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Multi-scale Predictability of High-Impact Weather in the Battlespace Environment

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Abstract

Objectives of our study include: i) examination of the predictability of regional-scale weather phenomenon that have a high impact on military missions, ii) exploration of new methods to initialize ensembles for global and mesoscale atmospheric models, and iii) diagnosis of mohourdel error and uncertainty, and inclusion in ensemble design. For the global ensembles, the Ensemble Transform initial perturbation method is superior to the current operational method, and work is underway to determine the exact configuration that will be transitioned to operations. On the mesoscale, we have developed and tested a new mesoscale ensemble forecast system using the atmospheric portion of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) that is targeted for operational implementation as part of the Joint Ensemble Forecast System. We also have performed ultra high-resolution simulations of airflow over complex terrain to explore aviation turbulence hazards.

1. Introduction

The accurate prediction of the coastal atmosphere-ocean environment is critical to the success of US Navy operations. Operations, such as strike warfare, special operations, carrier flight operations, mission planning and rehearsal, and sorties, can be adversely affected by the high-frequency spatial and temporal variations of environmental conditions that occur in the battlespace environment. The presence of horizontal and vertical wind shears, precipitation, clouds, ducting conditions, pronounced temperature and/or moisture gradients, and aerosols are among the conditions that can adversely impact Navy operations. Because of the chaotic nature of the atmosphere-ocean system, and its sensitive dependence on initial conditions, there will always be uncertainty associated with forecasts of these phenomena. Due to inevitable uncertainties in the initial state, forecasts are most appropriately viewed in a probabilistic sense; that is, forecasts should provide probabilities of the occurrence of specific events, as well as estimates of forecast skill (e.g., Leith, 1974). The only computationally feasible approach to this problem is to perform an ensemble of forecasts from equally plausible initial states. Due to the high dimension of the system, a large number of ensembles are necessary to accurately forecast the probability that a specific high-impact event will occur. These high-impact events can be extreme events, such as strong windstorms that generate aerosols and impact electro-optical (EO) conditions, or relatively weak forcing events such as stratus clouds that may impact flight operations and electromagnetic (EM) ducting conditions.

While progress has been made in ensemble forecasting, many significant questions remain unanswered. There is still considerable uncertainty and disagreement on the most effective way to perturb the initial conditions for both global scale and mesoscale models. Model errors and uncertainties should also be included in ensemble configuration, yet much of that work remains in its infancy. Inclusion of model uncertainties will become particularly important for tropical phenomena such as tropical cyclones. Here we report on recent advances in ensemble design facilitated by the HPC program, including research on the impact of model uncertainty through perturbation physics.

2. Objective

The objective of this project is to determine the predictability and define the methodologies for effective ensemble prediction of high-impact weather in the battle-space environment. To accomplish this goal, we test and evaluate methodologies for the generation of initial condition perturbations in ensemble forecasts. We also test and evaluate methodologies for the inclusion of model error in ensemble design, both in the global and mesoscale ensembles. We examine a variety of metrics to explore and validate ensemble performance.

3. Methodology

We first describe the global and mesoscale models, then briefly describe the method to perturb the initial conditions, followed by a description of the methods used to introduce model perturbations.

3.1. NOGAPS Model Description

The Navy Operational Global Atmospheric Prediction System (NOGAPS) atmospheric model is a global spectral model (Hogan and Rosmond, 1991) with a hybrid-sigma coordinate in the vertical. The prognostic variables are vorticity, divergence, virtual potential temperature, specific humidity, and terrain pressure. The parameterizations of physical processes include deep convective precipitation (Emanuel and Zivkovic-Rothman, 1999); shallow cumulus mixing (Tiedtke, 1984); convective and stratiform clouds (Slingo, 1987); boundary layer vertical mixing (Louis, et al., 1982); surface flux parameterization (Louis 1979); gravity wave drag (Palmer, et al., 1986); and the Harshvardhan, et al., (1987) radiation scheme.

