# Quantifying Uncertainty through Global and Mesoscale Ensembles

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## LONG-TERM GOALS

The long-term goal of this project is to develop robust global and mesoscale ensemble analysis and forecast systems that are able to provide probabilistic forecast guidance in an operational environment. Although most operational centers rely solely on single deterministic forecasts from numerical weather prediction models, recent advances in probabilistic prediction, or ensemble forecasting, have made this a very powerful tool for providing more complete input on environmental conditions, including a measure of the forecast confidence. Since the atmosphere is inherently chaotic, the model predictions of most, if not all phenomena will always be sensitive to the model initial conditions and physical parameterizations. Mesoscale models are additionally constrained by potential errors inherent in the specification of the lateral boundary conditions (LBC). Due to these inevitable uncertainties, forecasts are most appropriately viewed in a probabilistic sense; that is, forecasts should provide probabilities of the occurrence of specific high-impact events, as well as estimates of forecast skill. Recent research at NRL and other research centers has demonstrated that probabilistic information can be obtained from ensemble of forecasts created from equally plausible initial states and equally-likely model formulations. However, such a probabilistic prediction of Navy relevant high-impact weather will significantly benefit sea strike and sea shield functions only if there are clearly identified *user-relevant* norms. For example, METOC impacts on operations are typically listed in a “stoplight” format, often with multiple weather criteria that must be satisfied (e.g., for the Predator, precipitation, winds, ceiling, visibility, cloud cover, icing, turbulence, and temperature). Probabilistic forecasts allow for a different probability threshold to be set for each criterion individually (e.g. a 90% probability for winds, but only a 70% probability for visibility), reflecting the relevant importance of each weather factor. Ensembles also allow for the covariance between relevant weather variables to be taken into account. In a particular instance, wind and visibility may have a wide range of values they might take on (broad probability distribution functions), but information in the covariance could tell you that *if* the wind speed is high, *then* visibility will also be high.

A prototype global Ensemble Transform (ET) ensemble system has been developed as part of research performed in recent NRL base projects on global modeling and predictability (Bishop and Toth 1999, McLay et al. 2007). In addition, a prototype ET mesoscale ensemble system, driven by this global ensemble, has been developed within the NRL 6.2 project "Probabilistic Prediction of High-Impact Weather" that was approved for FY06-FY09. The work in this NRL base project on mesoscale ensembles has been incorporated into this RTP project, and the funding for it, and the additional ONR and PMW-180 funding approved for this RTP, will allow for both the global and mesoscale ensemble systems to be more fully developed, tested, validated, and transitioned to operations during the time period of FY07-FY09.

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**The long-term goal of this project is to develop robust global and mesoscale ensemble analysis and forecast systems that are able to provide probabilistic forecast guidance in an operational environment. Although most operational centers rely solely on single deterministic forecasts from numerical weather prediction models, recent advances in probabilistic prediction, or ensemble forecasting, have made this a very powerful tool for providing more complete input on environmental conditions, including a measure of the forecast confidence.**

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## OBJECTIVES

The objective of this project is to incrementally develop and test an integrated multi-scale ensemble modeling framework and forecasting system, and validate and transition it to operations at the Fleet Numerical Meteorology and Oceanography Center (FNMOC). This system will be a state of the art global and mesoscale ensemble forecasting system using the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled/Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]). It will incorporate consideration of uncertainty in the initial state (and lateral boundaries where appropriate) along with consideration of uncertainty in the model formulation. It will be a user-friendly, easily re-locatable system flexible enough to incorporate new advances in data assimilation and post-processing schemes. The system will provide high fidelity, dynamically consistent probabilistic forecasts, and estimates of forecast uncertainty for the battlespace environment. These global and mesoscale ensemble forecasts will lead to superior probabilistic weather forecasts that will directly improve tactical decision aids (TDA) for support of FORCENET and the Sea Power 21 pillars (Sea Basing, Sea Shield, and Sea Strike), and for applications to homeland security and the global war on terrorism (GWOT).

