SKILL OF REAL-TIME SEASONAL ENSO MODEL PREDICTIONS DURING 2002–11
Is Our Capability Increasing?

by Anthony G. Barnston, Michael K. Tippett, Michelle L. L'Heureux, Shuhua Li, and David G. DeWitt

Table A1. Basic information and references for the 20 ENSO prediction models whose real-time forecasts, and some of their longer-term hindcasts, are evaluated in this paper.

<table>
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<th>Model Type</th>
<th>Key Details</th>
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<td>Fully Coupled or Anomaly Coupled Dynamical Models</td>
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<td>The European Centre for Medium-Range Weather Forecasts (ECMWF)</td>
<td>fully coupled ocean–land–atmosphere model has had two versions over the forecast period. System 2 (S2; Anderson et al. 2003; Balmaseda et al. 2004; Alves et al. 2004) was operational from the beginning of the period through February 2007. Beginning in March 2007 System 3 (S3) was the operational model (Anderson et al. 2007; Balmaseda et al. 2008; Stockdale et al. 2011). The atmospheric model in S3 is cycle 31r1 of the ECMWF Integrated Forecast System (IFS) with a spectral truncation at T159 with 62 vertical levels, while that for S2 was cycle 23r4 with a spectral truncation of T95 and 40 vertical levels. Both S2 and S3 used the same oceanic model, the Hamburg Ocean Primitive Equation Model (HOPE), version 2 (Latif et al. 1994; Wolff et al. 1997), with a horizontal resolution of 1° zonally and a telescoping resolution in the meridional direction of 1° in midlatitudes and 0.33° near the equator. The ocean model has 29 vertical layers with 10-m resolution over the upper 100 m.</td>
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<td>The Met Office (UKMO)</td>
<td>uses the Global Seasonal (GloSea) coupled model. GloSea has had four versions over the period of this study. GloSea1 became operational in March 2003. It was based on the third climate configuration of the Met Office Unified Model (HadCM3) coupled climate model (Gordon et al. 2000). The AGCM component model had a horizontal resolution of 3.75° in the zonal direction and 2.5° in the meridional direction with 19 levels in the vertical. The OGCM component model had a horizontal resolution of 1.25° in the zonal direction and a telescoping grid in the meridional direction with 0.28° resolution near the equator and stretching to 1.25° in the middle and high latitudes. GloSea2 became operational in October 2004 and used essentially the same AGCM and OGCM as version 1; in particular, the component models had the same resolution. GloSea3 became operational in September 2005. The AGCM component model had the same resolution as previous versions and the OGCM horizontal resolution was also the same. GloSea4 (Arribas et al. 2011) became operational in October 2009. The AGCM resolution is 1.25° in latitude and 1.875° in longitude with 38 vertical levels. The OGCM has a horizontal resolution of 1.0° in the zonal direction; in the meridional direction the resolution telescopes from 0.3° near the equator to 1.0° in the middle and higher latitudes with 42 vertical levels.</td>
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The U.S. National Weather Service had two coupled models over the period of study. From 2002 to early 2004 the coupled model was the Coupled Model Project (model version 12) (CMP12; Ji et al. 1998). From March 2004 onward, the model was the Climate Forecast System, version 1 (CFS; Saha et al. 2006). The atmospheric component model of the CFS is the NCEP Global Forecast System (GFS) at a horizontal resolution of T62 with 64 vertical levels. The oceanic component model is the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model, v3 (MOM3) (Pacanowski and Griffies 1998). The ocean model has a horizontal resolution of 1° in the zonal direction and a variable resolution grid in the meridional direction, with 0.33° resolution near the equator stretching to 1° poleward of 30°. The ocean model has 40 vertical levels.

The Center for Ocean–Land–Atmosphere (COLA) anomaly coupled model consists of the COLA atmospheric model at T42 horizontal resolution with 18 vertical layers coupled to the GFDL Modular Ocean Model version 3 (MOM3; Pacanowski and Griffies 1998) with constant 1.5° zonal resolution and meridional resolution that varies from 0.5° near the equator to 1.5° poleward of 30° and 25 vertical layers. Details of the anomaly coupling strategy and forecast skill are described in Kirtman (2003).

The NASA Global Modeling and Assimilation Office (GMAO) coupled model consists of the POSEIDON ocean model (Schopf and Loughe 1995) and NASA's Seasonal-to-Interannual Prediction Project (NSIPPI) AGCM (Bacmeister et al. 2000). The ocean model has a horizontal resolution of 0.625° in the zonal direction and 0.33° in the meridional direction with 27 vertical layers. The atmospheric model has a horizontal resolution of 2.5° in the zonal direction and 2° in the meridional direction with 34 vertical levels.

