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Ocean Initialization for Seasonal Forecasts

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ABSTRACT. Several operational centers routinely issue seasonal forecasts of Earth's climate using coupled ocean-atmosphere models, which require near-real-time knowledge of the state of the global ocean. This paper reviews existing ocean analysis efforts aimed at initializing seasonal forecasts. We show that ocean data assimilation improves the skill of seasonal forecasts in many cases, although its impact can be overshadowed by errors in the coupled models. The current practice, known as "uncoupled" initialization, has the advantage of better knowledge of atmospheric forcing fluxes, but it has the shortcoming of potential initialization shock. In recent years, the idea of obtaining truly "coupled" initialization, where the different components of the coupled system are well balanced, has stimulated several research activities that will be reviewed in light of their application to seasonal forecasts.

INTRODUCTION

The skill of climate system forecasts at the seasonal scale largely depends on the ocean initial conditions fed into models, in particular, information on the ocean's upper thermal structure. Data gathered from ocean instrumentation is commonly used as input for the initial conditions. Assimilating data into models is important because it improves the estimation of ocean state, which in principle should improve the skill of seasonal forecasts.

Seasonal forecasting is now a routine activity in several operational centers around the world, requiring near-real-time knowledge of the state of the ocean. Seasonal forecasting systems are based on coupled ocean-atmosphere general circulation models that predict sea surface temperatures (SSTs) and their impact on atmospheric circulation. Ultimately, the aim of seasonal forecasts is to predict climate anomalies (e.g., temperature, rainfall, frequency of tropical cycles) for the forthcoming seasons (about one or two seasons ahead).

This paper summarizes the advances in seasonal forecasts during the past decade. It offers a brief description of assimilation systems used in operational seasonal forecasts and discusses the impact of data assimilation on ocean state estimates and seasonal forecasts. Finally, we briefly review recent coupled initialization procedure initiatives.

OCEAN INITIALIZATION IN EXISTING SEASONAL FORECASTING SYSTEMS

Table 1 summarizes the ocean analyses used for initializing operational or quasi-operational seasonal forecast systems. In all these systems, initialization of the ocean and atmosphere is done separately, with the goal of generating the best analyses of the ocean and the atmosphere

Table 1: Summary of different ocean assimilation systems used to initialize operational and quasi-operational seasonal forecasts

Analysis Product (Institute)	Assimilation System
MRI-JMA: http://ds.data.jma.go.jp/tcc/tcc/products/elnino/index.html	MOVE/MRI.COM-G: Multivariate 3DVAR; Usui et al., 2006
ORA-S3 (ECMWF): http://www.ecmwf.int/ products/forecasts/d/charts/ocean ECMWF System 3: http://www.ecmwf.int/products/forecasts/d/charts/seasonal	HOPE/OI: Multivariate OI; Balmaseda et al., 2008a
POAMA-PEODAS (CAWCR, Melbourne): http://poama.bom.gov.au/research/assim/index.htm	Multivariate Ensemble OI: Alves and Robert, 2005
GODAS (NCEP): http://www.cpc.ncep.noaa.gov/products/GODAS	MOMv3/3DVAR: Behringer, 2007
Mercator (Meteo France): http://bulletin.mercator-ocean.fr/html/welcome_en.jsp	PSYS2G: Multivariate reduced order Kalman filter; Pham et al., 1998
MO (Met Office): http://www.metoffice.gov.uk/research/seasonal	Glosea3.OI: Martin et al., 2007
GMAO ODAS-1: http://gmao.gsfc.nasa.gov/research/oceanassim/ODA_vis.php GMAO Seasonal Forecasts: http://gmao.gsfc.nasa.gov/cgi-bin/products/climateforecasts/index.cgi	ODAS-1 OI and EnKF: Keppenne et al., 2008

through comprehensive data assimilation schemes in both media.