## APPROACH

Our approach is to take existing prototype global and mesoscale ensemble forecast systems, built through current and previous NRL in-house funding, and incrementally develop these individual systems into an operationally feasible, next-generation, multi-scale ensemble prediction system. This system will consist of (a) the representation of initial and model uncertainty in NOGAPS, (b) the representation of initial, lateral boundary condition (LBC), and model uncertainty in COAMPS, (c) an integrated, robust global-mesoscale ensemble infrastructure (to ensure consistent perturbations between the global and mesoscale systems, result in improvements to the global system having an immediate impact on the mesoscale system, and promote ease of use), (d) an ensemble verification system, including scorecard, and (e) a demonstration of performance capabilities in an operational setting. The system will be thoroughly tested using scientific studies and norms and comprehensive ensemble forecast experiments.

## WORK COMPLETED

For the development of the global ensemble system, a comparison between the new ET (Bishop and Toth 1999) and the current operational Bred Vector (BV, Toth and Kalnay 1993) scheme has been completed for two summer and two winter months with a 24-h cycling period. In addition, experiments for June-July 2005 were performed to investigate i) the impact of a 6-h cycling period, ii) the impact of rescaling the initial perturbations to smaller size, and iii) the use of a 64-member ensemble rather than a 32 member ensemble. Research was also completed investigating the performance of ensembles with and without the addition of stochastic perturbations to the tendencies produced by the cumulus convection parameterization (Teixeira and Reynolds, 2007). Finally, research was performed using an archive of ensemble perturbations to stochastically enhance the ET scheme in regions where the initial ET perturbations were deficient in matching analysis error variance estimates.

For the development of the mesoscale ensemble system, the new ET method for generating initial perturbations has also been implemented within COAMPS. Perturbed lateral boundary conditions to drive the ensemble were obtained from the global NOGAPS ET ensemble (McLay et al., 2007a, b). The 29-member COAMPS ensemble system has been tested by running it over a three week period for summer 2005. To quantitatively evaluate the performance of the mesoscale ensemble, a large suite of diagnostics was developed and employed. A method for predicting forecast error covariance due to the misspecification of parameters governing the effect of sub-grid scale processed on grid box means was also developed. The performance of this "multi-parameter" ET ensemble was tested over the same three week period as the ET ensemble without perturbed parameters. The ability of the multi-parameter ET ensemble to work with high resolution nests was tested by applying it to the problem of simulating urban meteorology over Tokyo at 1.67 km resolution using 11 members. Work is underway to create sea surface temperature (SST) perturbations and investigate their impact on ensemble forecasts.

## RESULTS

For the global ensemble system, it has been shown that the new ET scheme is superior to the operational BV scheme under a variety of metrics, including the RMS error of the ensemble mean, the relationship between ensemble variance and forecast error variance, probabilistic (brier) skill scores, and the effective number of directions spanned by the ensemble subspace (Fig. 1), for a number of different fields of interest to the Navy, including low-level and upper-level winds (McLay et al. 2007a).

