Characterization of Mesoscale Predictability and Downs scale Error Propagation and Mesoscale Predictability

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LONG-TERM GOALS

One of the major efforts in the atmospheric sciences has been to develop and implement high-resolution forecast models with sufficient numerical resolution to directly simulate deep moist convection. For the last three decades, the relatively pessimistic predictions of Lorenz (1969) about the predictability of small-scale (i.e., convective and mesoscale) atmospheric features have been largely ignored as routine weather forecasts were conducted at increasingly finer scales. Recent research suggests there are nevertheless, significant limitations to the predictability of mesoscale atmospheric circulations. Our goal is to develop an understanding of the predictability of such circulations in forecasts generated by state-of-the-art high-resolution mesoscale models.

OBJECTIVES

Key questions addressed in our research include:

1. How is mesoscale predictability influenced by the presence of vigorous deep convection?
2. What is the impact of initial-condition errors at the 100-km scale compared to those at the 10 km scale on the predictability of thunderstorms and deep moist convection?
3. Can a relatively coarse resolution initial state (with cut-off length scales of 100 to 200 km) be used to generate an ensemble of skillful one-day thunderstorm forecasts?

The answers to these questions are of direct benefit to Navy forecasters using COAMPS to produce aviation and other forecasts of mesoscale phenomena.

APPROACH

We are examining the extent to which downscale error propagation dominates the error in forecasts with the Navy's COAMPS model and in idealized simulations of thunderstorms. We are also carefully examining the relationship between the error fields in spectral and in physical space. Having looked at error growth in midlatitude cyclones striking both the northwest and the east coast under previous
ONR support, we have turned our attention to deep convection in the center of the country. We will hindcast selected convective outbreaks using large ensembles of high-resolution convection-permitting COAMPS simulations. Creating appropriate initial conditions for the ensemble members when the atmosphere is driven by such small-scale dynamics has been an unresolved theoretical challenge, but our recent ONR supported results (Durran and Gingrich, 2014) suggest a novel way forward.

We initialize our ensembles using simple downscale interpolation from special high-resolution NAVGEM ensembles created by the Navy for April of 2014. We typically initialize our simulations at 00 UTC and simulate for 36 hours, providing a forecast for deep convection on the next day. This approach follows the practice in Weisman et al (2008), in which a single deterministic WRF-ARW forecast was cold started daily from 00-UTC data. The initial fields for the cold start were interpolated to a 4-km mesh using the 40-km NAM/Eta analysis. Based on the success reported in Weisman et al (2008), we expect each of our ensemble members to develop a robust convective response and thereby arrive at a large-member ensemble forecast of convective activity for 4--8 representative test events.

Our first major goal is to assess the usefulness and fidelity of these novel ensemble forecasts. The possibility of forecasting organized convection in this manner is potentially transformative and would allow atmospheric scientists to leapfrog a legion of difficulties associated with directly generating proper small-scale ensembles. Our second goal is to determine the rate at which the perturbation ensemble kinetic energy $KE'$ spreads downscale, and to contrast the downscale and upscale error propagation. The weather to be investigated, organized deep convection, is likely to provide the greatest real-world opportunity for upscale error propagation to occur more rapidly than it does in the idealized Lorenz (1969) model whose behavior was analyzed in Durran and Gingrich (20014).

WORK COMPLETED

Before tackling real-world forecasts, a new first-year graduate student Jonathan Weyn and the P.I. began by exploring the influence and growth of initial condition errors in idealized squall-line simulations. We considered environments with low-level shear in a large doubly periodic domain with a uniform thermodynamic profile matching that in the seminal paper by Weisman and Klemp (1982). We triggered three individual updrafts with warm bubbles and conducted ensembles of stimulations at 1 km horizontal resolution in which monochromatic low-level temperature perturbations were imposed at wavelengths of either 8 or 128 km. The phases of the wave perturbations were random and there were no initial perturbations in the velocity fields. The temperature perturbations imposed in the 8-km ensemble were four times larger than those imposed in the 128-km ensemble.

We followed up these idealized simulations with COAMPS 80-member ensemble simulations of convection on the evening of 29 April, 2014, when a line of strong thunderstorms extended from Kentucky through Mississippi.

