Development of High-Resolution Rapid Refresh (HRRR) Ensemble Data Assimilation, Forecast and Post-Processing

Isidora Jankov, Curtis Alexander, David Dowel, Trevor Alcott, Stan Benjamin and EMB
- RAP and HRRR models development including DA
- Shifting focus toward ensemble DA and forecasting
- Moving toward next generation of regional rapid-refresh storm-scale ensemble
- Starting points in DA
- Experiments in stochastic physics arena for the purposes of both DA and forecasting
- Statistical post-processing
**RAP/HRRR: Hourly-Updating Weather Forecast Models**

- **13-km Rapid Refresh (RAPv3)** – to 21h (July 2016)
- **Initial & Lateral Boundary Conditions**
- **3-km High-Resolution Rapid Refresh (HRRRv2)** – to 18h (July 2016)
- **Initial & Lateral Boundary Conditions**
- **750-m HRRR nest Wind Forecast Improvement Project Experiment (ongoing)**
- **3-km High-Resolution Time Lagged Ensemble (HRRR-TLE)**
- **Expanded RAP to match NAM for SREF** (July 2016)
- **Prototype 3-km storm-scale HRRR ensemble (HRRRE)** (Spring 2016)
- **3-km High-Resolution Rapid Refresh Alaska Testing (HRRR-AK) w/MRMS radar data** (Spring 2016)
Spring 2016 Experimental HRRRE

$\Delta x = 15\ km$

$\Delta x = 3\ km$

BC from GFS

IC mean from RAP, pert from GFS ensemble

Real-Time Web Graphics
http://rapidrefresh.noaa.gov/HRRRE
HRRRE Design

- **Community tools**
  - WRF for numerical weather prediction
  - GSI for observation processing and ensemble-prior calculation
  - EnKF for data assimilation

- **Hourly data assimilation** from 2100 UTC day 0 to 1800 UTC day 1
  - conventional observations only (radar reflectivity soon)
  - pure ensemble Kalman filter (EnKF)
    - variety of scales, including explicit convection, represented in background error covariances from 3-km ensemble
    - updated state variables: $u, v, T, q_v$, geopotential, column dry air mass
  - covariance localization: 500 km horizontal, 0.4 scale height

- **Ensemble 12+ h forecasts** at selected times
  - 18-member forecast at 1500 UTC provides initial and boundary conditions for NEWS-e

- **Sources of ensemble spread**
  - initial condition perturbations from GFS ensemble
  - model integration
  - adaptive, multiplicative posterior inflation
HRRRE Real-Time System on NOAA R&D “Jet”
2 May - 20 June 2016 (testing in March/April)
HRRRE ~650x550 = 357,500 grdpts
HRRR 1800x1060 = 1,908,000 grdpts
HRRRE ~ 20% HRRR (1/5th)

Ensemble Pre-Processing
LBC 64 cores ~ 15 min
IC 120 cores ~ 30 min

Ensemble 3-km Data Assimilation (20 mem)
WRF 1-hr cycle 72 cores/mem ~ 20 min
GSI-EnKF 240 cores ~ 25 min

Ensemble 3-km Forecast (3-18 mem)
WRF 18-hr fcst 180 cores/mem ~120 min
Post-processing 16 cores/mem ~5 min
DA + FCST = ~5,000 cores (18 fcst mem)
Convective initiation along dryline

Rain-cooled Boundary

Tornadic supercell development near residual outflow boundary intersection
HRRRE: Case Study 09 May 2016

1-hr Maximum Updraft Helicity Valid 22z
(colors > 25 m²/s²)

HRRRX 15z-17z initializations
Time-Lagged Ensemble

HRRRE 15z + 7hr fcst valid 22z

Effective use of the boundary observations in storm-scale ensemble data assimilation
**HRRRE Observation Space Diagnostics: 1-hr cycling**

- **Black** = Observation Error
- **Red** = Ens Bias (mean obs innovation)
- **Green** = Total Spread (ensemble standard deviation + ob error)
- **Blue** = Ens Forecast Error (innovation standard deviation)

Need accurate specification of observation error
Ensemble spread \(<\) Observation error \(\rightarrow\) Not drawn towards obs in DA
Based on results observation errors reduced for some datasets

Want total spread to track with forecast errors of the day
Ensemble spread \(<\) Forecast error (green \(<\) blue) \(\rightarrow\) Underdispersive
Ensemble spread \(>\) Forecast error (green \(>\) blue) \(\rightarrow\) Overdispersive
Ensemble generally underdispersive

Ensemble design refinements planned including… statistical post-processing
Stochastic physics for use in Regional/Storm Scales Ensembles

**Motivation**
- Issues with mixed-physics approach
  - Maintenance
  - Inconsistent ensemble system (some schemes closer related than others)
  - Each member has a unique climatology and mean error
- Compare mixed-physics approach to stochastic parameter perturbation (SPP), Stochastic Kinetic Energy Backscatter (SKEB) and Stochastic Perturbation of Physics Tendencies (SPPT).

