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Data Assimilation for the Coupled ESPC Model

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LONG-TERM GOALS

To improve U.S. Navy's Earth System Prediction Capability (ESPC) by assimilating observations that are sensitive to the coupled dynamics of the coupled ocean-atmosphere-ice-wave system.

OBJECTIVES

Develop practical data assimilation algorithms that will allow assimilation of observations relevant to the coupled dynamics.

Implement and test developed algorithms with a minimal impact on the existing modeling infrastructure.

APPROACH

To minimize the development risks and to maximize the re-use of the existing software, we propose to implement coupled data assimilation using the interface solver framework (Frolov et al. 2015) in which the existing ocean data assimilation (DA) scheme (NCODA) (Cummings and Smedstad 2013) is modified to assimilate key atmospheric observations and the existing Hybrid atmospheric DA scheme (Hybrid NAVDAS-AR) (Kuhl et al. 2013) is modified to also assimilate key oceanic observations (see schematic description in Figure 1). The required inter-fluid error covariance models will be built using the sample covariance of both archived off-line seasonally relevant error proxies and real-time on-line flow dependent ensemble perturbations. Mathematical analysis shows that the analyses obtained from this interface solver approach can be made to have vanishingly small differences from a bottom-of-the-ocean-to-top-of-the-atmosphere type solver (Frolov et al. 2015).

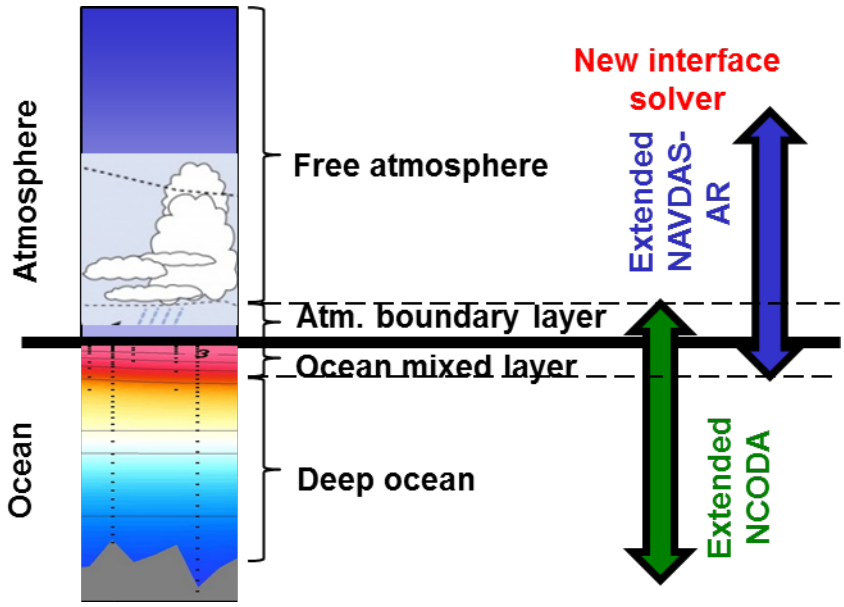

Figure 1: schematic description of the interface solver shows that the existing NAVDAS-AR and NCODA solvers will be modified to accept innovation from the coupled fluid. Only innovations in the interface layer will be accepted.

The interface solver allows us to update the atmospheric and ocean states by assimilating both in-situ and remote sensing observations of the full coupled state near the interface, such as scatterometer wind measurements, as well as coupled radiance observations that measure an integral of low-level atmospheric moisture and temperature and Sea Surface Temperature (SST).

For both observation types, we will specify the missing cross-fluid covariances and TLM models using coupled ensembles. A prototype of this system has been already developed in the mesoscale application using the ocean NCODA solver (Frolov et al. 2015). We propose to fully test this prototype in a global system under this work unit. In case of the atmospheric solver, we propose to incorporate coupled covariances and an Ensemble Tangent Linear Model (ETLM) and adjoint operator inside of the Hybrid-NAVDAS-AR solver.