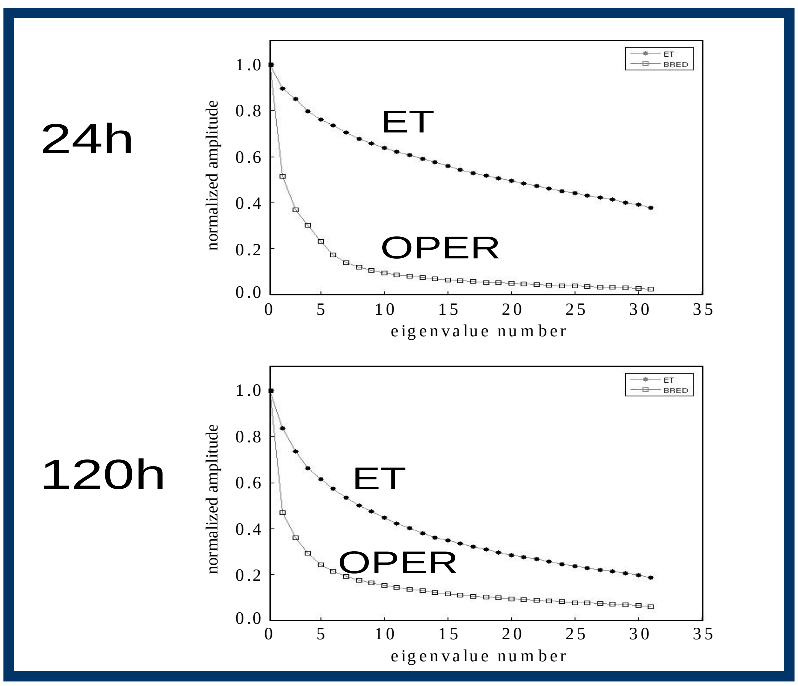


***Fig. 1. The normalized amplitude of the eigenvalues of the global ensemble perturbation covariance matrices after 24 hours (top) and 120 hours (bottom), for the new ET scheme (solid circles) and the operational bred vector scheme (open squares). Values closer to 1 indicate less redundancy between ensemble members. The global ET ensemble exhibits significantly less redundancy among ensemble members than the operational scheme at both longer and shorter forecast periods.***

In addition, it was shown that the short (6-h) cycling period produced ensembles that better matched the analysis error variance estimates produced by the NRL Atmospheric Variational Data Assimilation System (NAVDAS) than the 24-h cycling period. The scaling of the initial perturbations, in general, resulted in a degradation of the ensemble performance. It was also shown that the improvement in skill using 64 members instead of 32 members was marginal. On the other hand, the addition of stochastic cumulus perturbations to the ET ensemble resulted in significant improvements under a variety of metrics in the tropics (Fig. 2), with little impact in the extra-tropics. In addition, the ET forecast ensemble was post-processed with balanced, correlated, growth-conditioned stochastic perturbations generated from a historical archive of forecast perturbations. With the post-processing, the ET forecast ensemble showed a significantly improved match between the ensemble variance and the analysis error variance estimates from NAVDAS (McLay et al. 2007b).