**Experiment Design**
- Regional RAP model simulations
- 7 days from 2013 convective season: May 23, 29; June 7, 14, 20, 28; July 4
- 24 h forecasts
- 00 and 12 Z initializations using different GEFS members
- Stochastic Parameter Perturbation, SKEB and SPPT
- Focus on convective Grell-Freitas and MYNN PBL
- Verification performed over CONUS
- Statistical significance testing by employing boot strap method with 95% confidence interval
Experiments

- Control mixed physics (CU and PBL)
- SPP (CU and PBL)

CU comparison

PBL comparison

- SPP+SKEB (CU + PBL)
- SPP+SPPT (CU+PBL)
- SPP+SKEB+SPPT (CU+PBL)

Impact of adding SKEB and SPPT on stochastic parameter perturbation
Mixed-physics and stochastic members

<table>
<thead>
<tr>
<th>Mixed-physics members</th>
<th>Convective</th>
<th>PBL</th>
<th>LSM</th>
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<tr>
<td>control0</td>
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Perturbed parameters

**MYNN PBL**: Turbulent mixing length
Sub-grid cloud fraction
Roughness length (T & moist.)

**GF CU scheme**: Closures
Precipitation Rank histograms for 00 Z initialization:
Ensemble Mean Bias – 00Z init.

- **0.254mm**: Statistically Significant
- **6.35mm**: Statistically Significant
- **12.7mm**: Statistically Significant
Ensemble Mean GSS – 00Z Init.

0.254mm

6.35mm

12.7mm

Forecast Lead Time (h)
During the day stochastic experiments significantly outperform the control. `spp_skeb_sppt` significantly better than others. Situation opposite during the night.
spp_skeb_sppt spread significantly higher when compared to the control experiment, for most of the lead times (longer than 6hrs) and all variables.

Very similar results for 12Z simulations
CRPS for 00Z and 12Z Initializations

- t2m
- t850
- u10
- u250
- h500

Legend:
- control
- spp
- spp_skeb
- spp_sppt
SPP+SPPT – SPPT experiments

**RMSE 00Z**

**Spread 00Z**

**Spread/Error 00Z**

**CRPS 00Z**
Stochastic Physics Tests Summary

- Alone, the parameter perturbations of SPP introduce insufficient spread.
- When combined with SKEB and/or SPPT the spread is as large and for some instances even larger than for a multi-physics ensemble.
- An ensemble created by combining three stochastic approaches (SPP, SKEB and SPPT generally outperformed the multi-physics, control ensemble for most of the examined variables, most of the evaluated lead times, and most of the employed statistics.
- SKEB made a larger impact on spread associated with upper level wind and geopotential heights, while SPPT had a larger impact on spread for near-surface temperature.
- Combining SPP with SPPT has generally a positive impact, on the order of a 2-10% improvement over an ensemble using SPPT alone.

1. The results confirm the findings of previous studies that parameter perturbations alone do not generate sufficient spread to remedy the under-dispersion in short-term ensemble forecasts
2. A combination of several stochastic schemes outperforms any single scheme. This result implies that a synthesis of different approaches is best suited to capture model error in its full complexity.
Current and Future Work

- Adding 14 more cases to the previous study
- Experimenting with HRRR (3km grid spacing) for application in HREF
- Focus on PBL and LSM:
  - PBL - In addition to mixing length, roughness length and cloud fraction we added perturbations to mass fluxes
  - LSM - Hydraulic Conductivity is currently being perturbed
HRRR Time-Lagged Ensemble (HRRR-TLE)

Deterministic HRRR:
- High-resolution forecast provides small-scale details
- Hourly-updating with fresh forecast always available

Time-Lagged Ensemble (HRRR-TLE):
- Leverage runs in ensemble of opportunity
- Form hazard likelihood probabilities
- Less small-scale detail
- Proxy for confidence/certainty
- Underdispersive

HRRR Ensemble (HRRRE):
- More expensive ensemble
- More spread/dispersive/skill
HRRR-TLE Severe Weather Example

Forecasts valid 22-23z

Forecasts valid 23-00z

Neighborhood Search

Point Probability

Spatial radius 45 km
Time radius 1 hr
UH threshold 25 m²/s²

All six forecasts combined to form probabilities valid 22z 27 April 2011
HRRR Time-Lagged Ensemble (HRRR-TLE)

Current Experimental Probability Products:
- Based on 3 HRRRX runs (equal weight)
- Starting with forecast hour two
- 40-km neighborhood probabilities
- 120-km spatial filter applied after identifying neighborhood hazard exceedance

Real-Time Web Graphics (and grids via LDM/FTP)
http://rapidrefresh.noaa.gov/hrrrtle

Thunderstorms

Hail
Frequency Bias Correction Using “Quantile Mapping”

Model forecast climatology adjusted to observation climatology for a particular threshold (1 inch / 6 hrs)

Exploring modified gamma distribution for additional refinement in bias correction
HRRR-TLE Precipitation Products

Results: Probability of 0.5” Precipitation in 6 hours
May-Aug 2015

With relatively small sample size (~50 forecasts)

Produce statistically reliable probabilities
60% forecasts observed 60% of the time

Produce probabilities with sufficient
resolution/sharpness
Large dynamic range to probabilities
including extremes

Still fundamentally underdispersive
(overconfident)
HRRR-TLE forecasts > 60% probability of 6hr QPF exceeding 100 year average return interval (ARI) in Houston, TX area based on ATLAS14
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<th>Hazard</th>
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<td>Column graupel, updraft speed,</td>
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<td>ASOS or future CIMSS technique</td>
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<tr>
<td>Initiate NCO ‘on-boarding”</td>
<td>All</td>
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<td>Late 2017 or 2018</td>
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HRRRE Future Work

Refine ensemble data assimilation and forecasting
• Install radar reflectivity data assimilation
• Stochastic physics (parameter perturbation, tendencies for both DA and forecasting)
• Apply HRRR-TLE statistical post-processing
• Include lagged members?

Real-Time Status
Resume real-time HRRRE runs in Oct/Nov 2016 after ending 20 June 2016
HRRR-TLE runs continually available

Together (EMC, ESRL, NSSL, NCAR, …) work toward building a national real-time storm-scale ensemble system (and eventually a global storm-scale ensemble system)