To assimilate coupled radiance measurements, we propose to also use the readily available information from the radiative transfer model to translate the impact of the radiance innovation in to the coupled state of the ocean and atmosphere. Then, we will use either the NCODA (in the ocean) or the NAVDAS-AR (in the atmosphere) system to spread the information from the observation locations to the rest of the gridded state. This radiance assimilation capability was already demonstrated for SST estimation using version 4 of the NCODA solver and was shown to be beneficial over assimilation of traditional SST retrievals. In the case of the NAVDA-AR solver, we will implement this capability by adding SST as one of the estimated state variables. The missing cross-fluid (and oceanic) tangent linear model will either be set to zero (one) or specified using ensemble-based TLM (ETLM) methodology (Frolov and Bishop 2015). The initial-time coupled error covariance will be specified using a combination of climatological and flow-dependent ensemble members.

Using the proposed approach, we will obtain two estimates of the SST field: one inside of the coupled NCODA solver and one inside of the coupled NAVDAS-AR solver. We expect these estimates to be very close because they will use the same first guess from the coupled model and they will use a very similar set of SST-sensitive observations. However, we do expect these two estimates to be slightly different, in part because they will be produced on different resolution grids and in part because they will be constraint by slightly different set of measurements. However, we expect that these differences can actually be beneficial to reducing the forecast errors of the coupled model.

The key performers on this work unit are Craig Bishop and Sergey Frolov from NRL-Monterey and Charlie Barron and Clark Rowley from NRL-Stennis.

WORK COMPLETED

A detailed comprehensive work plan was developed this year that outlines future technical milestones. The proposed work includes analysis of flux errors and assimilation of cross-interface flux-related properties at the ocean atmosphere interface, implementation of a diurnal SST observation operator to provide the appropriate background context for assimilating observations sensitive to diurnal surface temperature variations, and development of NCODA to implement the interface solver and the use of ensemble or hybrid covariances relating to boundary layer properties. Development and evaluation of coupled covariances will initially be based on hindcast coupled model reanalyses, preparing the way for covariances derived from real-time coupled ensemble forecasts that are under development in companion work units. Work on NAVDAS-AR focuses on incorporating SST into the NAVDAS-AR analysis state. The proposed work builds on simple model studies and previous efforts including Frolov et al. 2015 and May et al. 2015. This work plan was developed in close collaboration between scientists in NRL-SSC and NRL-MRY. To sustain communications between the two groups of scientists, we established a bi-weekly phone conference focused on problems of coupled data assimilation and coupled ensemble generation. This teleconference proved to be a useful tool and we plan to continue with this schedule in FY 2016.

In collaboration with the Coupled Ensembles work unit (WU-3), we developed several prototypes of the ocean ensemble based on the perturbed observation theory (performers, Rowley, Frolov, Bishop). The developed code will be tested with a global HYCOM ensemble in FY16.

RESULTS

(i) Experiments with idealized coupled model

To provide a simple framework to test and evaluate strategies for coupled data assimilation, a new simplified coupled model was created by carefully linking four versions of model 1 of Lorenz (2005). The resulting model has two atmospheric levels of 20 variables and two oceanic levels of 100 variables each. The upper most atmospheric layer has only weak coupling to the other layers. It features relatively large scale chaotic waves with predictability time scales very similar to the atmosphere (~10 days). The lower atmospheric layer has a moderate coupling to the upper ocean layer. It features chaotic waves of a similar scale to the upper atmosphere, but the predictability time scale is longer (~45 days) due to its coupling to the more slowly evolving ocean. The upper most ocean level is moderately coupled to the lower atmosphere and features chaotic waves with wavelengths characteristic of both the large scale waves of the upper atmosphere and the smaller scale waves of the deeper ocean. Its predictability limit is also about 45 days. The lowest ocean layer has relatively weak

coupling to all other layers and features chaotic but slowly evolving waves of a much smaller length scale than in the atmosphere. The predictability limit of waves in this deepest layer is about 180 days.