The Japan Meteorological Agency (JMA) coupled model Three versions of the JMA coupled forecast model have been used during the period of study. The first version called JMA-CGCM01 had an atmospheric component model with T42 horizontal resolution and 21 vertical layers. The oceanic component model had 20 vertical layers, a constant zonal resolution of 2.5°, and a telescoping meridional resolution of 2.0° in middle and high latitudes and 0.5° near the equator with linear stretching in between the boundaries of these two domains. This model was replaced in 2003 by an improved version of the model (called CGCM02) that had the same horizontal resolution atmospheric component model but with 40 vertical layers. The ocean model resolution was the same as in the previous version but the ocean assimilation was now a three-dimensional variational scheme that assimilated temperature, salinity, and sea surface height. The final version of the seasonal forecast model became operational in February 2010. This version of the coupled model is called the JMA/Medium Range Institute (MRI)-CGCM and consists of the JMA/MRI Unified AGCM (JMA 2007) at T95 horizontal resolution with 40 vertical layers and the ocean model is the MRI Community model for GCM (Ishikawa et al. 2005) with longitudinal resolution of 1.0° and variable latitudinal resolution from 0.3° in the equatorial zone to 1.0° in the extratropics with 50 vertical layers.

The Predictive Ocean Atmosphere Model for Australia (POAMA) has used two versions of a coupled ocean–atmosphere model during the study period, both developed at Australia's Bureau of Meteorology Research Centre (BMRC) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine Research. POAMA1.5 (Wang et al. 2002) was in use from 2002 through 2007, while POAMA1.5 (Wang et al. 2008; Hudson et al. 2011; Zhao and Hendon 2009) began in January 2008. The atmospheric models of both versions have T47 horizontal resolution and 17 vertical levels, while the ocean grid resolution is 2° zonally and 0.5° meridionally at the equator, increasing to 1.5° near the poles. The atmospheric GCM is a unified climate/NWP model (version 3), and the ocean GCM is called ACOM2. Ocean initial conditions in both versions are provided by an assimilation using optimum interpolation of ocean temperatures. Atmosphere–land initial conditions are generated using nudging to observed analyses in POAMA1.5 (Hudson et al. 2011), versus Atmospheric Model Intercomparison Project (AMIP)-style initial conditions in POAMA1.5.

The ECHAM-MOM is a coupled atmosphere–ocean GCM system developed at the International Research Institute for Climate and Society (IRI; DeWitt 2005), combining the Max Planck Institute for Meteorology ECHAM4.5 AGCM ( Roeckner et al. 1996) and the GFDL Modular Ocean Model, version 3 (MOM3; Pacanowski and Griffies 1998). The atmospheric model has a horizontal resolution of T42 with 19 vertical levels. The ocean model resolution is the same as described earlier for the COLA anomaly coupled model. Up until June of 2009 the coupling between atmosphere and ocean was direct. Subsequent to that period, half of the 24 ensemble members use an anomaly coupling strategy and the other half are directly coupled. In this newer version of the direct coupled model the surface stress calculation includes the ocean surface current, and the solar cycle used for the coupling has a parameterized diurnal cycle following that of Danabasoglu et al. (2006).

Intermediate or Hybrid Dynamical Models

The Scripps-Max Planck Institute for Meteorology hybrid coupled model (HCM) (Barnett et al. 1993) contains an ocean GCM developed at Max Planck Institute (MPI; Latif 1987), and a statistical atmospheric model using a canonical correlation analysis (CCA)-like scheme to derive the wind stress forcing for the ocean GCM using the GCM's SST. Systematic SST errors in the ocean GCM are corrected in the coupling process. An improved model version (Pierce 1996) used the Hamburg Ocean Primitive Equation (HOPE)-2.4 ocean model from MPI.

The Lamont–Doherty (LDEO) intermediate coupled model, the first dynamical ENSO prediction model (Cane et al. 1986; Zebiak and Cane 1987), uses simplified linear shallow water dynamics for both the ocean and atmosphere, while using more complex nonlinear forms for atmospheric heating and ocean mixed layer thermodynamics. The model has undergone several modifications/improvements, some related to spinup using low-level winds (Chen et al. 1995). LDEOS is currently used (Chen et al. 2004).
The South Korea Meteorological Administration (KMA) Seoul National University intermediate coupled model uses an intermediate ocean model and a statistical atmospheric model. The ocean model is similar to the original Cane and Zebiak model (Cane et al. 1986; Zebiak and Cane 1987), while the statistical atmospheric model uses singular value decomposition (SVD) with wind stress and SST as its input data. Refinements have been made in the use of the wind stress data (Kug et al. 2001). Ensembles are formulated using random noise (Kirtman and Schopf 1998). Multivariate statistical systematic error correction is employed.

