Climate model biases and El Niño Southern Oscillation (ENSO) simulation

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Over the last two decades the representation of ENSO in climate models has significantly improved, as documented by the extensive literature describing ENSO simulations in the Climate Model Intercomparison Project versions 3 and 5 (CMIP3 and CMIP5). Several aspects of ENSO, however, are still not satisfactorily represented in the current generation of climate models (Bellenger et al. 2014). In addition, as our understanding of ENSO and its complex coupled feedbacks deepens, we want any "realistic" ENSO simulations to be achieved as a result of a correct representation of those feedbacks, and not from compensating errors.

Part of the problem is that it is not always clear what is meant by "realistic". ENSO behavior is strongly modulated in time, in both observations and climate models (see article by Wittenberg, this issue). The relatively short observational record means that the ENSO target for modelers is somewhat murky, and may not be fully representative of the full range of ENSO behavior that is achieved in nature (Wittenberg 2009). On the other hand, the tropical Pacific mean state is better resolved by the observational record, and several biases are clear and shared by most of the present generation of models: an equatorial cold tongue that is too intense and too far west; a "double" or "alternating" Intertropical Convergence Zone (ITCZ) in the eastern Pacific; and warm sea surface temperature (SST) biases near the coast of South America (Guilyardi et al. 2009, 2012a).

Figure 1 shows the time evolution of the Niño3.4 index, the area averaged SST over the region 5°S-5°N, 170°W-120°W, over the last century for one observational data set (HadISST, Rayner et al. 2003) and three models from the CMIP5 archive (GFDL-ESM2M, NCAR-CCSM4, MRI-CGCM3) - illustrating inter-model differences in ENSO character. The figure shows some similarities between the observations and the models. The ENSO evolution is quite "irregular" in all the models, as in the observational time series, so that ENSO can be more adequately described as a series

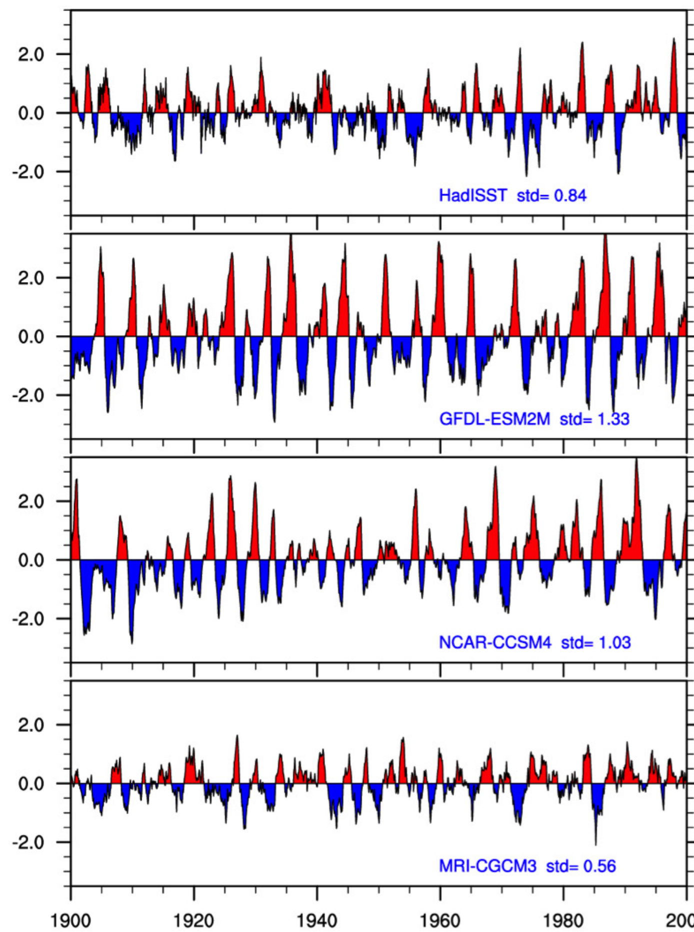

Figure 1. Evolution of the Niño3.4 index (area averaged interannual SSTAs over the region 5°S-5°N, 170°W-120°W) over the period 1900-2000 for HadISST (top panel) and 20th-century climate simulations (only one ensemble member of which is shown) from the CMIP5 archive: GFDL-ESM2M, NCAR-CCSM4, MRI-CGCM3. The time series standard deviation, computed over the period 1950-2000, is also indicated in each panel as a measure of the ENSO amplitude. Vertical axis units are °C.

