

Data Analysis, Modeling, and Ensemble Forecasting to Support NOWCAST and Forecast Activities at the Fallon Naval Station

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Grant Number: N00014-08-1-0451

<http://www.adim.dri.edu/>

LONG-TERM GOALS

The goals of this project are to increase our understanding of weather predictability and its advantages and limitations, and to develop methods to provide more accurate forecasts and nowcasts in complex terrain using multi-model ensemble modeling techniques and special observations including remotely sensed data.

OBJECTIVES

The main objectives of the study are: 1) To further develop, test, and continue operational forecasts using both the real time Weather and Research Forecasting (WRF) model (Skamarock et al. 2005) and Mesoscale Model 5 (MM5) (Grell et al. 1994) with sub-kilometer horizontal resolution to support the NOWCAST system at the Fallon Naval Air Station (NAS); 2) To produce multi-model ensemble forecasts using WRF and MM5; 3) To subsequently include forecasts from the Coastal Oceanic and Atmospheric Modeling Prediction System (COAMPSTM) (Hodur et al. 1997) as part of the multi-model ensemble; 4) To develop methods that combine multi-model ensemble forecasts with climatological fields to improve the skill of the forecasts and nowcasts; and 5) To develop a framework that complements the ensemble forecasting to better understand the sources of error and uncertainty in dynamical forecasts relevant to nowcasting key parameters such as wind speed and visibility over the Fallon NAS area.

APPROACH

This project broadly focuses on two components: (1) maintenance and data collection, quality control, and analysis of data from four special weather stations in the Naval Air Station area, and (2) real time mesoscale operations and mesoscale multi-model ensemble forecasts. The forecast system is capable

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 2009		2. REPORT TYPE		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Data Analysis, Modeling, And Ensemble Forecasting To Support NOWCAST And Forecast Activities At The Fallon Naval Station				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Desert Research Institute,2215 Raggio Parkway,Reno,NV,89512				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The goals of this project are to increase our understanding of weather predictability and its advantages and limitations, and to develop methods to provide more accurate forecasts and nowcasts in complex terrain using multi-model ensemble modeling techniques and special observations including remotely sensed data.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

of using data from the on-site weather stations for evaluation and data assimilation. The results from the model runs are updated every 12 hours and posted on the dedicated web site with password protection. The data are also available for the NAS use through the web with links to various components of the system as shown in Figure 1.