RESULTS

We recently obtained two key results:

- After a couple hours, the initial perturbations at both scales produce essentially identical error growth independent of scale.
- Deep moist convection generates a $k^{-5/3}$ kinetic energy spectrum through a upscale energy transfer that only crudely approximates a cascade.
Both of these results are illustrated by the spectra in Fig. 1, which shows the ensemble averaged total KE (solid curves) and perturbation KE’ (dashed curves) 30 minutes (blue) and four hours (red) into the simulation for cases with initial temperature perturbations at an 8-km wavelength (left) and a 128-km wavelength (right). The only initial kinetic energy in these simulations is in a horizontally uniform wind field; the spectra for the ensemble mean kinetic energy (KE) therefore develop from zero along with the growing squall line. Thirty minutes into the simulations, both ensembles have generated very similar mean KE spectra (solid blue lines), but the error spectra (dashed blue lines) are different. In the 8-km ensemble, errors with similar magnitudes have developed at all scales, whereas in the 128-km ensemble, there is a pronounced maximum in KE’ at the scale of the initial perturbation, and much weaker values at other wavelengths.

Yet by four hours, the KE’ spectra for the 8-km and 128-km ensembles (dashed red curves) are virtually identical, implying that all trace of the differences in the scale and magnitude of the initial errors has disappeared. Moreover, at those wavelengths less than 25 km, the values of KE’ and KE are almost the same and all predictability in both ensembles has been lost. The loss of predictability in our simulations is generally consistent with recent assessments of the impact of fine-scale weather radar data on real-time thunderstorm forecasts from the National Oceanic and Atmospheric Administration’s (NOAA) Hazardous Weather Test Bed (HWT) Spring Forecasting Experiment (Kain, et al. 2010).

As also evident in Fig. 1, our simulated moist convection is capable of generating a $k^{-5/3}$ (or equivalently $\lambda^{5/3}$) background KE energy spectrum (shown by the gray curve) that agrees very well with that observed at scales below about 400 km in the Earth’s atmosphere (Nastrom and Gage, 1985). A classic scaling analysis by Kolmogorov shows that isotropic three-dimensional turbulence should generate a $k^{-5/3}$ energy spectrum as energy cascades from larger to smaller scales, but at scales between

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**Fig. 1**: Ensemble-averaged total KE (solid) and perturbation KE’ (dashed) spectral densities as a function of horizontal wavelength $\lambda$ from the squall line simulations after 30 minutes (blue) and 4 hours (red) for the ensemble with random initial temperature perturbations at scales of (a) 8 km and (b) 128 km. Also plotted is a grey line with $\lambda^{5/3}$ slope approximating background kinetic energy spectrum observed in the atmosphere.
10 and 400 km, atmospheric motions are not even approximately isotropic across all three dimensions. Our new results are the first verification of the long-standing hypotheses due to Gage (1979) and Lilly (1983), that the observed mesoscale kinetic energy spectrum may be the result of up-scale transfer of energy input at the convective scales. These results are included in Durran and Weyn (2016) which is in press at the Bulletin of the Atmospheric Sciences; they were also the core of an invited talk presented at the 16th American Meteorological Society Conference on Mesoscale Processes, 3-6 August, 2016.

Turning from the idealized cases, we completed an 80-member ensemble hindcast of the convective weather in the central US at 00 UTC on 29 April 2014. Fig. 2a shows the composite radar reflectivity observations for this time, while Fig. 2b shows the 24-hour forecast Probability-Matched-Ensemble mean of the synthetic radar reflectivity from our simulations. Clearly the ensemble product is showing some predictive utility, and a detailed analysis of this case is underway.

Fig. 2: (a) observed composite radar reflectivities for 00 UTC, 29 April 2014 and (b) the probability-match-mean of synthetic radar reflectivities computed from the 80-member COAMPS ensemble.

IMPACT/APPLICATIONS

Forecasting mesoscale meteorological phenomena is of importance to many naval operations, including those in coastal zones, aviation, and tasks requiring information about the structure of the planetary boundary layer. Understanding the extent to which small-scale initial data is required to produce successful small-scale forecasts is crucial to the use of the Navy's weather forecast tools in unfamiliar or hostile regions. If we can demonstrate an approach for successfully initializing ensemble mesoscale forecasts using moderately high-resolution global ensembles, this may lead to operational implementations allowing the Navy to more easily generate well-calibrated high-resolution ensemble weather forecasts for unfamiliar, data-void regions.
RELATED PROJECTS

ONR Award Numbers N00014-11-1-0331 and N00014-14-1-0287 are both listed in this report. The former award was in no-cost extension at the start of the reporting period; in prior years it supported research on mesoscale predictability upon which this project builds.

REFERENCES


PUBLICATIONS