of events rather than a regular oscillation. This represents a big improvement relative to the ENSO simulation in some of the CMIP3 models for which the ENSO evolution was quite periodic. Both GFDL-ESM2M and NCAR-CCSM4 also show some degree of asymmetry between the positive and negative events. Large El Niño events tend to be stronger than large La Niña events, as also seen in the observational time series, indicating that the models may capture some of the observed ENSO nonlinearities – though it remains a challenge in many models (An et al. 2005; Choi et al. 2013; Dommenget et al. 2013; Zhang and Sun, 2014). Despite these "realistic" features, which indicate improvement relative to previous model generations, the models shown in Figure 1 either overestimate or underestimate the ENSO amplitude (as quantified by the standard deviation of the Niño3.4 index). Though the amplitude can vary from one ensemble member to the next in a given model, generally both GFDL-ESM2M and NCAR-CCSM4 have a stronger ENSO than HadISST, while MRI-CGCM3 has weaker variations. An examination of the whole CMIP5 and CMIP3 archives shows that the spread in ENSO amplitudes is significantly reduced in the CMIP5 relative to the CMIP3, but still relatively large (Bellenger et al. 2014).

Some aspects of the model mean state may be important in influencing the characteristics of interannual variability (Guilyardi et al. 2012a). For example, the intensity of the equatorial cold tongue, which helps set the strength of the zonal and meridional SST gradients near the equator, is key for determining how readily atmospheric deep convection spreads into the equatorial eastern Pacific during El Niño. The convection responds to the pattern of total, not anomalous, SST - so to get the warmest total SST on the equator in the east Pacific, an overly intense cold tongue requires an overly intense warm event. Thus models with stronger cold tongue biases tend to shift the ENSO-related atmospheric response farther to the west (Ham and Kug 2015). The westward extension of the cold tongue is also important, since it determines the position of the maximum zonal SST gradient. If the cold tongue extends too far west, the ENSO sea surface temperature anomaly (SSTA) pattern can take on an unrealistic "double-peaked" structure in which SSTAs driven by zonal advection in the west are displaced too far west of SSTAs driven by vertical advection in the east (Graham et al. 2015).

The structure of the time-mean tropical ocean thermocline can also be expected to affect ENSO amplitude in the eastern equatorial Pacific, where vertical temperature advection is one of the leading terms in the heat budget of interannual SSTAs. Sensitivity experiments with an earlier version of the NCAR climate model showed that stronger near-surface vertical temperature gradients, due to a sharper and/or shallower thermocline, resulted in larger SSTAs (Meehl et al. 2001). Similar results were found in GFDL experiments that indirectly perturbed the climatological equatorial thermocline, via changes in the depth of penetration of off-equatorial solar radiation (Anderson et al. 2009). The implication is that vertical mixing and thermal stratification, which affect the equatorial thermocline intensity, can play a very important role in determining the ENSO amplitude.

The magnitude and spatial distribution of the mean surface wind stress also appear to influence some of the ENSO properties - in particular its amplitude - due to the control of the surface zonal wind stress upon the mean upwelling and zonal SST gradient (Wang and An 2002). A tendency for weaker ENSO amplitudes with increasing zonal wind stress in the Niño4 (5°S-5°N, 160°E-150°W) region is detected in the CMIP3 archive (Guilyardi 2006). ENSO events tend to peak during boreal winter (December-January-February), an indication of a phase locking with the annual cycle, and can be viewed as a disruption of the annual cycle. As such, the ENSO amplitude can be expected to be somewhat related to the amplitude of the annual cycle, and indeed an inverse relationship between the ENSO amplitude and the relative strength of the annual cycle is found in the CMIP3 models (Guilyardi 2006; An et al. 2010).

Just as model biases in the climatology can affect ENSO, biases in ENSO can affect the mean state. For example, strong ENSO variability enhances the long-term rainfall in the equatorial central Pacific and also assists with vertical and lateral diffusion of heat by undulating the equatorial thermocline and cold tongue (Watanabe & Wittenberg 2012; Watanabe et al. 2012; Ogata et al. 2013). This two-way feedback between ENSO and the mean state suggests that biases in one aspect could easily affect the other.