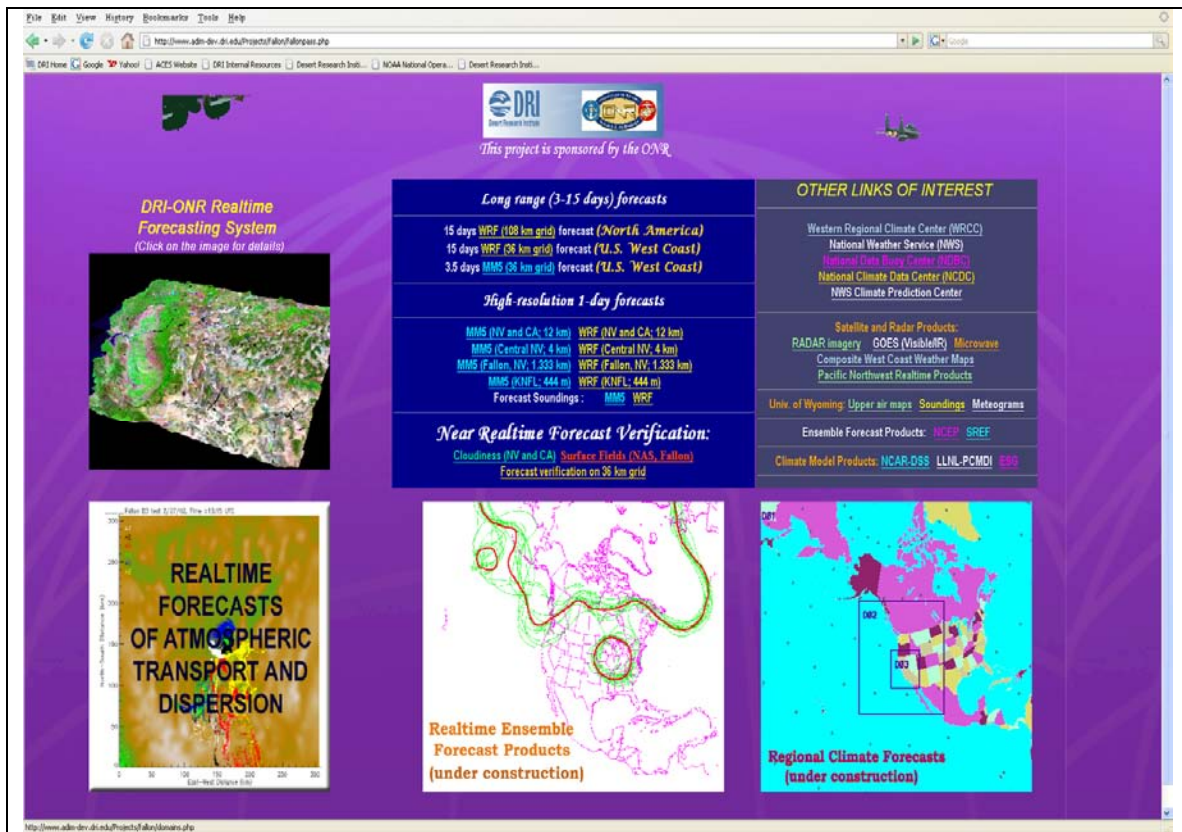


Figure 1. An updated web page of DRI's real time MM5 and WRF forecasting systems [http://www.adim.dri.edu/].

One of the primary goals of this study is to implement a regional/mesoscale multi-model (COAMPSTM, WRF, and MM5) ensemble forecasting system. One of the ways to provide ensemble forecasts from a particular model is to perform multiple model runs where each run has the same initial and boundary conditions, but different physical parameterization options. Although perturbations in both the initial and boundary conditions should be considered for operational forecasting, studies such as Stensrud et al. (2000), Stensrud (2001), and Stensrud and Weiss (2002) have shown that variations based on altered physical parameterization alone lead to meaningful probability density functions (pdfs) of the forecast variables. The results are especially promising for short-term severe weather forecasts.

Our approach is based on generation of an ensemble member set by randomly varying the available planetary boundary layer schemes (Eta PBL, Burk-Thompson scheme, Pleim-Xiu scheme, Blackadar scheme, MRF PBL scheme, and Gayno-Seaman scheme), cloud microphysical schemes (Thompson scheme, Eta microphysics, Goddard microphysics, Lin scheme, Reisner scheme, and Dudhia scheme),

radiation schemes (Rapid Radiative Transfer model computations, Dudhia scheme, CCM2 scheme, Goddard scheme, GFDL scheme, and CAM scheme as used in NCAR CCSM3 climate model), and cumulus parameterizations (Kain-Fristch scheme, Betts-Miller scheme, and