The Earth System Science Interdisciplinary Center (ESSIC) intermediate coupled model of the University of Maryland, NASA/Goddard Space Flight Center, and NOAA is described in Zhang et al. (2003), with an ocean model based on the intermediate model of Keenlyside and Kleeman (2002). An empirical procedure parameterizes the subsurface entrainment temperature (T) in terms of sea surface pressure anomalies. The atmospheric model uses singular value decomposition of observed SST and wind stress fields.

### Statistical Models

**The CDC/University of Colorado’s linear inverse model (LIM)** (Penland and Magorian 1993) is a linear multivariate technique used to predict Indo-Pacific SST anomalies using the past history of that field. Predictions are made using a statistically obtained Green function keyed to observed initial SST anomalies. Although the model parameters are obtained statistically, LIM also uses specific dynamically preferred scenarios or optimal growth structures (Penland 1989; Penland and Sardeshmukh 1995).

**The UCLA Theoretical Climate Dynamics (TCD) multiple polynomial regression model** for Indo-Pacific SST anomalies includes both linear and nonlinear stochastically forced models of ENSO (Kravtsov et al. 2005; Kondrashov et al. 2005). The white noise that is used has the spatial correlation properties observed in nature. The regression models capture the maximum variance in the predictor variables and highest correlations with response variables. The nonlinear version of the model produces higher cross-validated skill and is therefore selected.

**The Florida State University (FSU) regression model** is a multiple regression in which equatorial Pacific upper ocean heat content, Indo-Pacific low-level wind stress anomalies, and initial Niño-3.4 SST anomaly are used as predictors for the coming Niño-3.4 SST anomaly (Clarke and Van Gorder 2003). Wind stress anomalies in the western tropical Pacific (Clarke and Van Gorder 2001), and in the eastern Indian Ocean, are integrated variably over time as a function of the season. The weights of the wind stress, heat content, and Niño-3.4 anomaly itself vary by start and lead time, based on the historical data in a cross-validation design.

**The CPC Markov model** (Xue et al. 1994, 2000) works with multivariate EOFs of SST, surface wind stress, and sea level data. Transition matrices are derived among adjacent months, creating a seasonally specific lag-1 Markov model. The operational formula turns out to be closely related to that of linear inverse modeling (Penland and Magorian 1993). For forecasts having longer lead times, the sequence of the appropriate transition matrices is used.

**The Colorado State University (CSU) CLIPER regression model** is a multiple regression using persistence and trends in recent observed SST conditions (Knaff and Landsea 1997). Specific models are used for each calendar month and lead time. When cross-validated skill is insufficient, the climatology forecast is issued. Predictors include 1-, 3-, or 5-month averages of initial predictor anomalies as well as their recent trends. Limits on predictor selection are imposed to reduce overfitting, and skills are degraded from training sample results following Davis (1979).

**The CPC (of NCEP) constructed analog (CA) model** combines the use of analogs and multiple regression to forecast SST in the Niño-3.4 region (Van den Dool 1994, 2007). Construction of a synthetic analog from a weighted average of all of the past cases permits a perfect match to the current climate state. The analog predictor is a set of leading EOFs of the global SST field at several 3-month periods prior to forecast time. The synthetic analogue assigns a weight to each year’s SST state, which is then applied to the subsequently occurring Niño-3.4 SST.

**The CPC (of NCEP) CCA model** captures relationships between evolving patterns in the predictor fields and the SST predictand field (Barnston and Ropelewski 1992). The predictor fields include global seasonal sea level pressure, observed or modeled tropical Pacific thermocline depth (until 2010, when discontinued), and tropical Pacific SST itself. These predictors are taken from several 3-month periods immediately prior to forecast time. The leading EOFs are taken both of the predictor data and the predictand data (Barnett and Preisendorfer 1987), and the time series become the input to the CCA.

**The University of British Columbia (UBC) neurological network model** captures the nonlinear aspects of the ENSO system (Tangang et al. 1997; Hsieh and Tang 1998). Nonlinear functions are defined by a set of neurons between the input and a “hidden layer” (HL), and another set between HL and the output. Here, the predictors are the first four EOFs of tropical Pacific sea level pressure and the Niño-3 SST anomaly for two prior 3-month periods (Tangang et al. 1998), and the predictands are the same at the later time. The UBC’s neural net system has evolved through several versions.