3.2. COAMPS® Model Description

The Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]) atmospheric model is a nonhydrostatic model (Hodur, 1997) capable of accurate prediction at high resolution and makes use of a terrain following vertical coordinate. The model is a finite-difference approximation to the fully compressible, nonhydrostatic equations. Physical parameterizations are used to represent surface fluxes, boundary layer, radiation, and moist processes including microphysical quantities including cloud water, cloud ice, snow, rain, graupel/hail, and water vapor. For a more complete description of the physical parameterizations (see Hodur, 1997 and Chen, et al., 2003).

3.3. Initial Perturbations

A new way of perturbing the initial conditions in the ensemble are compared with the operational ensemble perturbation method currently employed for NOGAPS. The current operational technique is based on the bred vector (BV) method first introduced by Toth and Kalnay (1993). In this technique, the initial perturbations are based on short-term evolved ensemble perturbations that have been rescaled to reflect spatial differences in the global observing system. This operational technique is compared with a new technique called the ensemble transform (ET) method, first proposed by Bishop and Toth (1999). In the ET method, the initial perturbations are produced using evolved forecast perturbations, as in the BV method, but in the ET technique, the transformation is performed such that the initial perturbations are consistent with the analysis error variance estimates produced by the operational three-dimensional (3D) variational data assimilation scheme, NAVDAS (Daley and Baker, 2001). The ET technique is used in both the NOGAPS and COAMPS ensembles. The results shown here are either case studies or averages from the period 25 June through 17 July 2005. The NOGAPS ensembles are run at a T119L30 resolution (approximately 1 degree horizontal resolution), with 33 members, with a forecast length of 7 days. The COAMPS® ensembles are run with a 45 km resolution with 28 members with a forecast length of 48 hours.

3.4. Model Perturbations

In the NOGAPS ensemble, model uncertainty is introduced following Teixeira and Reynolds (2006), in which a methodology is developed to utilize physical parameterizations in a stochastic manner in the context of ensemble prediction, based on the knowledge of the variance provided by the parameterization. Ensemble experiments are performed where model uncertainty in the form of stochastic perturbations is considered. The perturbations are only added to the tendencies of the model parameterization of deep convection. Ensembles with only initial condition perturbations are compared to ensembles that contain both initial condition perturbations and stochastic convection perturbations.

In the COAMPS® ensemble, model uncertainty is introduced through variations in parameters based on typical uncertainty ranges, focusing on moist processes and the boundary layer. These processes and minimum and maximum values are described in the table below.

Process	Description	min	max
PBL	buoyancy calculation	on/off	
PBL	mixing length	0. 5	5
PBL	surface flux factor	0.25	2.0
Cumulus	Temp pert scaling coeff at LCL	0.25	3.0
Cumulus	Vertical velocity at LCL	0.25	3.0
Cumulus	Temp perturbations at LCL	−6.0°C	−6.0°C
Cumulus	Heating tendency	0.10	2.0
Microphysics	Autoconversion	0.05	5.0

[1] COAMPS® is a registered trademark of the Naval Research Laboratory.

4. Results

4.1. Improvement of New ET Scheme Over Operational Scheme for the Global Ensembles

For the global ensemble system, the new ET scheme has been shown to be superior to the current operational scheme under a variety of metrics (McLay, et al., 2007a, 2007b). These metrics include improved ensemble mean values for many different fields, improved relationship between ensemble spread and forecast ensemble mean skill (allowing for better forecast reliability estimates), and improved probabilistic prediction of wind speeds occurring above a certain threshold. One reason that the ET performs better than the operational method is that the ET ensemble is less redundant than the operational ensemble. Figure 1 shows the normalized eigenvalue spectrum of the ET and operational NOGAPS ensembles at 24-hours and 120-hours. The higher the values, the more independent directions are spanned by the ensemble subspace, and the less redundant are different ensemble members. The results show that the ET is superior to the operational ensemble at both 24-h and 120-h.