modified Grell ensemble scheme) of each model. A large random set of 50 WRF and 50 MM5 ensemble members using different physics options are created by using the built-in Fortran random function utility. The WRF and MM5 control runs (non-ensemble base states) use essentially similar physical parameterization schemes.

The main objective is to create and analyze probability density functions (pdfs) for variables from each model and then combine the models (two-model ensemble) with a total of 100 ensemble members. The high-resolution control runs serve as a valuable means of comparison with the ensemble results (Houtekamer and Mitchell 1999). Once the ensemble runs are completed, the analysis of the ensemble set includes: (a) pdf properties, statistics, and evolution; (b) Rank histograms (Talagrand diagrams); and (c) Evolution and spread of parameter trajectories (“spaghetti plots”: Superposition of forecast isolines for the ensemble members).

WORK COMPLETED

We have made ensemble forecasts with 50 WRF members and 50 MM5 members for a period of fifteen days (12-27 December 2008). This case was chosen because of the dramatic frontal passages that occurred over NW Nevada during this period. Specification of initial and boundary conditions relied on the GFS forecasts (<ftp://tgftp.nws.noaa.gov/>) with a $0.5^\circ \times 0.5^\circ$ grid resolution were used for 0-180 hours and forecasts from 180-384 hrs were used with available $2.5 \times 2.5^\circ$ resolution.

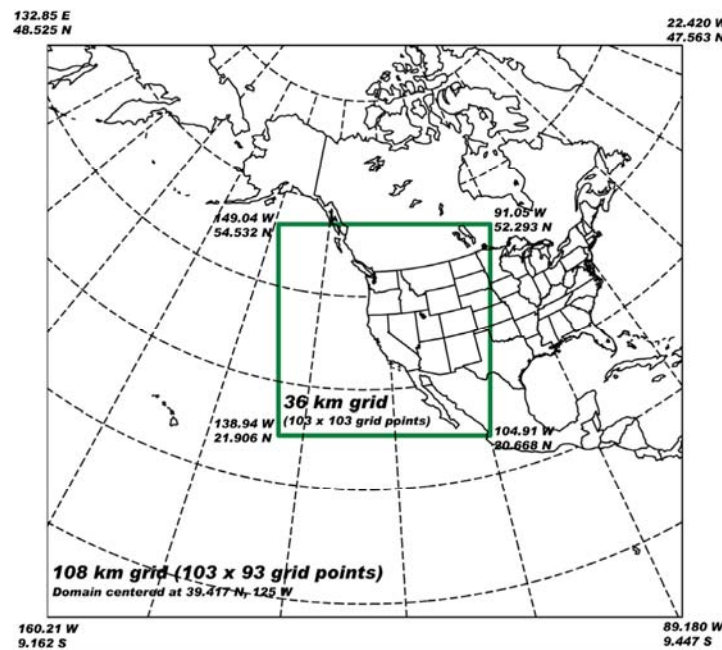


Figure 2. The model domains for the ensemble runs.

