Understanding El Niño in Ocean-Atmosphere General Circulation Models: progress and challenges

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Summary:

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.

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Abstract:

Determining how El Niño and its impacts may change over the next ten to hundred years remains a difficult scientific challenge. Ocean-atmosphere Coupled General Circulation Models (CGCMs) are routinely used both to analyze El Niño mechanisms and teleconnections and to predict its evolution on a broad range of timescales, from seasonal to centennial. The ability to simulate El Niño as an emergent property of these models has largely improved over the last few years. Nevertheless, the diversity of model simulations of present-day El Niño indicate current limitations in our ability to model this climate phenomenon and anticipate changes in its characteristics. A review of the several factors that contribute to this diversity, as well as potential means to improve the simulation of El Niño, is presented.

Introduction

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 to 7 years 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 or 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 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, intra-seasonal 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), and 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 lying 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 2007, Meehl et al. 2007b) as well as community discussions initiated during an "ENSO in IPCC AR4" meeting held in May 2006 in Paris (http://ncas-climate.nerc.ac.uk/~ericg/Projects/ipcc_enso_06.html) and continued at the "3rd Working Group on Numerical Experimentation (WGNE) Workshop on Systematic Errors in Climate and Numerical Weather Prediction Models" held in San Francisco in February 2007

(http://www-pcmdi.llnl.gov/wgne2007).

2. 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 resolutions have increased (Guilyardi et al., 2004, Roberts et al. 2008) 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 4th assessment report (AR4) of the IPCC (Randall et al. 2007, Meehl al. 2007a) can now not only simulate 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 by earlier generations of CGCMs. Indeed, many CGCMs now exhibit a behavior that is qualitatively similar to that of the real-world ENSO – a considerable achievement given the complexity of the interactions involved.

Despite this progress, recent multi-model analyses show that serious systematic errors in the simulated background climate (time mean and annual cycle, see box 1) 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 models errors can often be traced back to the atmosphere component (Braconnot et al. 2007, L'Ecuyer and Stephens 2007, Sun et al. 2008, Guilyardi et al. 2008)

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 to 7 years. The observed seasonal phase locking – El Niño and La Niña anomalies tend to peak in boreal winter and are weakest 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 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 observed amplitude (van Oldenborgh et al. 2005, AchutaRao & 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 the ENSO cycle in the real world.

Box 1 – 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 and 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 2007). 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 can ultimately impact the fidelity of the simulated El Niño (Guilyardi et al. 2003, Sun et al. 2008).

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 CMIP1 fifteen years ago, arise from numerous factors 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 semi-annual 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).

3. 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 underway, 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 due to 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 (due to surface heat fluxes and also negative), the zonal advection feedback (positive), the Ekman pumping feedback (positive) and the thermocline feedback (positive) (see Burgers et al. 2005 and Jin et al. 2006 for details). 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, i.e. the effect of thermocline depth variations on SST (van Oldenborgh et al. 2005), as the 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 by too little thermal damping, mainly due to reduced cloud-shading feedback (Philip and van Oldenborgh, 2006, Sun et al. 2008, Guilyardi et al. 2008).

4. Non-linearities and the role of tropical multi-scale 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 intra-seasonal 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 which 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. Non-linearity 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. 2008). 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 needs to be increased to resolve the coupling of these small ocean features, which have sizes that are 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. 2008).

Non-linear interactions have further been proposed to explained the observed positive skewness of ENSO, i.e. 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 2007) 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 al. 2001, van Oldenborgh 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 other sources than non-linearity, for instance the superposition of ENSO, decadal variations, and global warming trends (Lau and Weng 1999).

5. 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 – for example, 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, 2008). 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 coupled GCMs depends more on improving the atmospheric or oceanic component of CGCMs will be answered over time. Properties of atmospheric GCMs appear to be critical, perhaps because their sensitivity, complexity and non-linearity, 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. 2008), 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 (Guilyardi et al. 2008).