The ENSO time evolution is another challenge for the models to reproduce correctly. The spatial pattern of the anomalous zonal wind stress during El Niño - in particular its meridional width and longitudinal position - helps to set the ENSO period by controlling the ocean adjustment timescale. A multiple regression analysis performed on a subset of the CMIP3 models shows a statistically significant relationship between the ENSO period and meridional width/longitudinal position of anomalous zonal wind stress (Capotondi et al. 2006). And many of ENSO's temporal asymmetries – with warm events being shorter, more intense, and more likely to transition to the opposite phase than cold events – also depend on the nonlinearity of the anomalous wind stress response to SSTAs (Choi et al. 2013). But what determines the spatiotemporal patterns of that wind response? Changes in atmospheric parameterizations, in particular of convective momentum transport, have considerably improved the wind stress responses in some GCMs - resulting in a dominant timescale of about four years (similar to observed) and a much broader spectral width, albeit with too large of an amplitude (Wittenberg et al. 2006; Kim et al. 2008; Neale et al. 2008).

An aspect of ENSO that has received much attention over the last decade is the large diversity in spatial patterns among different events (see Capotondi et al. 2015 for a review). Warm events, for instance, range from strong cases - like the 1997-1998 El Niño - with the largest anomalies close to the South American coast, to weaker events that exhibit the largest amplitude in the central equatorial Pacific - like the 2002-2003 El Niño. Since the atmospheric response to SSTAs is very sensitive to the details of those anomalies, a realistic simulation of the full range of ENSO diversity is very important to ensure correct atmospheric teleconnections. However, models seem to have difficulty in reproducing ENSO diversity, as most models, to different degrees, simulate SSTAs that extend too far west relative to observations.

To characterize diversity, ENSO events have often been divided into two groups, with SSTAs peaking in the equatorial eastern or central Pacific. Different criteria have been used to identify these two groups of events, and, accordingly, different definitions have been introduced for them as summarized in Capotondi et al. (2015). Figure 2 compares the composite equatorial profiles of warm ENSO events with maximum anomalies in the eastern and central Pacific for observations and 20 CMIP5 models. While some models (NCAR-CCSM4, CMRM-CM5, GFDL-CM3, GFDL-ESM2M) show distinct zonal maxima for the two groups of events, somewhat similar to the observations, other models (e.g., HadGEM2-CC, HadGEM2-ES, INM_CM4, MIROC-ESM, MRI-CGCM3) display longitudinal evolutions for the two groups that are strongly overlapping. Ham and Kug (2011) and Kug et al. (2012) have related the models' inability to simulate diversity to the severity of the models' cold tongue and precipitation biases, since the confinement of the ENSO-related atmospheric response to the western Pacific may result in a limited range of precipitation and SSTA patterns.