While we hope to use the model to explore other ideas in the future, so far we only have used it test whether an ensemble initialized by random draws from climatological states would be of use in initializing coupled and uncoupled Ensemble Kalman Filter data assimilation schemes. In order to avoid having to localize the ensemble covariances, we used a 480 member ensemble. The black lines on Figure 2 depict the initial state of these ensemble members. The yellow line gives the ensemble mean. The red line depicts the initial truth and the cyan crosses give the error prone observations to be assimilated in the first data assimilation cycle.

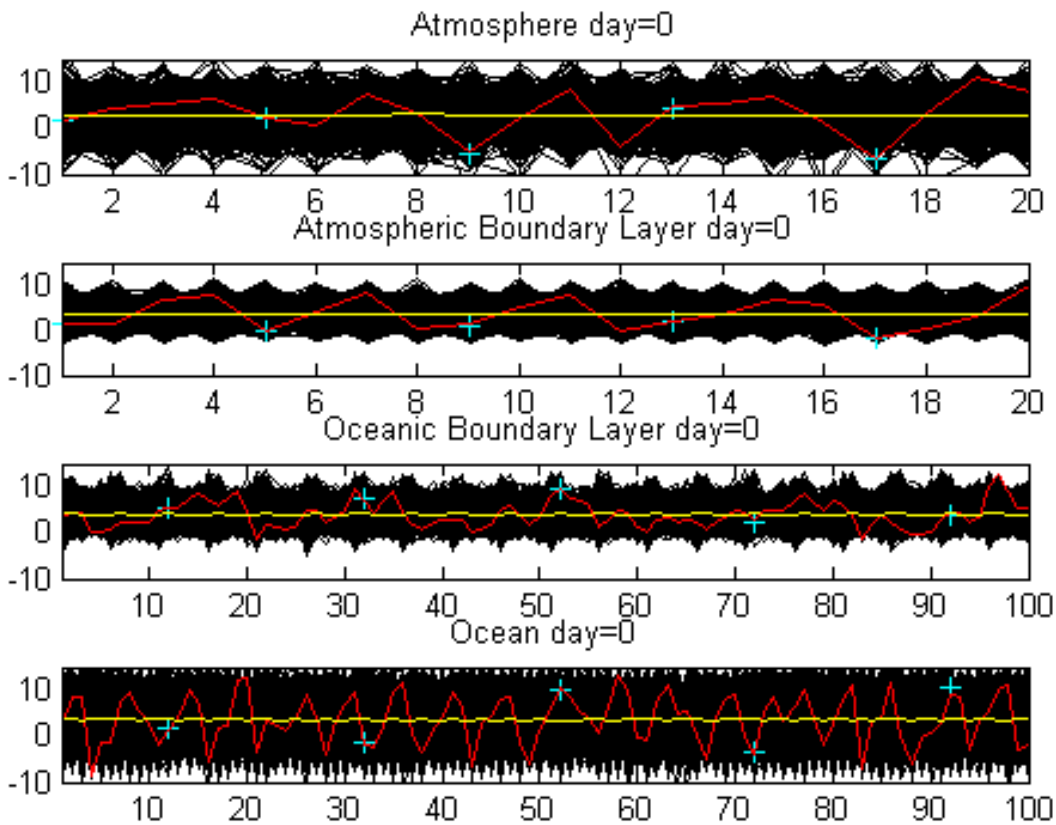

Figure 2: Ordinate axis gives the value of the models "temperature-like" variables at each of the levels. Abscissa axis gives both the horizontal location of the model variable and the horizontal index of the associated grid point. Red line gives the initial true state of the idealized coupled model. Black lines give individual ensemble members obtained by randomly sampling the climatology of the model. The yellow line gives the mean of this ensemble. Cyan crosses give the locations and values of error prone observations.