The coarse domain covered most of the eastern Pacific and the entire U.S. with a horizontal resolution of 108 km; the nested domain has horizontal resolution of 36 km. Both domains have 36 vertical

levels. Since there is an ongoing discussion in the literature (see, e.g., Houtekamer and Mitchell 1999) concerning the justification of running ensemble model with many members compared to a control run with high resolution, we have performed control runs for WRF and MM5 with an additional innermost nested grid with 12 km resolution that covers the entire states of Nevada and California. The forecasts from the WRF and MM5 ensemble members and control runs were evaluated using data from a total of 80 upper-air stations, where 26 upper-air stations were located within the 36 km resolution nested domain.

RESULTS

Figure 3 shows pdf ensemble histograms for WRF and MM5 at particular forecast times (2, 5, 10, and 15 days).

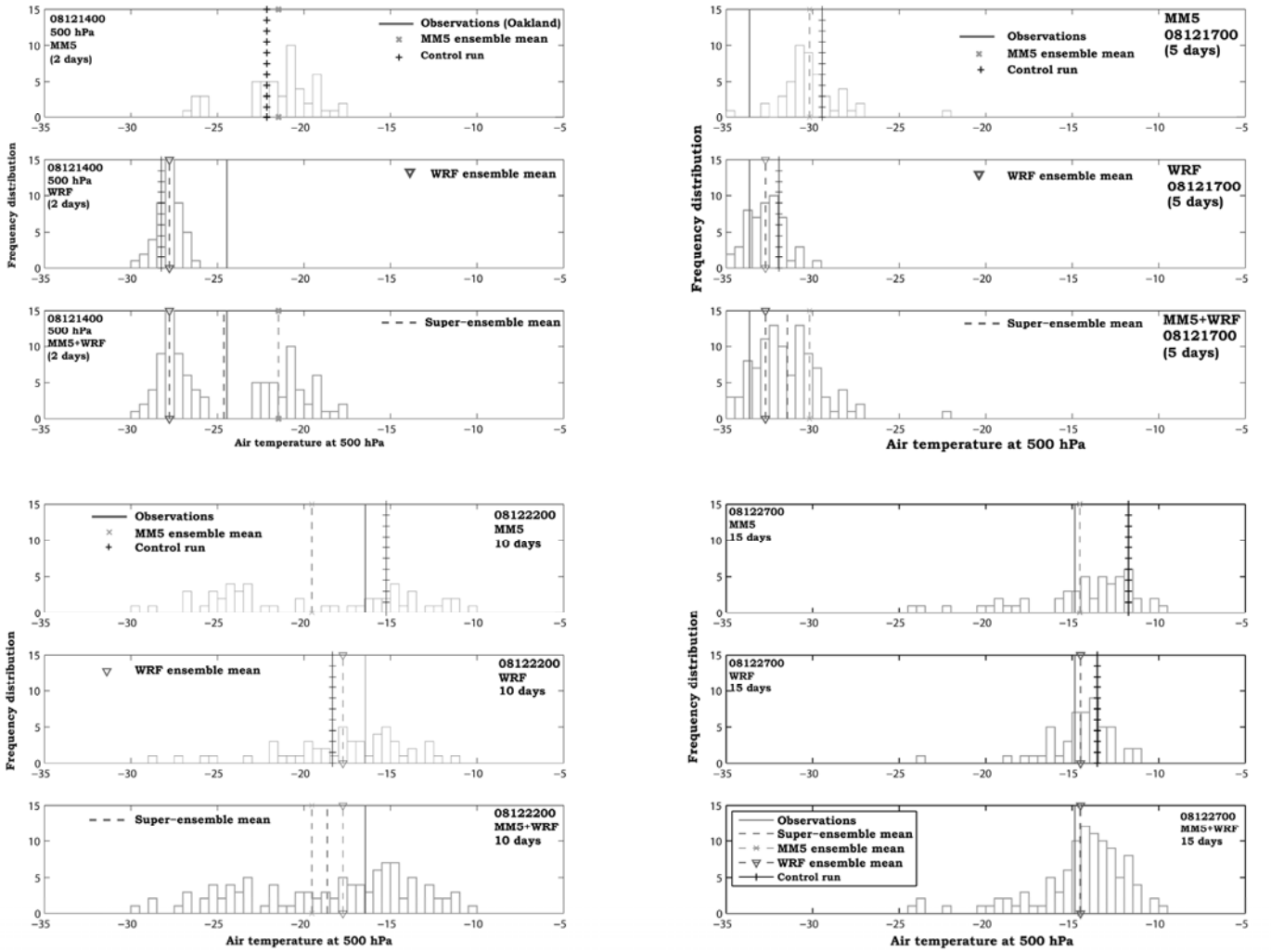


Figure 3. PDF histograms of 500 hPa forecasted air temperature at Oakland, CA. The forecasts at $t = 2, 5, 10$, and 15 days are shown in the upper-left, upper-right, lower-left, and lower-right corners of the diagram. In addition to the histogram, the observation, the control forecast, and the two-model ensemble mean are indicated. Super-ensemble mean is the mean for the two-model ensemble forecast.

The WRF and MM5 pdfs exhibit significant differences at $t = 2d$ and the combined ensemble therefore exhibits a bi-modal distribution. By $t=5d$, the combined distribution does not display a bi-modal structure and the observations fall near the mean. Notice that the ensemble averages showed some skill following radiosonde observations even at later forecast times. The correlation coefficient between the MM5 [WRF] ensemble forecast mean and air temperature observations at 500 hPa at Oakland, CA is 0.61 [0.74], and between super-ensemble mean and observations is 0.70.

Previous research indicates that shorter forecasts are dominantly driven by the dynamics and later forecasts driven by physical parameterizations. Prior to the 10-day forecasts, the spread (amplitude) of each of the models is only about 15 K; in the later stage the spread increases to 35-40 K. To investigate the dispersive properties of the ensembles, Talagrand diagrams are used as shown in Figure 4. The figure shows WRF and MM5 rank histograms for the air temperature at 500, 700, and 925 hPa at Oakland, CA, using radiosonde observations.