4.2. Impact of Stochastic Perturbations in the Global Ensembles

The "spread-skill" relationship is one of the most important characteristics of an ensemble. Ensembles give reliability estimates of the skill of the forecast through the ensemble variance or "spread". Large (small) spread should be related to large (small) error, on average. In Figure 2, the spread skill relationship for the 10-m wind for the 48-h forecast is compared for the ET and operational ensembles. The inclusion of stochastic convection improves this relationship in the tropics (closer to the diagonal line), however, it has little impact in the mid-latitudes. Current research is investigating how to improve the mid-latitudes through the inclusion of different types of model uncertainty, such as stochastic perturbations to the planetary boundary layer and parameter variations, such as have been introduced in the mesoscale ensemble.

4.3. Impact of Parameter Variations in the Mesoscale Ensemble

Figure 3 shows the 5,840 meter isoheights for the 48-h COAMPS® mesoscale ensembles run during Hurricane Dennis, from 00Z 9 July 2005. There is some ensemble spread in the ensemble with initial perturbations only (left panel), particularly in the vicinity of Hurricane Dennis. The COAMPS® ensemble with both initial perturbations and parameter variations, right panel, shows a significant increase in ensemble spread, particularly in the tropics.

4.4. Skill of the COAMPS® Ensemble Mean vs. the Deterministic (Single) Forecast

Figure 4 shows the RMS error of the 48-hour COAMPS® forecasts of zonal wind as compared with Radiosonde observations, averaged for the period from 25 June to 17 July 2005. One can see that, at all altitudes, the ensemble mean error is smaller than for the single, deterministic forecast.

5. Summary and Significance to DoD

This research in ensemble design shows that new methods being developed for the Navy's global ensemble forecasting system will bring considerable improvement over the current operational system. In addition, this research will lead to new capabilities for the Department of Defense (DoD) in the form of mesoscale ensemble forecasts. It is found that the inclusion of model perturbations has a significant impact on both global and mesoscale ensemble performance, particularly in the tropics. New methods for perturbing the initial conditions provide superior ensemble performance in terms of ensemble mean error and spread-skill relationships when compared to the current operational system.

NOGAPS and COAMPS® are critical, central components of the day-to-day operations of the DoD. NOGAPS is a state-of-the-art, global numerical weather prediction system that provides global weather prediction products to the entire DoD community. NOGAPS is run four times daily at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and provides global analyses and 7-day forecast fields. NOGAPS fields are used to drive a large suite of ocean, ice, and wave models, aircraft and ship routing software, and provide boundary conditions for COAMPS®. The fields produced from these forecast models are used by the US Navy and Air Force throughout the world for weather guidance in support of real-time operations, mission planning, mission rehearsals, etc. COAMPS® and NOGAPS are also used for tropical cyclone guidance at the Joint Typhoon Warning Center (JTWC) and are the backup NWP systems for the National Weather Service. This work will result in critical upgrades to the current forecasting capability of the DoD by providing reliable probabilities of the occurrence of specific high-impact weather events, and providing information as to the expected skill and reliability of a forecast. It will lead to significant improvements over the current FNMOC global ensemble forecasts and mesoscale ensemble forecasting capabilities.

Our COAMPS® and NOGAPS developmental strategies are consistent with the Commander, Naval Meteorology and Oceanography Center (CNMOC) Strategic Plan and will provide environmental support for Sea Power 21 and ForceNet. The Naval Research Laboratory in Monterey, CA, is focused on ensuring that both NOGAPS and COAMPS® will be an end-to-end system that integrates, tests, evaluates, and transitions to operations, all components necessary to meet this Strategic Plan. In particular, with the assistance obtained through this work, we are addressing the development of multi-scale probabilistic forecasts to meet the needs of the Navy.

Acknowledgements

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References

Bishop, C.H. and Z. Toth, "Ensemble transformation and adaptive observations." *J. Atmos. Sci.*, 56, 1748–1765, 1999.