The observations were assimilated in two distinct ways:

(i) Strongly coupled mode in which a perturbed observations EnKF uses observations from the ocean and atmosphere to update the ensemble at every single model grid point, and

(ii) Weakly coupled mode in which only atmospheric (oceanic) observations are used to update the atmosphere (ocean)

After using the observations to initialize the ensemble, a 6 hr forecast was made and then this was used to assimilate a new set of observations valid at that time. In this way, two parallel 6 hr data assimilation cycles were performed for 5 days and one can simply measure how the mean square error of the ensemble mean evolves as these analyses are performed. In addition, it is straight-forward to repeat the procedure by this time using a different random draw from climatology as the initial truth, and differing random number of observation errors, etc. Repeating the procedure in this statistically independent way, allows one to accurately measure the statistical significance of any found differences between weakly coupled and strongly coupled data assimilation. Twenty eight independent 5 day data assimilation experiments were performed for both strongly and weakly coupled data assimilation. Each line on Figure 3 shows how the mean square error (mse) of the analysis ensemble mean evolved through time in each of these experiments. The fact that the dashed blue lines give higher mse than the solid black lines in the first 4-5 data assimilation cycles suggests that (a) strongly coupled DA was significantly superior to weakly coupled DA, and (b) that the climatological ensemble is a good basis with which to perform coupled data assimilation.

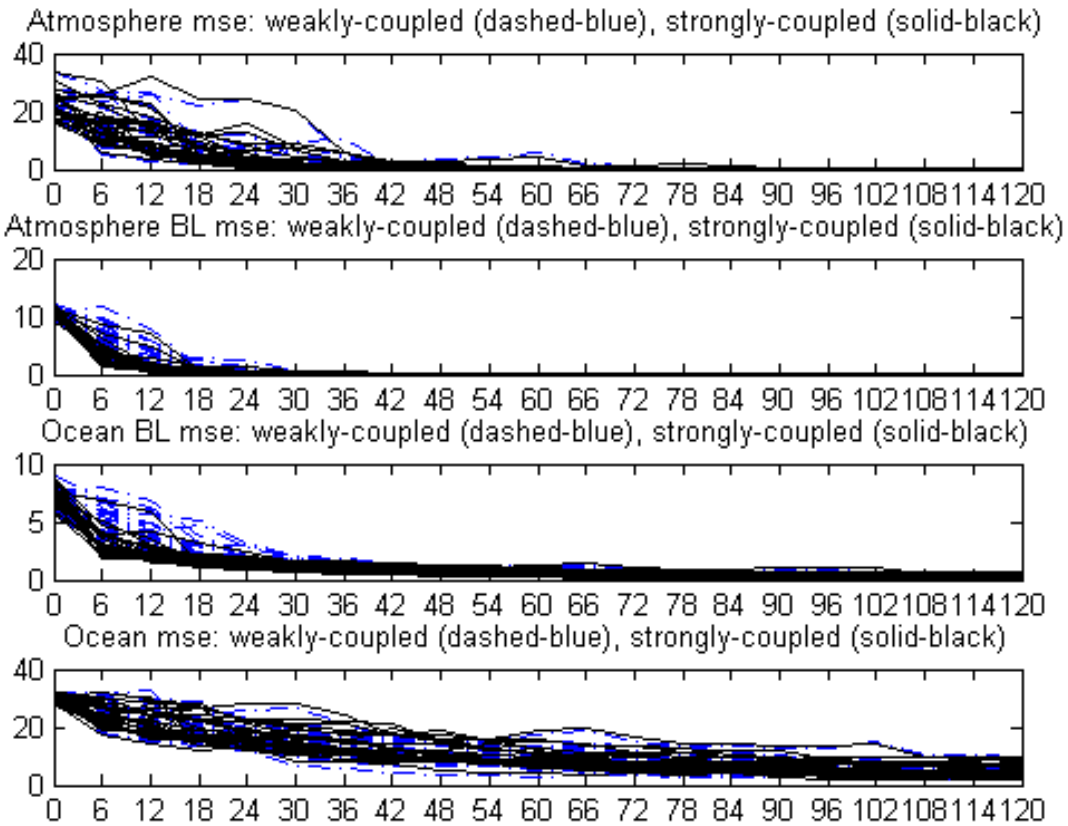

Figure 3: Ordinate-axis is mse, Abscissa-axis is time (in hrs). DA was performed every 6 hrs. Blue lines pertain to weakly-coupled DA, black lines pertain to strongly-coupled DA.