6. 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 dependant 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 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 years 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 CO_2 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 while 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 ($4xCO_2$). Hence, even though all models show continued ENSO

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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 21st 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 timescales, 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, paleo-evidence that ENSO may have been quite different in the past (e.g. Tudhope et al. 2001, Cobb et al. 2003) indicates that there is a risk ENSO and the associated teleconnections (see for instance Meehl et al. 2007c on the shift of ENSO teleconnections in North America) might be quite different in the future: a fact that is 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 towards increased El Niño amplitude in high CO_2 scenarios. 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. 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 or 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 to 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 analogue to the contemporary global warming, since 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 paleo-data 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 new additional questions on the horizon as full earth system models mature - how might ENSO's impacts 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-CO_2 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.

7. 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, multi-decadal 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[9]); (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[10] or VOCALS[11]) are needed as 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 TAO/TRITON (Tropical Atmosphere Ocean Project, http://www.pmel.noaa.gov/tao/, McPhaden et al. 1998) and RAMA moorings (Research Moored Array for African-Asian-Australian Monsoon, McPhaden et al. 2008), ARGO automatic floats (http://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..

8. 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 for instance 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 due to strong interannual (and decadal) variability. Nor can scientists and policymakers wait until the climate

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[9] http://www.nodc.noaa.gov/General/NODC-dataexch/NODC-godar.html
[10] http://www.ird.nc/UR65/SPICE/
[11] http://www.eol.ucar.edu/projects/vocals/

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 multi-model ensembles and to the use of seasonal forecast techniques.

A multi-model 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. Multi-model 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 multi-model 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 under-estimate 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 multi-model experiments (using several CGCMs as for the CMIP3 data base 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 multi-decadal) 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 as 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 which 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. But 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 intra-seasonal signals (Woolnough et al. 2007).

Such simulations are computationally cheap to perform and allow more possibilities for testing than multi-century simulations. For instance, an experiment using 6 month hindcasts with two starts per year, looking at 5 different situations (e.g. 1993/1995/1997/1999/2001) and using 5 member ensembles requires only 25 years 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)[12] 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 set up 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 (Fig. 7, Joly et al. 2008). 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

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[12] http://www.clivar.org/organization/wgsip/chfp/chfp.php

necessarily form the complete set of climate change processes and feedbacks, improving them in models will reap many benefits.

9. 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[13]), which may have the correct value for the wrong reasons (i.e. as a result of bias compensation, Guilyardi et al. 2008). Moreover, multi-model analyses should rely upon 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[14] 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 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 et al., 2005; Collins 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.

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[13] The Niño 3 region spans 5°S to 5°N and 150°W to 90°W in the east Pacific, see Fig. 4.
[14] http://www.clivar.org/organization/pacific/pacific.php

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 Box 2. When summarized by a single scalar the metrics are amenable to inter-model 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, Brown et al. 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 advective 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 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 co-located SST anomaly (Lin 2007a, Sun et al. 2006, 2008, Guilyardi et al. 2008). 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 (Brown et al. 2008).

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 multi-mechanism 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 re-analysis products for feedbacks as basic to ENSO as the ocean-atmosphere coupling strength (Wittenberg 2004) or the cloud radiative feedbacks (Cronin et al. 2001). 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, in order 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 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[15] and following community agreed metadata standards like NetCDF[16] and those developed for the next IPCC, e.g. http://metaforclimate.eu or http://www.earthsystemcurator.org/) and a repository of scripts to generate both the diagnostics for the observations and model data, and "distance" metrics between those diagnostics.

Box 2 – 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: anomaly standard deviation, skewness, phase locking, autocorrelation
    - wavelet decomposition leading to time-mean spectrum, ENSO modulation
    - 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 (Meinen and McPhaden 2001, http://www.pmel.noaa.gov/tao/elnino/wwv/).

- Trans-Niño index lag correlated with Niño 3 SST anomalies, which provides information about the type of El Niño event (Trenberth and Stepaniak 2001).