The production of seasonal forecasts is resource demanding, and the computational burden limits the practical resolution of an ocean model, which is typically about 1° with some equatorial refinement in the horizontal, and about 10 m in the vertical in the upper ocean. The emphasis is on initializing the upper ocean thermal structure, particularly of the tropics, where SST anomalies strongly influence atmospheric circulation. The quality of ocean analyses greatly depends on the atmospheric fluxes used to drive the ocean model in the production of the first guess. The forcing fluxes are usually provided by atmospheric reanalyses and by numerical weather prediction systems. A key parameter in the ocean analysis is SST. Most initialization systems also use subsurface temperature and, most recently, salinity (mainly from Argo) and altimeter-derived sea level anomalies. The latter usually need external mean dynamic topography to be prescribed, and this can be derived indirectly from gravity missions. Some of the initialization systems use an online bias correction scheme or relaxation to climatology to control the mean state.

IMPACT OF DATA ASSIMILATION ON OCEAN STATE

The simplest way to initialize the ocean is to run an ocean model forced with atmospheric fluxes and with strong relaxation of the model SST to observations. This technique (control run, or CNTL) would be satisfactory if errors in the forcing fields and ocean model were small. However, surface flux products and ocean models are both known to have significant errors. The uncertainty induced in the upper ocean by using different wind products can be as large as the interannual variability. Data assimilation is then used to constrain the ocean state estimation.

To evaluate the impact of data assimilation on the estimated ocean state, it is necessary to verify against independent data, such as velocity, which is usually not assimilated. This evaluation is used by Balmaseda et al. (2008b) to illustrate progress in ocean data assimilation methods during the last decade, showing results from the current and a previous generation of ocean analyses. The first generation assimilated only temperature data, and no other variable apart from temperature was modified directly by the assimilation system (i.e., there were no multivariate balance relationships). The current (second) generation of ocean analyses often assimilates salinity and altimeter data in addition to temperature, and imposes multivariate balance relationships. For instance, a constraint between temperature and salinity is frequently imposed so as to preserve water mass characteristics (Troccoli et al., 2002), or a geostrophic balance between the horizontal velocities and changes in density is imposed (Burgers et al., 2002). All of the analysis systems in Table 1 belong to this second generation. In the first generation of analyses, the fit to the temperature data improved with respect to the CNTL, but at the expense of degrading the ocean currents and ocean salinity. In the second generation, exemplified in the study by the PEODAS ocean assimilation system analysis in Table 1 (Alves and Robert, 2005), the fit to both temperature and salinity is greatly improved with respect to the CNTL without significant degradation of the ocean currents.

Fujii et al. (in press) also discuss the importance of the balance relationships. They argue that the relationship between temperature and salinity (T-S) can influence the representation of interannual SST variability. By conducting twin experiments with the MOVE/MRI.COM-G system mentioned in Table 1 (Usui et al., 2006), they show that without maintaining the T-S relationship, it is not possible to represent the high salinity of South Pacific Tropical Water, and this limitation leads to erosion of vertical stratification and eventual degradation of the barrier layer. The barrier layer acts as a reservoir of warm water (above 28°C), which can be instrumental for the development of El Niño when propagated eastward by westerly winds.

IMPACT OF DATA ASSIMILATION ON SEASONAL FORECAST SKILL

The skill of the seasonal forecasts is often used to gauge the quality of the ocean initial conditions. This measure may not always be appropriate, because the quality of the coupled model will determine the precision of the assessment—if the major source of forecast error comes from the coupled model, improvements in the ocean initial conditions would have little impact on forecast skill. This is something to bear in mind when interpreting results of the impact of ocean data assimilation on seasonal forecasts.