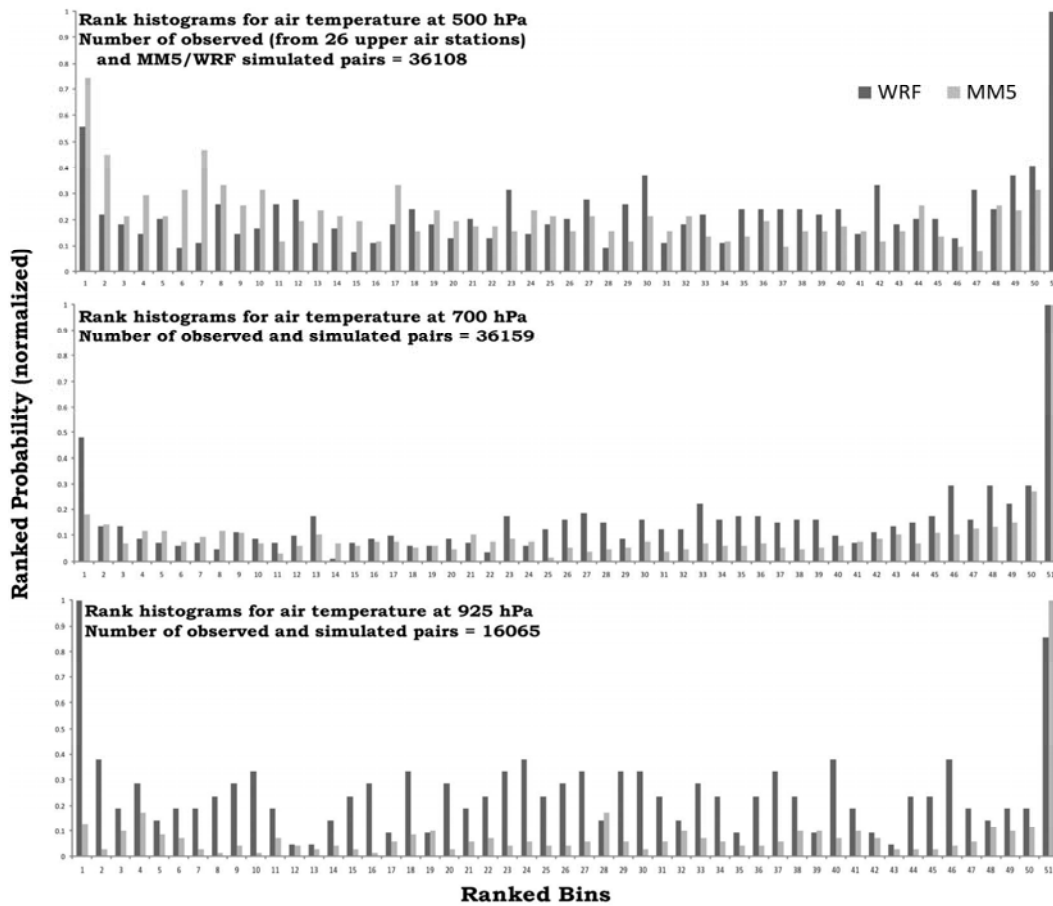


Figure 4. Talagrand diagrams for the air temperature at 500, 700, and 925 hPa for WRF (dark gray) and MM5 (light gray) based on the 26 upper air observations in the nested domain.

Both models somehow show larger under-estimation than over-estimation. Notice that each of the models was normalized by its own frequency maximum; however, WRF appears to have a more uniform distribution than MM5. It is quite clear that MM5 is not able to provide the same results as

WRF at the lowest level. An additional complication stems from the number of available pairs at the lowest level due to high elevation complex terrain. Gaps in the histograms at 925 hPa indicate that even 100 ensemble members may be insufficient to produce a uniform distribution at the lowest levels.

Figure 5 shows temporal dispersion in terms of “spaghetti plots” of the two ensemble-predicted isolines of geopotential heights 5250 and 5500 m and isotherms of 238 and 258 K.