The magnitude and statistical significance of these apparent improvements is given in Figure 4. It shows that the reduction in mse due to strongly coupled data assimilation is statistically significant in the atmospheric and oceanic boundary layers over almost the entire 5 day data assimilation period. The

percentage improvement is particularly large in the first data assimilation experiment – when the pure climatological ensemble is employed.

One can also notice from Figure 4 that strongly coupled DA also produced intermittent, small, statistically significant degradations in the upper atmosphere and deep ocean. One of our next tasks in this simple model work will be to see whether Frolov et al's (2015) proposed interface solver can preserve the benefits of strongly coupled DA in the boundary layers while removing deleterious effects far from the interface.

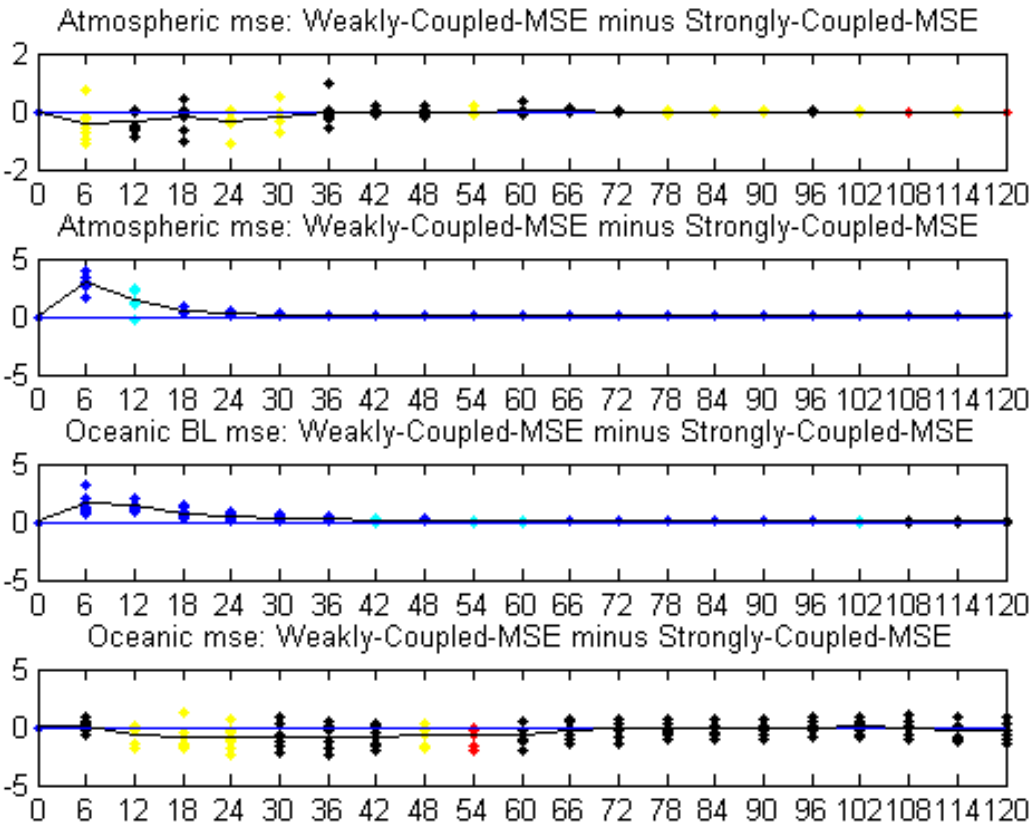

Figure 4: Blue diamonds => 99% statistical confidence in superiority of strongly-coupled over weakly coupled. Cyan diamonds => 95% statistical confidence in superiority of strongly-coupled over weakly coupled. Yellow diamonds => 95% statistical confidence in superiority of weakly-coupled over strongly coupled. Red diamonds => 95% statistical confidence in superiority of weakly-coupled over strongly coupled. Black diamonds => statistical confidence, either way, is less than 95%