Alves et al. (2004) found that data assimilation improved the skill of seasonal forecasts using the first version of the European Centre for Medium-Range Weather Forecasting (ECMWF) seasonal forecasting system. Balmaseda and Anderson (2009), using the latest version of the ECMWF seasonal forecasting system mentioned in Table 1, evaluate three different initialization strategies, each of which uses different observational information. Strategy 1 uses ocean, atmospheric, and SST information; Strategy 2 uses atmospheric information and SST; and Strategy 3 uses only SST. Differences between Strategies 1 and 2 are indicative of the impact of ocean observations, and comparison of 2 and 3 is indicative of the impact of atmospheric observations.

Results show that ocean initialization has a significant impact on the mean state, variability, and skill of coupled forecasts at the seasonal time scale. Figure 1 shows the relative reduction in the monthly mean absolute error (MAE) resulting from adding information from the oceanic and/or atmospheric observations for the one- to three-month forecast range in the regions defined in Table 2. The observational information has the largest impact in the western Pacific (EQ3): combining ocean and atmospheric observations can reduce the MAE more than 50% in the first three months. With the exception of the equatorial Atlantic (EQATL), Strategy 1 achieves the best scores. This means that, for the ECMWF system, the benefits of ocean data assimilation and the use of

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fluxes from atmospheric (re)analyses more than offset problems arising from initialization shock.

The positive impact of assimilating ocean data has also been confirmed using the Predictive Ocean Atmosphere Model for Australia (POAMA) seasonal forecasting system. The ocean initial conditions from the new PEODAS reanalysis (see Table 1) produced better forecast skill than the CNTL (without data assimilation). This skill is also better than that obtained with a previous ocean analysis, which did not use balance relationships. This result illustrates the importance of multivariate formulations to guarantee that observational information is retained during the forecast (Balmaseda et al., 2008b).

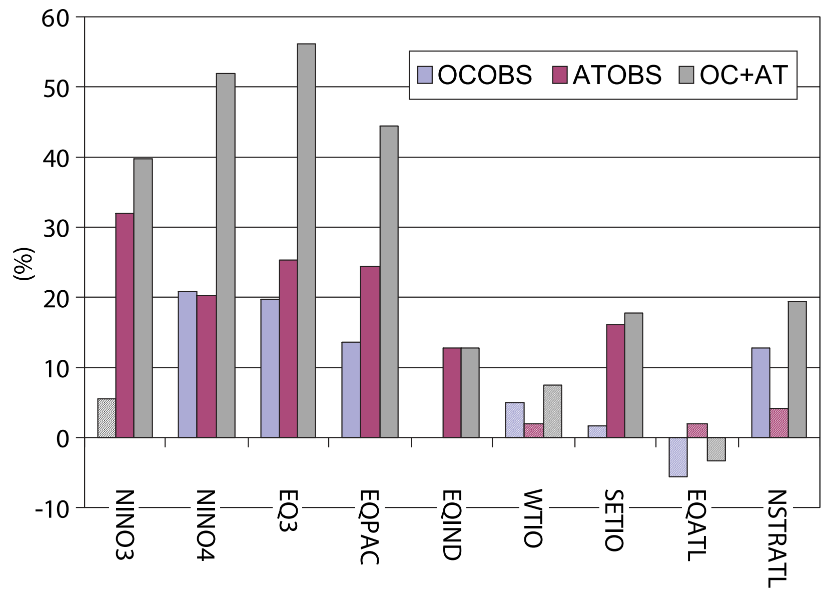

Figure 1. Impact of initialization on forecast skill for the different regions in Table 2, as measured by the reduction in mean absolute error for a one- to three-month forecast range. Solid bars indicate differences are above 80% significance level. Blue (OCOBS) indicates the impact of ocean observations, red (ATOBS) indicates the impact of atmospheric data, and grey (OC+AT) represents the combined impact of atmospheric and oceanic data.