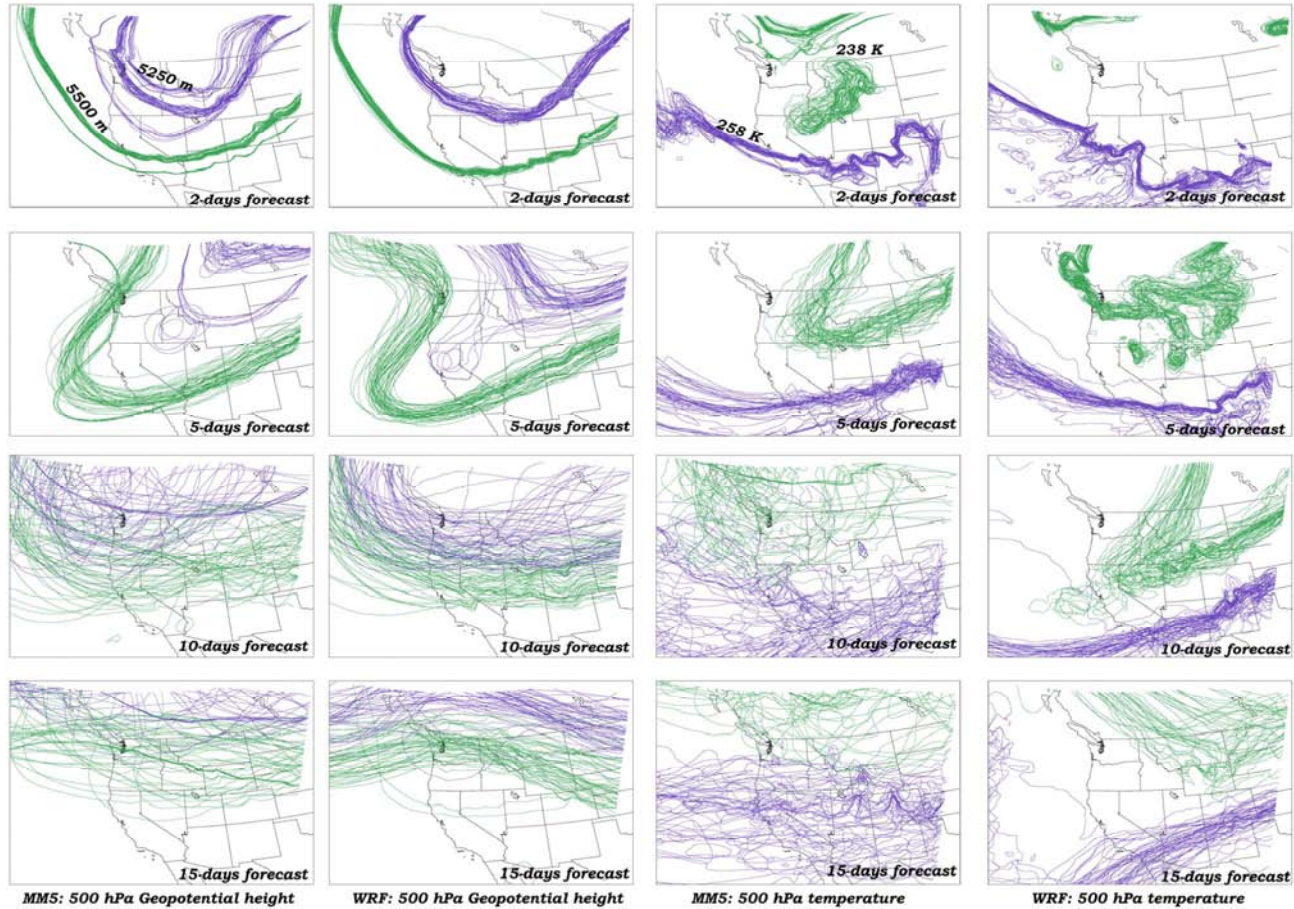


Figure 5. “Spaghetti” plots for the MM5 and WRF ensembles of the 5250 m (blue lines) and 5500 m (green lines) geopotential heights and 238 K (green lines) and 258 K (blue lines) isotherms at 500 hPa. Columns 1 and 3 (Columns 2 and 4) are plots of geopotential height and temperature, respectively from MM5 (WRF). Horizontal rows correspond to forecast times of 2, 5, 10, and 15 days.

Both model ensembles produced similar patterns of geopotential heights up to 5-days and started to significantly spread after that time. The air temperature forecasts show much larger differences even at the 2-day forecast time. However, the WRF temperature ensembles stay more coherent until the end of the simulation period. Better statistics for WRF indicate that, in this case, a larger spread does not necessarily guarantee that the results are better. However, from an operational forecasting aspect, a larger ensemble spread is generally more desirable.

Another way of looking into the ensemble spread is to compare ensemble trajectories for a particular parameter, location and height. Figure 6 shows trajectories of individual ensemble members for the air temperature and the geopotential height at Oakland, CA, at 500, 700, and 925 hPa with superimposed radiosonde observations. It appears that the spread characteristics are quite similar for both models and parameters.