(ii) Tests of interface solver approach using COAMPS

In the context of the coupled model COAMPS applied to the Mediterranean region, Frolov et al's (2015) tests with the interface solver showed that it is possible to achieve the same results as an exhaustive assimilation of all observations with assimilating just a small subset of relevant (interfacial) observations from the coupled fluid (Figure 2 below). Frolov et al. (2015) also show that the interface solver provides a wider variety of options for ameliorating imperfections in the inter-fluid covariances

used in strongly coupled data assimilation. All in all, these results serve to support our work plan that puts the interface solver as the centerpiece of our work plan for coupled Data Assimilation for the ESPC system.

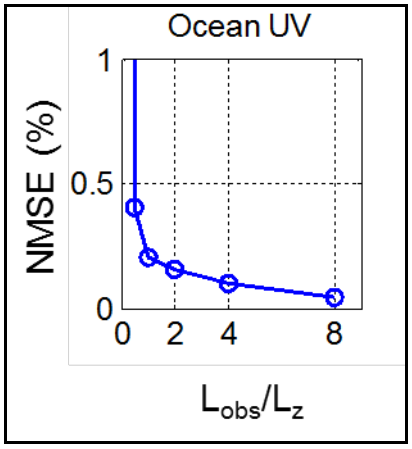

Figure 5: Reduction in ocean velocities errors (y-axis) as more observations from the atmosphere are assimilated. X-axis indicates the height of the atmospheric observations that were included in the assimilation. The L_{obs}/L_z=0 indicates that no atmospheric observations were assimilate; L_{obs}/L_z=2, that all atmospheric observations within the boundary layer were assimilated; and L_{obs}/L_z=0, that all atmospheric observations were assimilated. This figure presents twin experiment results over the Mediterranean Sea (Frolov et. al. 2015).

(iii) Ensemble generation using perturbed observations form of NCODA

To facilitate the development of the ocean ensemble, we developed an ensemble generation technique based on perturbed observations. Our initial tests for sea surface temperature and NCOM regional fields showed good (linear) relationships between the spread of the ensemble and the magnitude of forecast errors (Figure 6 below). Further work will be needed to tune the developed ensembles to ensure that the average magnitude of spread is similar to the average magnitude of errors. This result encouraged our team (in collaboration with the work unit 3) to develop the perturbed observation code for the global HYCOM model that will start testing in FY2016.