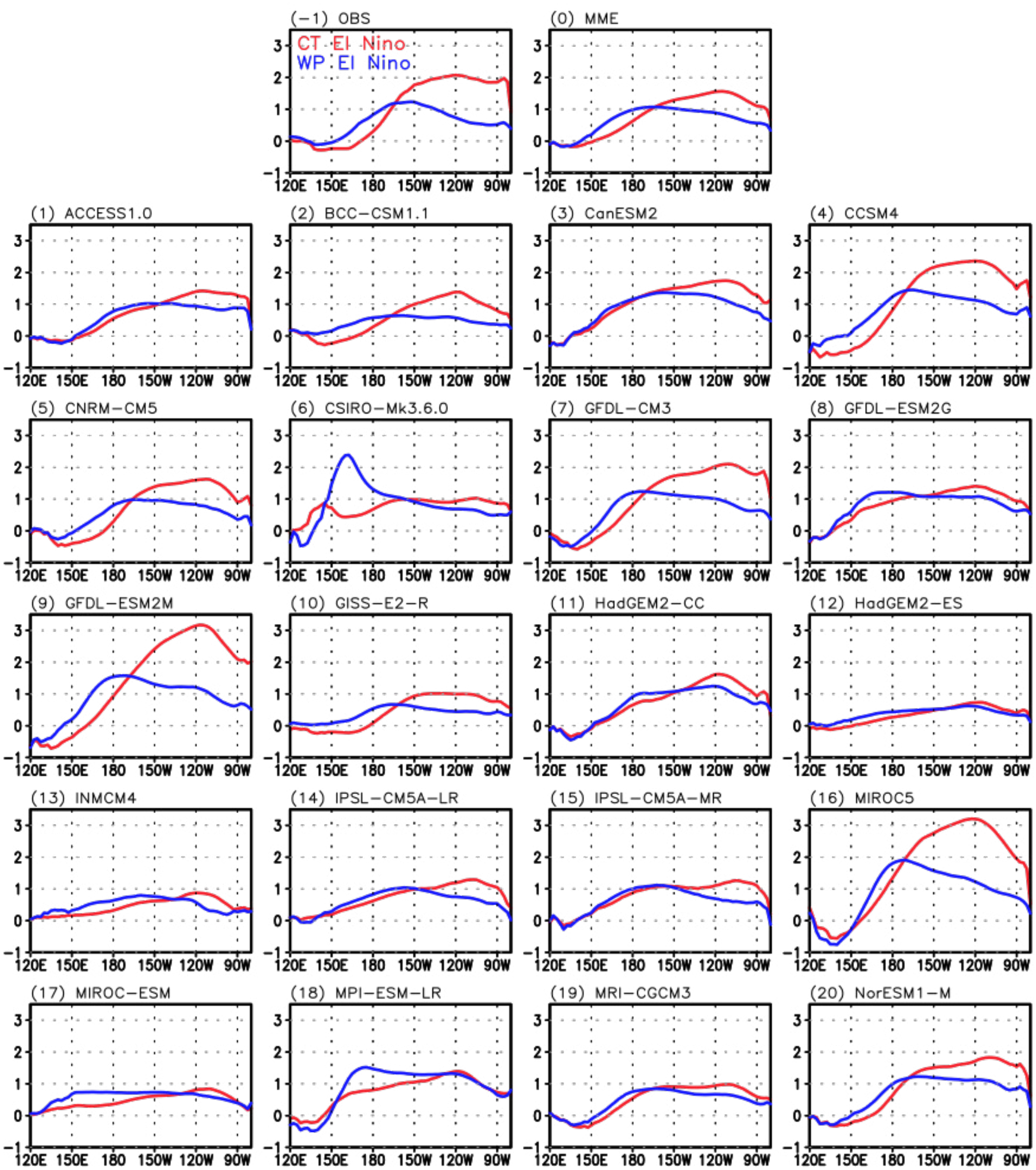

Figure 2. Equatorial average (5°S-5°N) SSTAs for composite "cold tongue" (CT) events (red line) and "warm pool" (WP) events (blue line) for observations (ERSST V2, Smith and Reynolds 2004; panel -1), the multi-model ensemble mean (panel 0) and 20 models from the CMIP5 archive (panels 1-20). CT and WP events are identified using the normalized Niño3 (area averaged SSTAs over 5°S-5°N, 150°W-90°W) and Niño4 (area averaged SSTAs over 5°S-5°N, 160°E-150°W) indices, respectively. CT events are characterized by a value of the Niño3 index greater than one, and greater than the value of the Niño4 index, and vice versa for the WP events. Equatorial profiles are shown as a function of longitude. Vertical axis units are °C.

As computer power increases, there are promising signs that increased model resolution may begin to alleviate some of the longstanding model biases in the mean state, with improvements in ENSO patterns, teleconnections, synchronization to the seasonal cycle, and forecast skill (Delworth et al. 2012; Vecchi et al. 2014; Jia et al. 2015; Krishnamurthy et al. 2015; Yang et al. 2015).

Going forward, a key question is what impact model biases may have on ENSO's sensitivity to external forcings (Vecchi & Wittenberg 2010; Collins et al. 2010). Are models simulating the proper level of intrinsic variability? What about the right sensitivities to natural forcings like volcanoes and anthropogenic emissions of CO2 and aerosols? More tests are needed to evaluate the response of simulated ENSOs to past climates - such as the mid-Holocene, Last Glacial Maximum, and Pliocene - and improved paleo reconstructions are needed to benchmark their performance. Improved observational reconstructions are also needed for the instrumental epoch, especially for dynamical constraints on ENSO feedbacks – including the surface fluxes of heat, water, and momentum, and subsurface advection and mixing. Improved physical diagnostics and metrics are also needed to constrain the dynamics of ENSO (Guilyardi et al. 2012b).

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