Chen, S., J. Cummings, J. Doyle, R. Hodur, T. Holt, C.-S. Liou, M. Liu, A. Mirin, J. Ridout, J. Schmidt, G. Sugiyama, and W. Thompson, COAMPS Version 3 Documention, 143 pp, 2003.

Emanuel, K.A. and M. Zivkovic-Rothman, "Development and evaluation of a convection scheme for use in climate models." *J. Atmos. Sci.*, 56, pp. 1766–1782, 1999.

Harshvardhan, R. Davies, D. Randall, and T. Corsetti, "A fast radiation parameterization for atmospheric circulation models." *J. Geophys. Res.*, 92, pp. 1009–1015, 1987.

Hodur, R., "The Naval Research Laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS)." *Monthly Weather Review*, 125, pp. 1414–1430, 1997.

Hogan, T.F. and T.E. Rosmond, "The description of the U.S. Navy Operational Global Atmospheric Prediction System's spectral forecast model." *Mon. Wea. Rev.*, 119, pp. 1786–1815, 1991.

Leith, C.E., "Theoretical skill of Monte-Carlo forecasts." *Mon. Wea. Rev.*, 102, pp. 409–418, 1974.

Louis, J.F., "A parametric model of vertical eddy fluxes in the atmosphere." *Bound.-Layer Meteor.*, 17, pp. 187–202, 1979.

Louis, J.F., M. Tiedtke, and J.F. Geleyn, "A short history of the operational PBL parameterization at ECMWF." *Proc. ECMWF Workshop on Boundary-Layer Parameterization*, Reading, UK, ECMWF, pp. 59–79, 1982.

McLay, J., C.H. Bishop, and C.A. Reynolds, "The ensemble transform scheme adapted for the generation of stochastic perturbations." Submitted to *Q. J. R. Meteorol. Soc*, 2007a.

McLay, J., C.H. Bishop, and C.A. Reynolds, "The ensemble transform analysis perturbation scheme." Submitted to *Mon. Wea. Rev.*, 2007b.

Palmer, T.N., G.J. Shutts, and R. Swinbank, "Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parameterization." *Quart. J. Roy. Meteor. Soc.*, 112, pp. 1001–1039, 1986.

Slingo, J.M., "The development and verification of a cloud prediction scheme in the ECMWF model." *Quart. J. Roy. Meteor. Soc.*, 113, pp. 899–927, 1987.

Teixeira, J. and C.A. Reynolds, "The stochastic nature of physical parameterizations in ensemble prediction: a stochastic convection approach." Submitted to *J. Atmos. Sci, 2006.*

Tiedtke, M., "The sensitivity of the time-scale flow to cumulus convection in the ECMWF model." *Proc. ECMWF Workshop on large-Scale Numerical Models*, Reading, UK, ECMWF, pp. 297–316, 1984.

Toth, Z and E. Kalnay, "Ensemble forecasting at NMC: The generation of perturbations." *Bull. Am. Meteorol. Soc.*, 74, pp. 2317–2330, 1993.

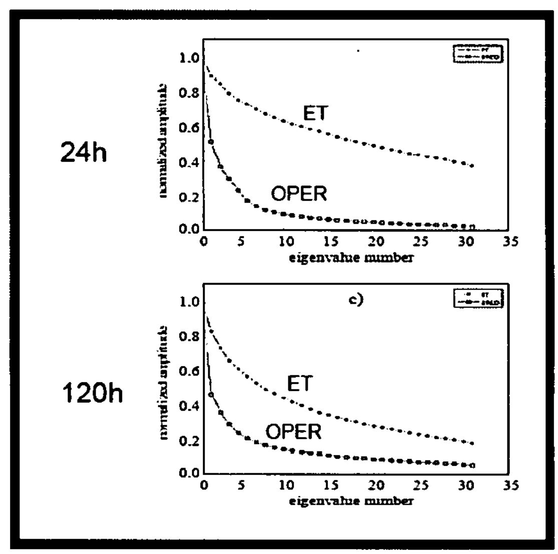

Figure 1. The normalized amplitude of the Eigenvalues of the ensemble perturbation covariance matrix at 24-h (top) and 120-h (bottom) for the ET (black circles) and operational (open squares) NOGAPS ensembles. The larger the values, the less redundancy between different ensemble members.