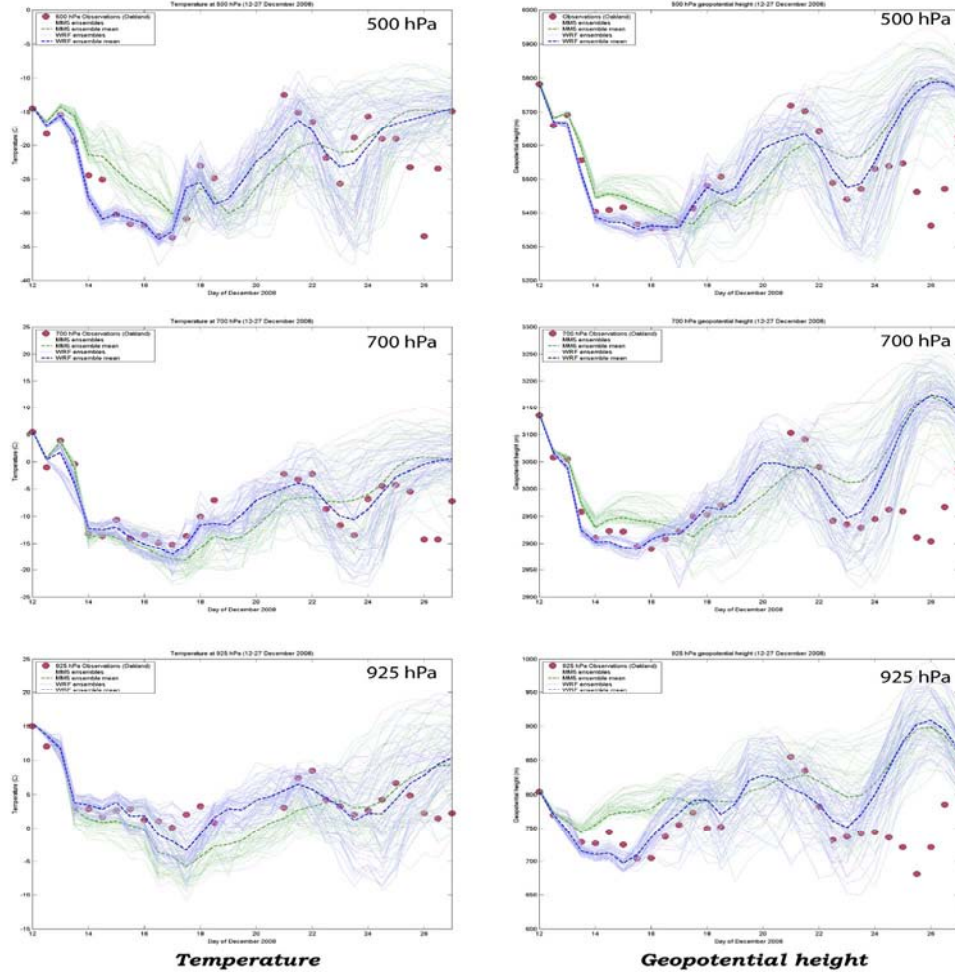


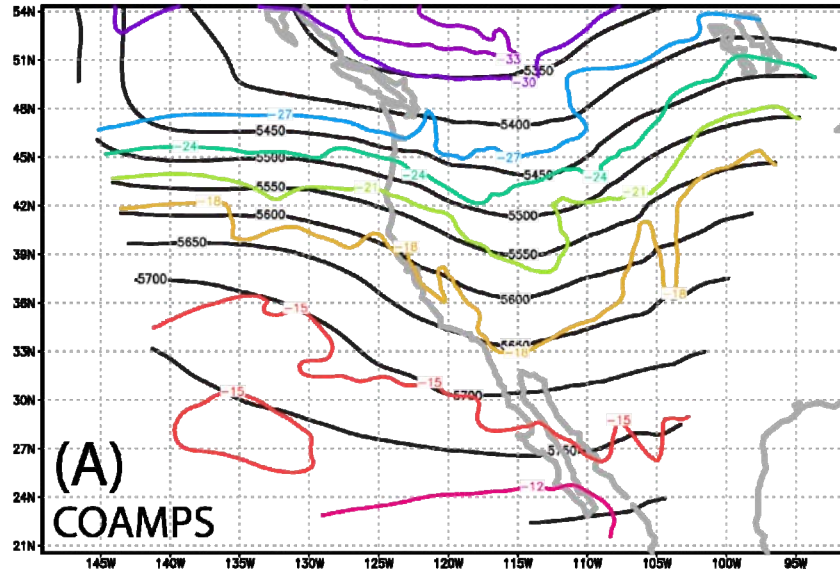
Figure 6. WRF (blue lines) and MM5 (green lines) ensemble trajectories for the air temperature (left panels) and the geopotential height (right panels) at Oakland, CA, at 500, 700, and 925 hPa with observations (red dots) for the period from 12-27 December 2008.

As noted earlier, the synoptic situation was characterized by frontal passages. In Figure 6, we see that the temperature drops at Oakland are evident between December 12-17, 2008 and during December 23-25, 2008. All ensemble members closely followed the frontal passage during the first two days of the predictions as indicated by the observations. The dynamics were fully dominant during this period. After the initial uniformity, there is a general bi-modal split in the 2-5 day forecast period between the WRF and MM5 trajectories. The ensemble forecasts at the time of second frontal passage (December 23-25, 2008) exhibits large spread and the spread does not increase monotonically with an increase in forecast time. Notice that the spread is quite similar at all levels and it does not appear to be larger at the lowest level where most of the complexity in the flow structure generally occurs. Both models

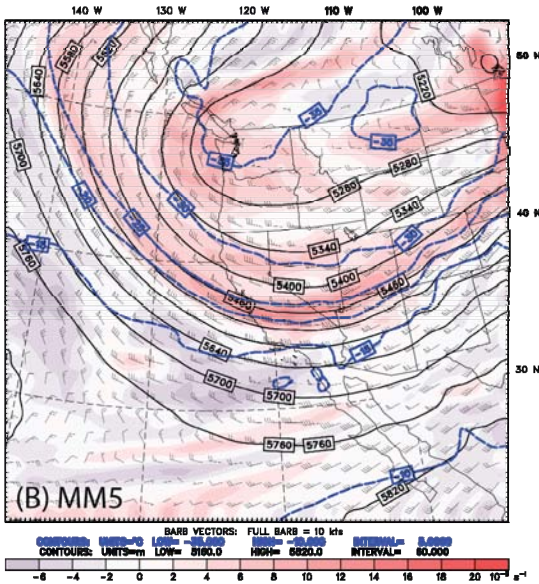
failed to reproduce the second cold advection at the end of the forecast period, mainly at the upper levels. This needs to be investigated further in terms of the propagation of the boundary conditions and the general accuracy of the boundary conditions from the global models for the medium range forecasts of 15 days.

Bear in mind that more models and more ensemble members are expected to provide a better forecast; an additional multi-model ensemble set using COAMPSTM is currently underway. The typical 3-day control forecast obtained from models COAMPSTM, MM5 and WRF from December 12 to December 15 is shown in Figure 7.