- Intra-seasonal activity as proposed by the MJO CLIVAR workgroup (http://climate.snu.ac.kr/mjo_metrics/index.htm).

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

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[15] http://opendap.org
[16] http://www.unidata.ucar.edu/software/netcdf

Conclusions

The IPCC AR4 projections offer a wide range of possibilities regarding what will happen to ENSO in the future. However, there is no indication of a complete disappearance of ENSO variability over the next century nor an explosion of 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 20th-century ENSO statistics, and 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

it 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.

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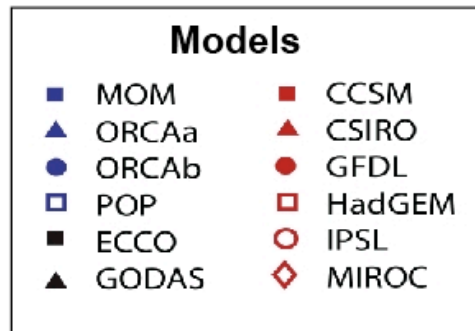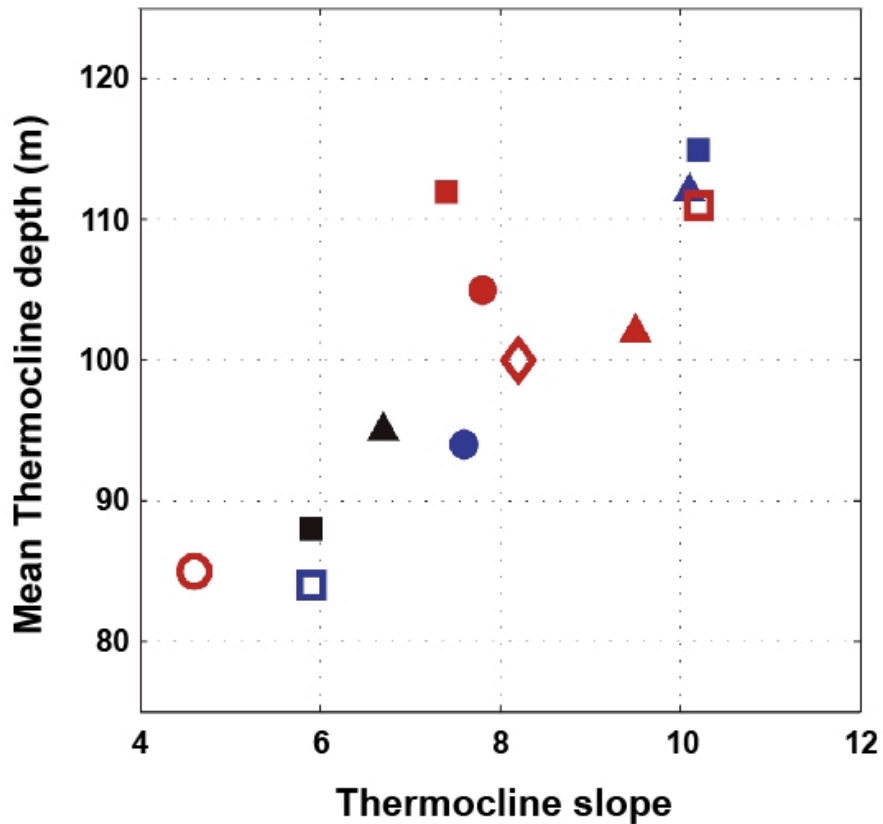
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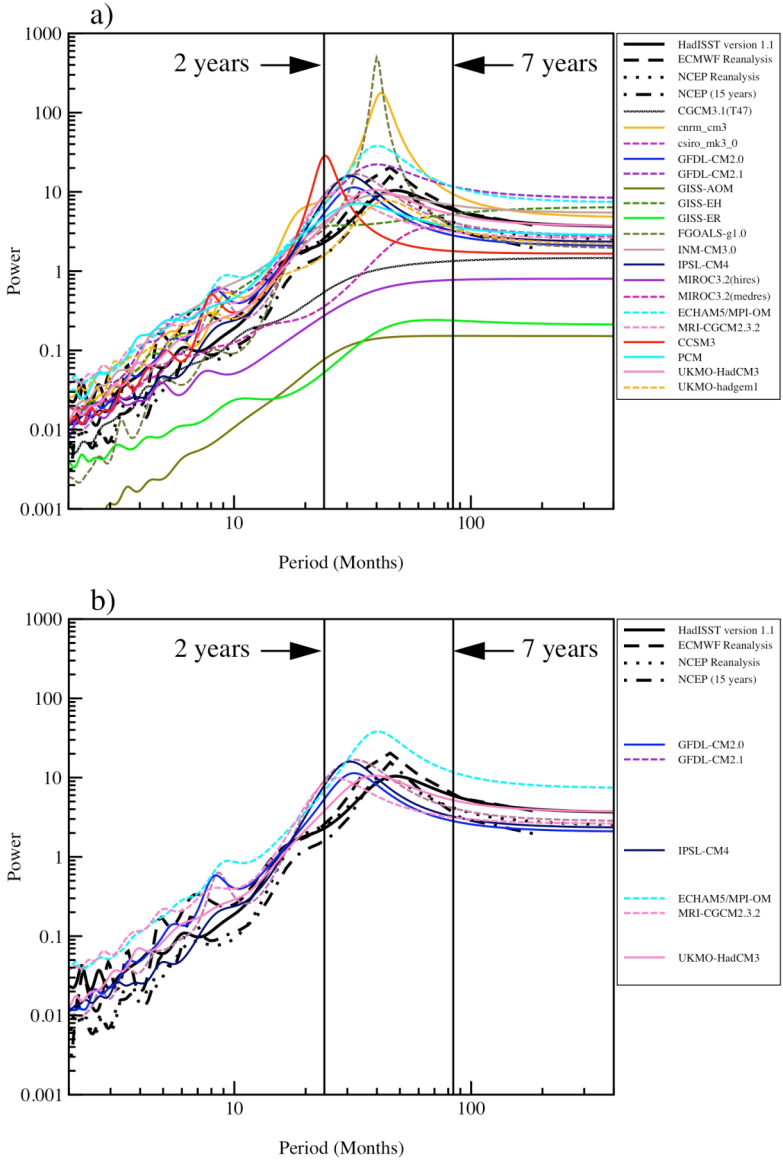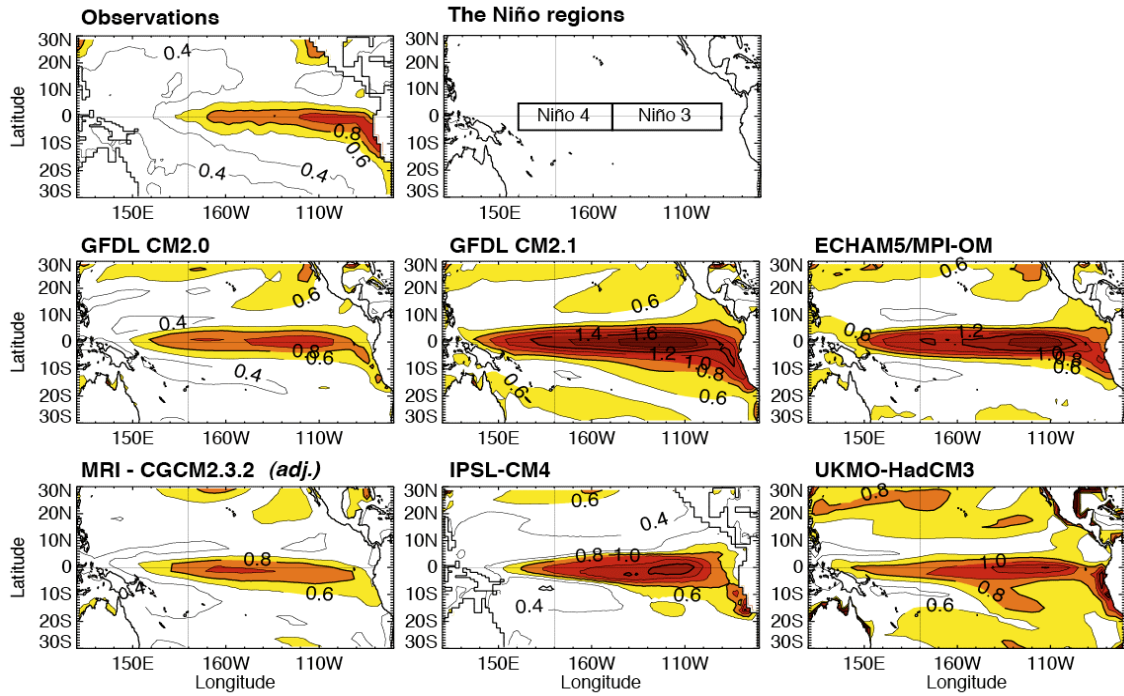
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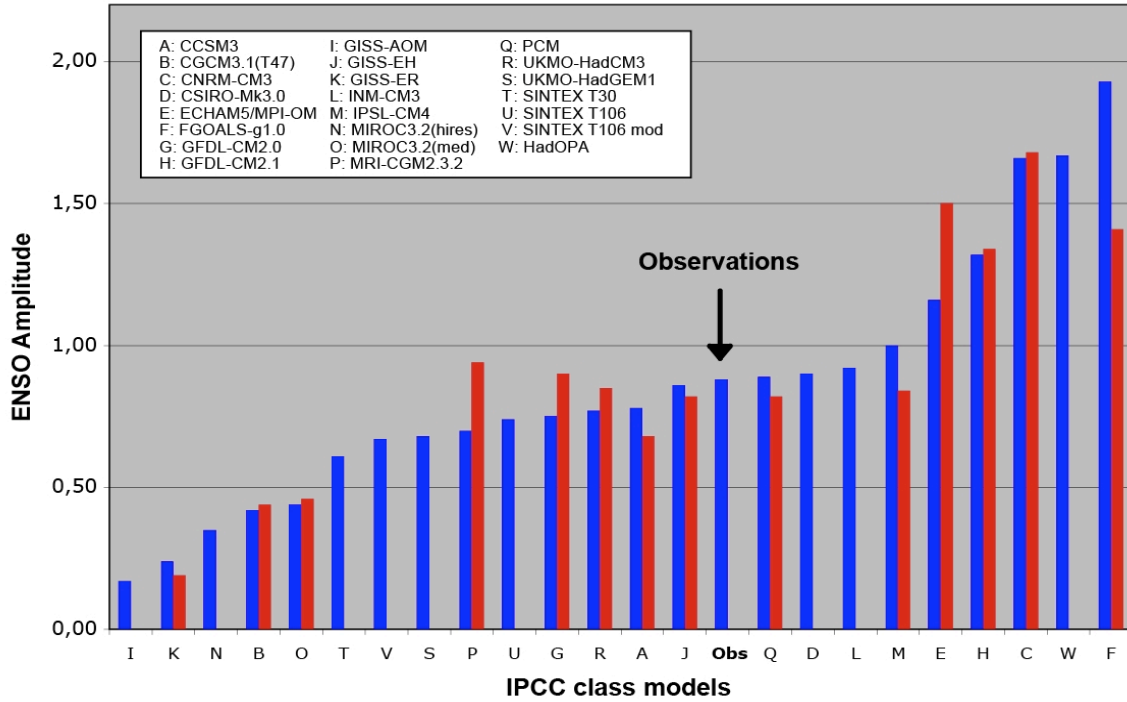