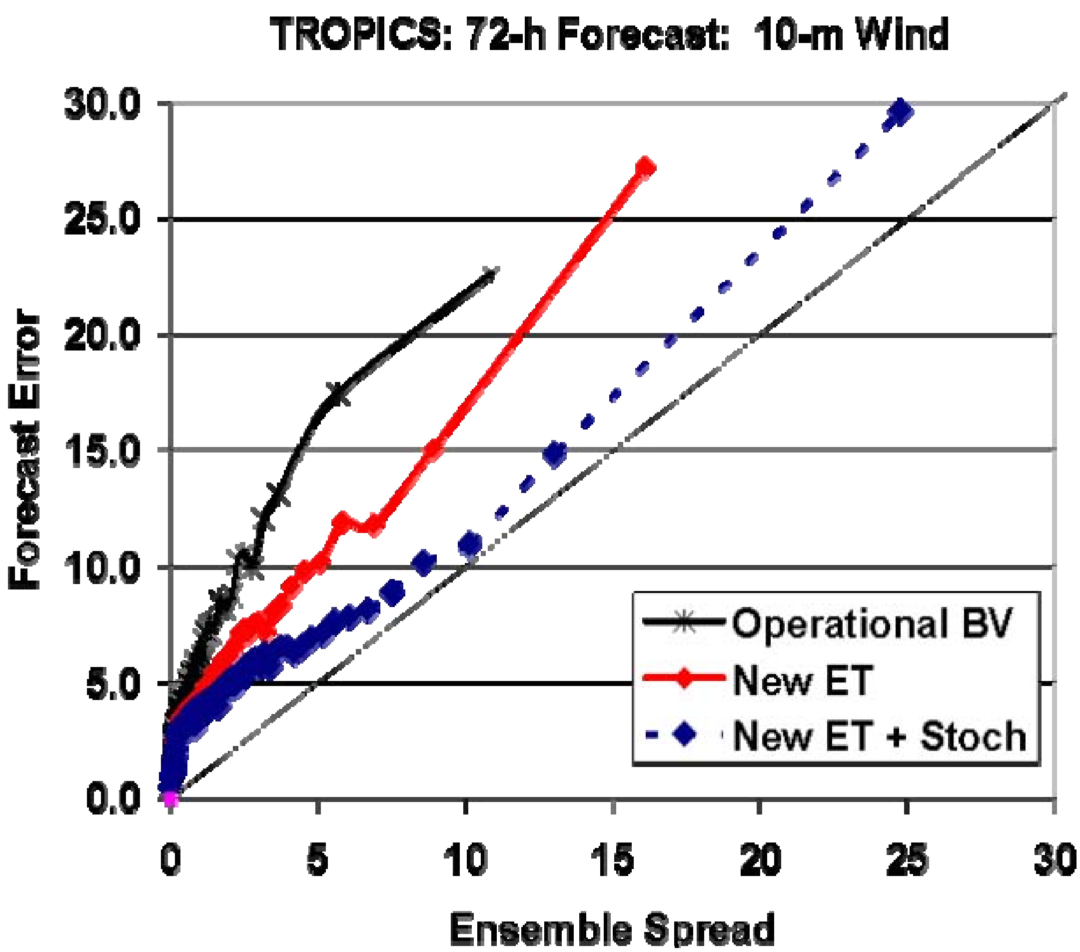


*Fig. 2. The relationship between ensemble variance, or "ensemble spread", and forecast error variance, or "forecast error", for the 10-m wind speed for the 72-h forecasts in the tropics for the operational global ensemble (black solid curve with cross hatches), new ET scheme (red solid curve with diamonds) and new ET scheme including stochastic convection (blue dashed curve with diamonds). Ideally, the curves have a slope of 1 and span a large range of forecast error values. The new global ET scheme is an improvement on the operational BV scheme. The addition of stochastic convection results in even further improvements.*

For the mesoscale ensemble system, the 29-member COAMPS 48-h forecasts for the 45-km CONUS domain for three weeks (25 June to 17 July 2005) show that the RMS error of the ET ensemble mean is less than that of the unperturbed control forecast (Fig. 3).

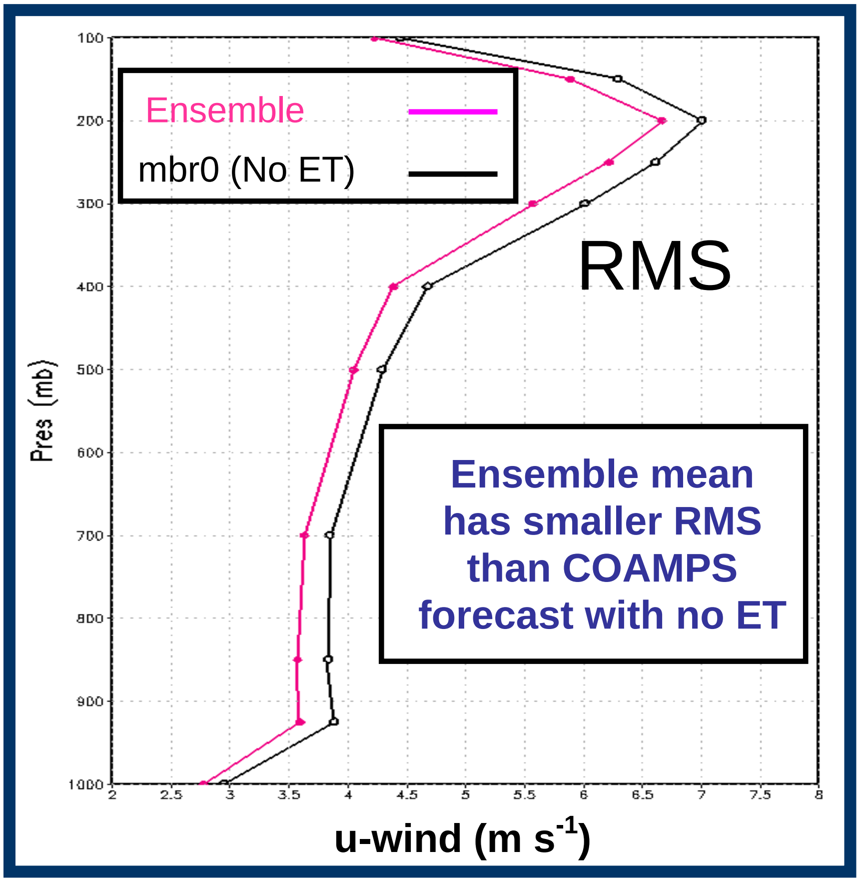


***Fig. 3. COAMPS 48-h ensemble forecasts for the 45-km CONUS domain from 25 June to 17 July 2005 of the vertical profile of RMS u-wind (m s$^{-1}$) of the ensemble mean (magenta) and the control member without ET (black).***