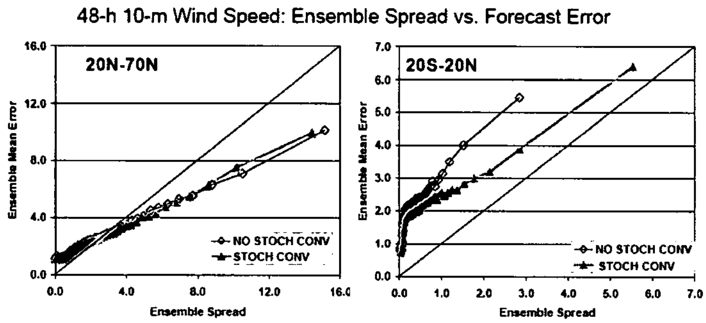

Figure 2. The relationship between ensemble spread and ensemble mean errors for the 10-meter wind speed for northern midlatitudes (left) and tropics (right), for the control (black with diamonds) and stochastic convection (grey with triangles) NOGAPS ensembles. While the stochastic convection improves performance over the control in the tropics, it has little impact in the mid-latitudes.

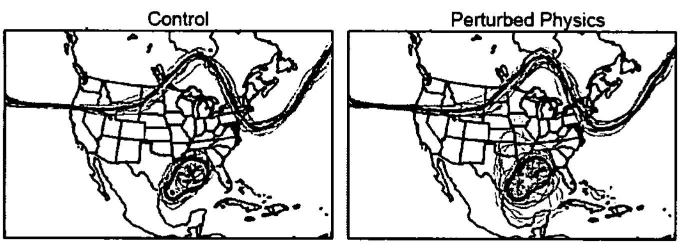

Figure 3. Ensemble isoheights (color) and ensemble mean (black) 48-hour COAMPS® forecasts for Hurricane Dennis, from 00Z 9 July 2005 for the 5840-meter isoheight. The ensemble with perturbed physics (right) shows considerably more ensemble variance then the control ensemble without perturbed physics (left).

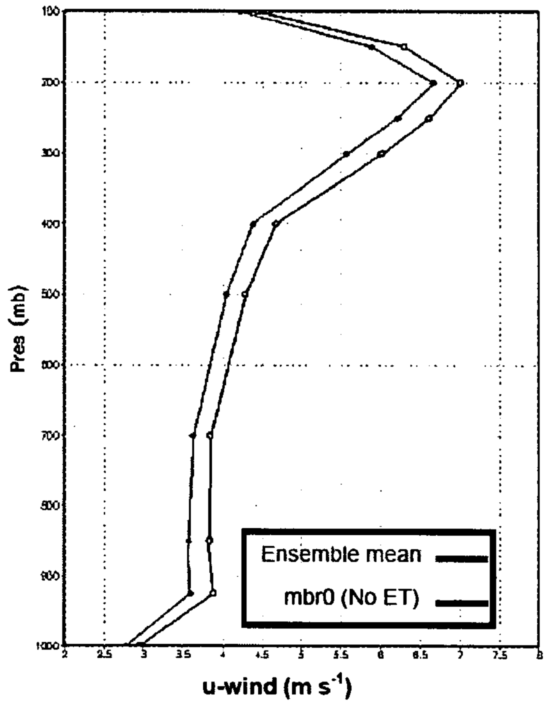

Figure 4. The 48-hour error of the zonal wind compared to radiosondes for the COAMPS® single forecast (black) and ensemble mean (pink), averaged from 25 June to 17 July, 2005