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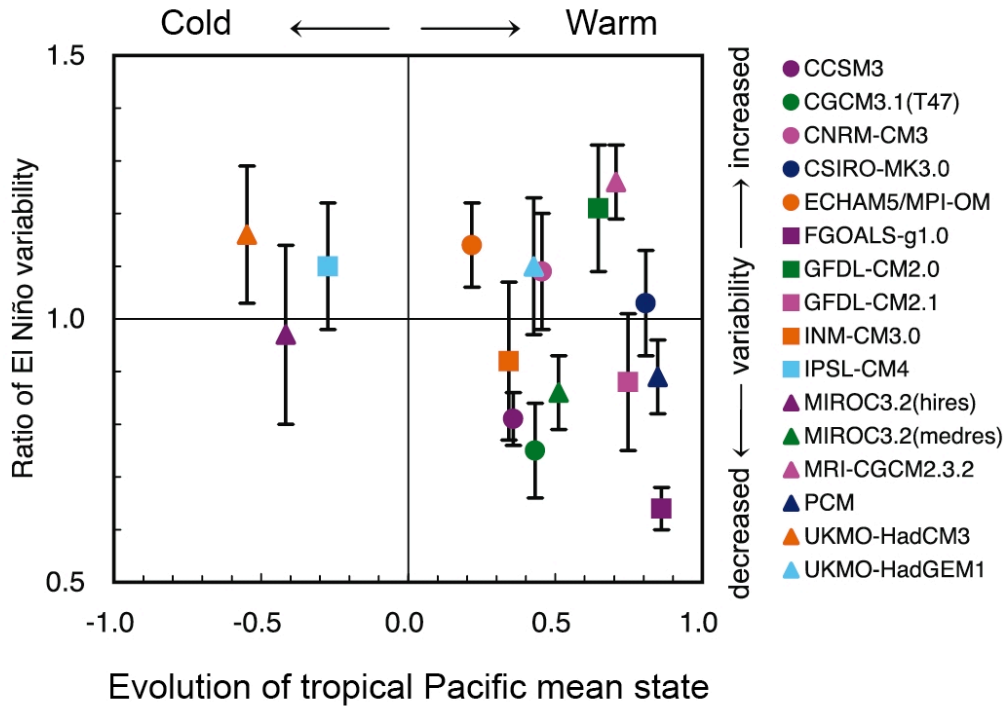
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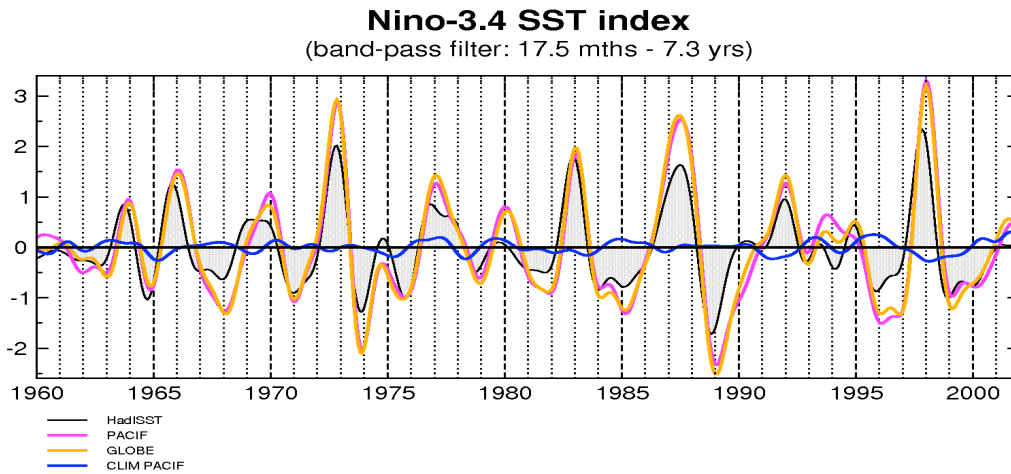
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Nino-3.4 SST index
(band-pass filter: 17.5 mths - 7.3 yrs)

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