Additional experiments were conducted in which perturbations to the COAMPS planetary boundary layer (PBL), surface layer, microphysical, and cumulus physical parameterizations were included along with the ET. For the 28 perturbation members of the ensemble, the perturbations included: 3 PBL, 2 surface flux, 2 microphysics, 13 cumulus, 7 PBL/surface flux/cumulus combination, and 1 PBL/surface flux combination. While the ensemble variance was found to be a good predictor of forecast error variance without perturbed parameters, the skill of the ensemble as represented by the spread-skill relationship was further improved with perturbed parameters (Fig. 4). In addition, all members were found to be numerically stable with no failure rates even though the period considered included two tropical cyclones.

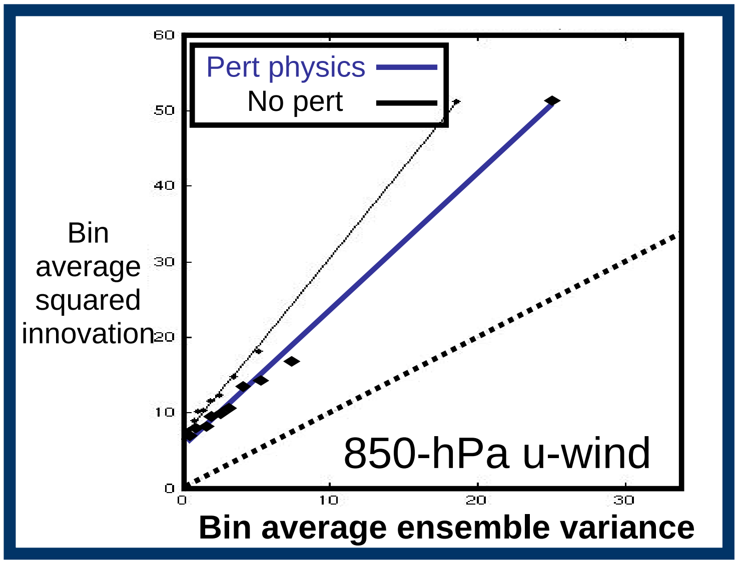


***Fig. 4. The COAMPS 48-h ensemble forecasts for the 45-km CONUS domain from 25 June to 17 July 2005 of the 850-hPa u-wind (m $s^{-1}$) ensemble variance versus innovation variance for COAMPS forecasts without perturbed physics (black) and with perturbed physics (blue).***

For the 1.67-km Tokyo simulations, the COAMPS urban canopy parameterization was used (Holt and Pullen 2007) with perturbations constructed based upon urban morphologies to include modifications to the mean building heights, roof fractions, anthropogenic heating, and building radiation extinction. Results show that the perturbed parameters actually improved the ability of the ensemble to distinguish large forecast error variance from small forecast error variance at high resolution (Fig. 5).