Table 2. Definition of area average indices

NINO12	10°–0°S, 90°–80°W	EQPAC	5°S–5°N, 130°E–80°W
NINO3	5°S–5°N, 90°–150°W	EQIND	5°S–5°N, 40°–120°E
NINO34	5°S–5°N, 170°–120°W	WTIO	10°S–10°N, 50°–70°W
NINO4	5°S–5°N, 160°E–150°W	STIO	10°S–0°N, 90°–110°E
EQ3	5°S–5°N, 150°E–170°W	EQATL	5°S–5°N, 70°W–30°E
NINO-W	0°–15°N, 130°–150°E	NSTRATL	5°N–28°N, 80°W–20°E

Dommenget and Stammer (2004) investigated the impact of ocean state estimates produced by the Estimating the Circulation and Climate of the Ocean (ECCO) project on seasonal forecasts. A series of seasonal hindcasts using the Massachusetts Institute of Technology (MIT) ocean model coupled to a statistical atmosphere showed that the anomaly correlation of SST forecasts was improved by assimilating data. However, it was thought that the impact of ECCO initial conditions in El Niño Southern Ocean (ENSO) forecasts was probably limited by the low quality of the statistical atmosphere. More recently, the impact of ocean data assimilation on El Niño forecasting has been tested using the ECCO-University of California, Los Angeles (UCLA) coupled system (Cazes-Boezio et al., 2008) by initializing ENSO hindcasts with the states obtained from the ECCO-Jet Propulsion Laboratory (JPL) ocean estimates (Fukumori, 2002) with and without data assimilation. The hindcasts initialized from the assimilation showed better skill in SST prediction.

Seasonal forecast skill can also be used to evaluate the ocean observing system. Fujii et al. (2008) evaluate the impact of the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) array and Argo float data on the Japanese Meteorological Agency (JMA) seasonal forecasting system by conducting data-retention experiments. Figure 2 shows the increase in root mean square errors (RMSEs) of SST hindcasts resulting from the exclusion of Argo and TAO/TRITON from the ocean initial conditions. The results are for a range of one to seven months in the regions defined in Table 2. Results show that TAO/TRITON data improve the SST forecast in the eastern equatorial Pacific (NINO3, NINO4), and that Argo floats improve SST prediction in all the areas of the equatorial Pacific and also have a positive (albeit modest) impact in the western Indian Ocean. Similar results have been obtained with the ECMWF seasonal forecasting system (Balmaseda and Anderson, 2009; Oke et al., 2009).

NEW DEVELOPMENTS IN COUPLED MODEL INITIALIZATION

The term *initialization shock* refers to the adjustment process that takes place when the ocean and atmosphere initial conditions are not a solution of the coupled model. If the initialization adjustment is large, it can degrade the skill of seasonal forecasts. Separate initialization of ocean and atmosphere is prone to initialization shock, because it is not possible to impose balance constraints between the ocean state and the coupled model. Alternative strategies to avoid initialization shock offer promising results and are currently being explored at different institutions.

Sugiura et al. (2008) demonstrate the feasibility of a four-dimensional variational coupled data assimilation system (4DVAR CDA) for a global coupled ocean-atmosphere model. Both initial conditions and parameters controlling the air-sea interaction can be modified by the analysis system. Several key events, such as El Niño, the Indian Ocean dipole, and the Asian summer monsoon, are successfully represented by 4DVAR CDA. Preliminary results suggest that the system has the potential for initialization of coupled ocean-atmosphere models for seasonal and interannual predictions.

Developments for assimilating ocean observations within a coupled model via an Ensemble Kalman Filter (EnKF CDA) are underway at NASA's Global Modeling and Assimilation Office (GMAO) and at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), aiming at the initialization of seasonal and decadal forecasts. A nice feature of EnKF CDA is that the ensemble of analyses can be used as initial conditions for the ensemble of coupled forecasts. An ocean analysis for the period 1979–2008 that used the GFDL CDA system (Zhang et al., 2007) may be found at http://data1.gfdl.gov/nomads/forms/assimilation.html.