Temp. & Geopotential Height at 500 hPa 2008121500



MM5-V3.7.2: 36-km grid
 Fast: 72 h
 500 hPa (Forecast chart): Relative vorticity (shaded: units 10^{-5} s^{-1})
 Geopotential height (m)
 Air temperature (deg C)
 Valid: 00 UTC Mon 15 Dec 08 (16 PST Sun 14 Dec 08)
 Init: 00 UTC Fri 12 Dec 08



WRFV3: 36-km grid
 Fast: 72 h
 500 hPa (Forecast chart): Relative vorticity (shaded: units 10^{-5} s^{-1})
 Geopotential height (m)
 Air temperature (deg C)
 Valid: 00 UTC Mon 15 Dec 08 (16 PST Sun 14 Dec 08)
 Init: 00 UTC Fri 12 Dec 08

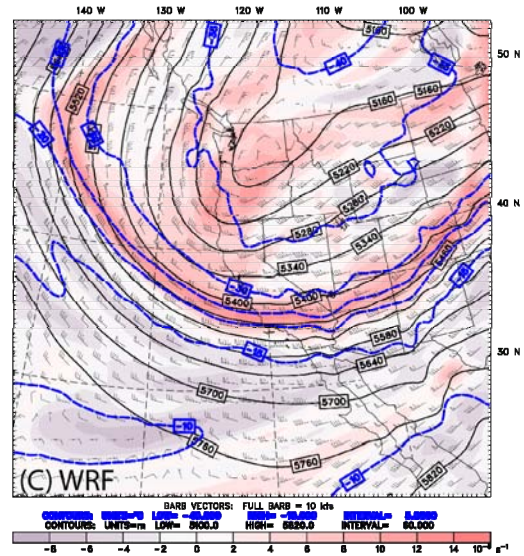


Figure 7. (A) COAMPSTM, (B) MM5, and (C) WRF 3-day control forecasts of air temperature and geopotential height at 500 hPa on 15 December 2008 at 0000 UTC.

As part of our effort to identify the sources of systematic error in dynamical prediction models, a method has been developed to determine the sensitivity of the model output to the elements of control (initial and boundary conditions, and empirical/physical parameters of the model). The process has been tested on a mixed-layer model with excellent results (Lewis 2007; Laksmivaran and Lewis 2009). We are exploring the feasibility of the procedure that determines the adjustments to the

elements to minimize the forecast error using a least square variational data assimilation strategy that complements ensemble forecasting through analysis of upper-air and surface observations complemented by satellite imagery and dynamical simulations using WRF. The analysis and deterministic forecast of a short-lived intense dust storm over the Fallon NAS is also being conducted as a preliminary to an ensemble forecast that emphasizes operational prediction of visibility.

IMPACT/APPLICATIONS

Although ensemble forecasting has been used for global predictions at major forecasting centers, regional and mesoscale ensemble forecasting is currently in research and development stage. Furthermore, high-resolution multi-model ensemble forecasting holds promise for regional/mesoscale models' structure through exploration of physical parameterizations that are necessary to improve high-resolution forecasts in complex terrain. Although our research is incomplete, the currently available real time ensemble forecasts are accessible by the Fallon Naval Air Station and will hopefully improve operational nowcasts and forecasts crucial to the Navy's operations.

TRANSITIONS

Both the special set of four weather stations in the Fallon area [<http://www.wrcc.dri.edu>] and the ongoing WRF and MM5 operational forecasting system [<http://www.adim.dri.edu>] have been developed as a complement to the forecasting and nowcasting at the Navy's Fallon Naval Air Station.

RELATED PROJECTS

Dr. Koracin is a co-P.I. on ARO Project entitled "Forecasting of Desert Terrain" where real-time experience and expertise is facilitating an interdisciplinary project linking dust emission modeling, atmospheric predictions and Lagrangian Random Particle Dispersion modeling. Dr. Koracin is a Lead Investigator for a Climate Modeling component of the multi-institutional NSF-EPSCoR Project on Climate Change, where they are developing new methods of weather and climate forecasting and use of satellite data assimilation for model evaluation. They are also investigating predictability limitations and chaotic behavior in weather and climate predictions and methods of downscaling global model results to regional, mesoscale, and microscale applications. As a Principal Investigator on a DOE-NREL Wind Energy project, he is improving high-resolution forecasts in complex terrain. Dr. Koracin is a Principal Investigator on a newly awarded DOE-Office of Science project, Simulating Climate on Regional Scale: North Pacific Mesoscale Coupled Air-Ocean Simulations Compared with Observations. The main task is to fully couple the ocean model (POP) and the atmospheric model (WRF) over the open ocean and coastal regions.

Dr. Lewis is involved in two projects that complement this ensemble research; (1) variational analysis used to identify sources of error in dynamical prediction, and (2) analysis and prediction of dust storms over western U.S. Both projects are supported by NOAA and this ONR project.

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