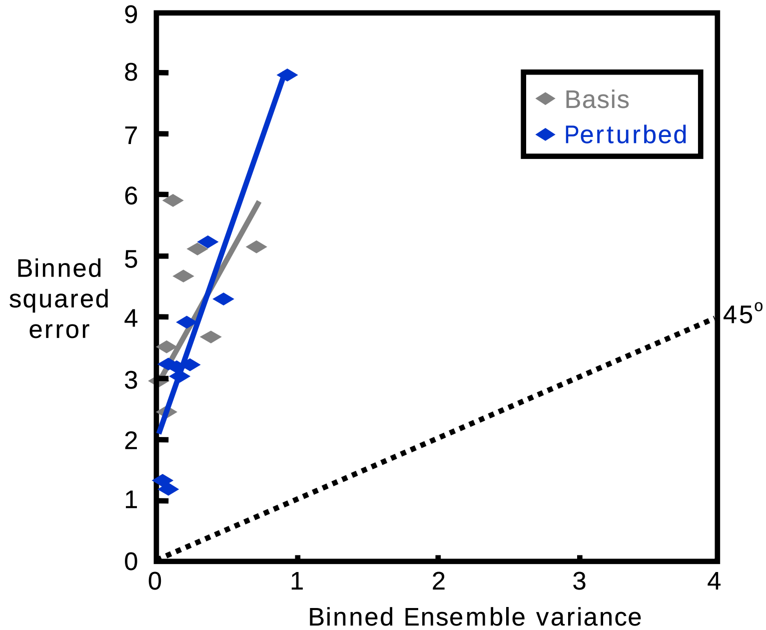


***Fig.5. Ensemble spread-forecast error relationship, similar to Fig. 4, but for 11-member COAMPS ensemble for 2-m air temperature for 6-h forecasts on nest 4 (1.67-km horizontal resolution) for the Tokyo metropolitan region for 25-30 June 2005. The gray line represents the basis COAMPS run without perturbed physics and the blue line represents the COAMPS run with perturbed physics.***

## IMPACT/APPLICATIONS

Since results indicate improved performance of the global ET system over the BV under a variety of metrics, this new scheme, once transitioned, should result in more skillful global ensemble forecasts for the Navy. This should have a direct impact on current and planned ensemble-based products, such as the probability of gale-fore winds, as well as other products that are currently forced by the global ensemble, or will be in the future, including the mesoscale atmospheric ensembles, and surface ocean wave ensembles. In the future, it is hoped that these more skillful probabilistic tools will lead to more applications of probabilistic forecasts in the DoD, including ship and air routing applications.

## TRANSITIONS

Based on the results shown above, new ET code has been transitioned through 6.4 to FNMOC (3rd Quarter 07) to run the ET with a 6-h cycling period and no initial scaling. The ET forecast ensemble will be run with 96 members for the 6-h cycle, and a 16-member subset of these 96 members will be run to the 240-h lead time. One of the thoughts behind transitioning a 96-member ensemble was to get FNMOC used to running a large ensemble and pave the way for ensemble data assimilation. Another was that a tradeoff had to be made between increased ensemble size over the 6-h cycling interval and increased ensemble size over the whole 240-h forecast interval. It was indicated that FNMOC would only approve a very small increase in ensemble size over the whole 240-h forecast interval (say 2-4 members). So, we traded the expense of 2 additional 240-h integrations for 80 additional members over the 6-h cycling interval. It is anticipated that the stochastic physics research will be transitioned through 6.4 to operations some time during FY08.

In addition, as part of the Navy/Air Force Joint Mesoscale Ensemble (JME) ensemble forecasting project we anticipate helping FNMOC set up a real time ensemble forecasting system over the Korean peninsula during 2008.

**RELATED PROJECTS**

The global ET and Stochastic Physics research began in preceding years under the NRL base-funded project 6.1-Quantifying Limits of Atmospheric Predictability and the NOAA funded project 6.2 Stochastic Physics. In addition, it is anticipated that research under the NRL base-funded project 6.2-Model Discovery, which will use ensembles to understand model behavior within parameter space, will eventually lead to methods to perturb parameters in ensembles and be transitioned to operations through this work unit in FY09.

For the mesoscale ensemble development related projects include ONR funded 6.2-Probabilistic Forecasting of High Impact Weather, 6.2-Hidden Volatility in Environmental State Estimation, and 6.1-Quantifying Limits of Atmospheric Predictability. The research is also related to the NOAA funded projects 6.2 Stochastic Physics and 6.2 Huge Ensemble State Estimation.

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McLay, J., C. H. Bishop, and C. A. Reynolds, 2007b: The ensemble transform scheme adapted for the generation of stochastic perturbations. *Q. J. R. Meteorol. Soc.*, **133**, 1257-1266.