The coupled ocean-atmosphere balance can also be considered in the creation of initial perturbations for forecast ensembles. This approach is being pursued at GMAO using so-called coupled bred vectors (BV), which aim to capture the uncertainties related to slowly varying coupled instabilities, especially those related to ENSO. Yang et al. (in press) show that BVs improve ensemble mean SST forecasts. Their study also shows that BVs capture information on flow-dependent uncertainty that can be used for background error covariances in ocean assimilation, improving water mass distribution in the analysis.

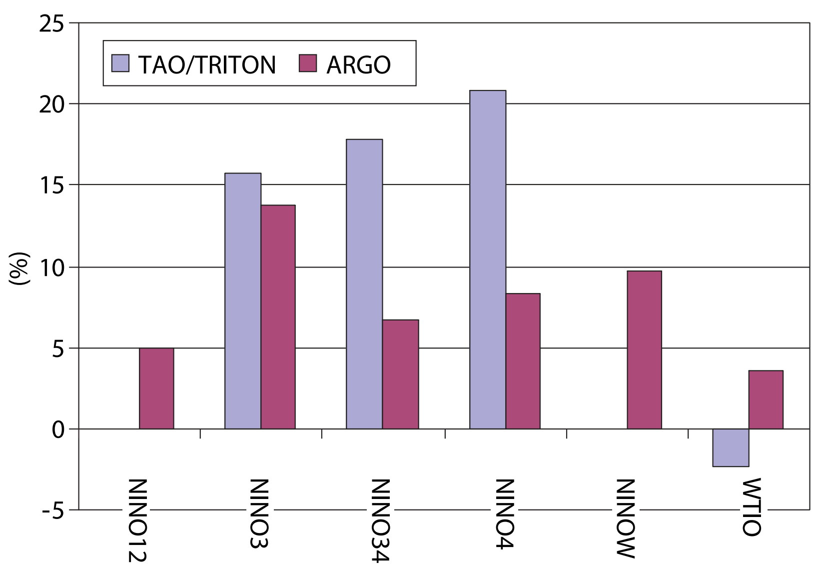

Figure 2. Impact of Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) and Argo data on seasonal forecast skill. The bars show the relative increase in root mean square errors of one- to seven-month forecasts of monthly sea surface temperature resulting from withholding TAO/TRITON and Argo data from the initialization of seasonal forecasts. The regions are defined in Table 2. *From Fujii et al. (2008)*

CONCLUSIONS

Assimilation of ocean observations into models is now commonly used to estimate ocean conditions, which are in turn used to initialize seasonal forecasts. Modelers at several institutions around the world produce routine ocean reanalyses to initialize their operational seasonal forecasts. These ocean reanalyses are reconstructions of ocean history that provide a valuable resource for climate variability studies, having the advantage of being continuously actualized with the latest (real-time) ocean state. They are being used experimentally for the initialization of decadal forecasts.

The first generation of ocean initialization systems was univariate and assimilated only temperature data. These systems were able to reduce uncertainty in the thermal structure, and would sometimes improve the forecast skill. However, the resultant velocity and salinity fields were often degraded. Currently, most ocean initialization systems are second generation: they assimilate temperature, salinity, and sea level via multivariate schemes, imposing physical and dynamical constraints among different variables. Results from several of these "second-generation initialization systems" show that ocean initialization using data assimilation improves seasonal forecast skill, although, ultimately, the impact of initialization in a seasonal forecasting system depends on the quality of the coupled model.

In most existing operational systems, ocean initialization is still done in an uncoupled mode, and there is no attempt to obtain ocean initial conditions that are balanced within the coupled system. By using surface fluxes from atmospheric reanalyses, uncoupled initialization has the advantage of incorporating relevant atmospheric variability, such as westerly wind bursts. However, unbalanced initialization can lead to initialization shock, which is likely to be larger in those regions where the model and the observed climate are far apart. A third generation of initialization systems is on its way, where oceanic and atmospheric initial conditions are generated simultaneously using a coupled model and so have the potential of retaining the balances relevant for the coupled system.

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