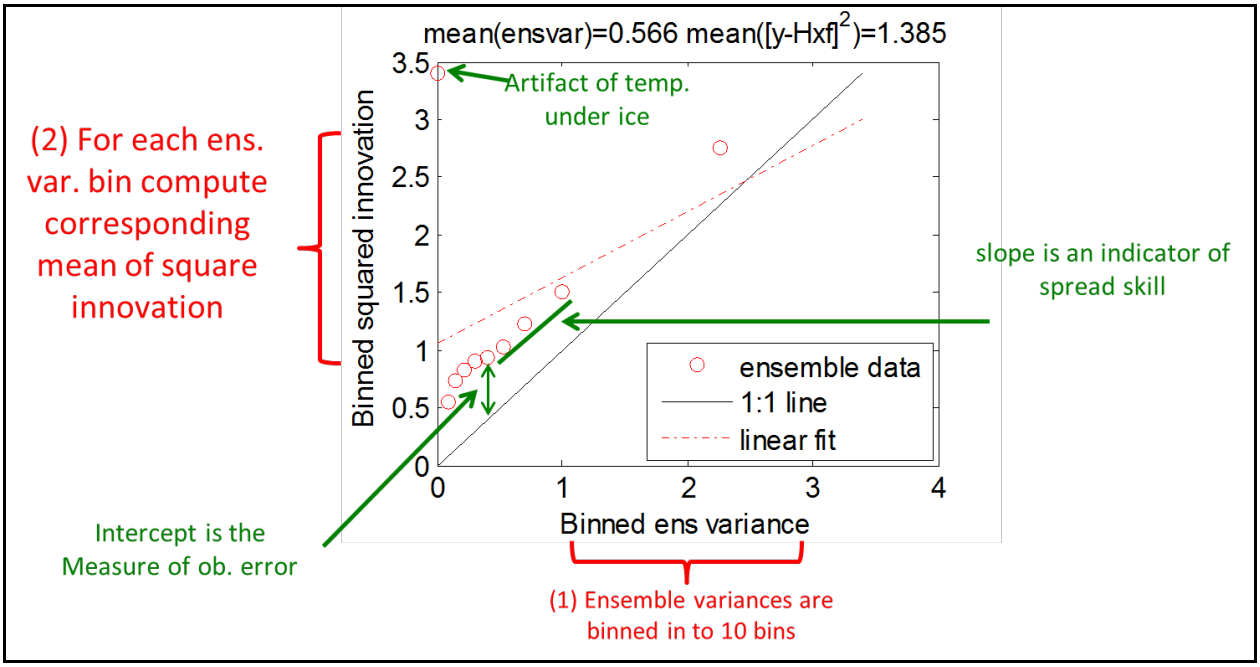

Figure 6: Spread skill-diagnostic is used to verify the skill of the SST ensemble. Good linear relationship of binned errors shows that ensemble has more spread where forecast errors are larger. The offset from the 1:1 relationship can be used to diagnose the magnitude of the observation error.

IMPACT/APPLICATIONS

Improved analyses of the coupled state will improve coupled model probabilistic forecasts by reducing initial condition error, helping ensure that the initial ensemble perturbations are consistent with the best available estimates of analysis errors, and by helping model developers identify errors in the coupled model. Such coupled model probabilistic forecasts ought to provide some skill in the sub-seasonal and seasonal forecast range, and thus be of assistance to the planning and execution of weather sensitive military activities.

RELATED PROJECTS

This interface solver and framework for incorporating coupled covariances into NCODA arise directly from the ONR 6.2 project "Ocean-Atmosphere State Estimation and Targeted Observing using Coupled Model Ensembles". The dependence in this work unit on coupled ensembles will be served in part by WU3, and some of the infrastructure required for coupled interface data assimilation will be generated by the data assimilation system developed for WU-1 for the multi-year reanalysis.

Work on the incorporating observations within the boundary layer between the ocean and atmosphere into flux estimates for assimilative guidance of ocean analyses and forecasts has been proceeding under the NRL base 6.2 Calibration of Ocean Forcing with satellite Flux Estimates (COFFEE) and PMW120 6.4 NFLUX projects. Development of global ocean ensembles, covariances, and assimilation-related capabilities such as an ensemble Kalman filter compose key elements of the NRL base 6.2 Decision Making Using Global Probabilistic and Uncertainty Forecasts project.

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Frolov, S., and C. H. Bishop, 2015: Localized ensemble-based tangent linear models and their use in propagating hybrid error covariance models. *Mon. Weather Rev.*, **(under review**)

Frolov, S., C. H. Bishop, T. R. Holt, J. A. Cummings, and D. D. Kuhl, 2015: Facilitating strongly-coupled ocean-atmosphere data assimilation with the an interface solver. *Mon. Weather Rev.*, **(accepted**).

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HONORS/AWARDS/PRIZES

2015: Distinguished Visiting Scientist, University of Reading. Dr. Craig H. Bishop was selected by a vote of the department of meteorology's Ph.D. students. The award provides an all-expenses paid one week visit to the University of Reading to interact with the researchers there.

2015: NRL Edison Patent Award: Dr. Craig H. Bishop for the patent "Method for predicting pirate attack risk in a geographical based on INTEL regarding pirates and pirate behavior coupled with METOC conditions" US Patent 8,838,515, pp1-13, September 16, 2014. (With Drs James Hansen, Daniel Hodyss and William Campbell).