stone, M. A. Cane, and H. Jarosh, 1994: El Niño chaos: Overlapping of resonances between

- the seasonal cycle and the Pacific ocean-atmosphere oscillator. *Science*, **264**, 72–74.
- , S. E. Zebial, and M. A. Cane, 1997: Mechanisms of seasonal-ENSO interaction. *J. Atmos. Sci.*, **54**, 61–71.
- van Oldenborgh, G. J., S. Philip, and M. Collins, 2005: El Niño in a changing climate: A multi-model study. *Ocean Sci.*, **1**, 81–95.
- Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006: Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, **327**, 216–219.
- , A. Clement, and B. J. Soden, 2008: Examining the tropical Pacific’s response to global warming. *Eos, Trans. Amer. Geophys. Union*, **89**, 81–83.
- Wang, C., 2001: A unified oscillator model for the El Niño–Southern Oscillation. *J. Climate*, **14**, 98–115.
- , and J. Picaut, 2004: Understanding ENSO Physics—A review. *Earth’s Climate: The Ocean–Atmosphere Interaction*, C. Wang, S.-P. Xie, and J. A. Carton, Eds., Amer. Geophys. Union, 21–48.
- Weisberg, R. H., and C. Wang, 1997: A western Pacific oscillator paradigm for the El Niño–Southern Oscillation. *Geophys. Res. Lett.*, **24**, 779–782.
- Wittenberg, A. T., 2004: Extended wind stress analyses for ENSO. *J. Climate*, **17**, 2526–2540.
- , A. Rosati, N. C. Lau, and J. J. Ploshay, 2006: GFDL’s CM2 global coupled climate models. Part III: Tropical Pacific climate and ENSO. *J. Climate*, **19**, 698–722.
- Woolnough, S. J., F. Vitart, and M. Balmaseda, 2007: The role of the ocean in the Madden-Julian oscillation: Sensitivity of an MJO forecast to ocean coupling. *Quart. J. Roy. Meteor. Soc.*, **133**, 117–128.
- Wu, Q., D. J. Karoly, and G. R. North, 2008: Role of water vapor feedback on the amplitude of season cycle in the global mean surface air temperature. *Geophys. Res. Lett.*, **35**, L08711, doi:10.1029/2008GL033454.
- Wu, X., L. Geng, X. Song, G. Vettoretti, W. R. Peltier, and G. J. Zhang, 2007: Impact of a modified convective scheme on the Madden-Julian oscillation and El Niño–Southern Oscillation in a coupled climate model. *Geophys. Res. Lett.*, **34**, L16823, doi:10.1029/2007GL030637.
- Yamaguchi, K., and A. Noda, 2006: Global warming patterns over the North Pacific: ENSO versus AO. *J. Meteor. Soc. Japan*, **84**, 221–241.
- Yeh, S.-W., and B. P. Kirtman, 2004: Tropical Pacific decadal variability and ENSO amplitude modulation in a CGCM. *J. Geophys. Res.*, **109**, C11009, doi:10.1029/2004JC002442.
- , and B. P. Kirtman, 2007: ENSO amplitude changes due to climate change projections in different coupled models. *J. Climate*, **20**, 203–217.
- , J.-G. Jhun, I.-S. Kang, and B. P. Kirtman, 2004: The decadal ENSO variability in a hybrid coupled model. *J. Climate*, **17**, 1225–1238.
- Yukimoto, S., and Y. Kitamura, 2003: An investigation of the irregularity of El Niño in a coupled GCM. *J. Meteor. Soc. Japan*, **81**, 599–622.
- Zelle, H., G. van Oldenborgh, and H. Dijkstra, 2005: El Niño and greenhouse warming: Results from ensemble simulations with the NCAR CCSM. *J. Climate*, **18**, 4669–4683.
- Zheng, W., P. Braconnot, E. Guilyardi, U. Merkel, and Y. Yu, 2008: ENSO at 6ka and 21ka from ocean-atmosphere coupled model simulations. *Climate Dyn.*, **30**, 745–762.