Development of the High Resolution Rapid Refresh Ensemble (HRRRE): A Storm-Scale Ensemble System Including Radar and Cloud Assimilation

Terra Ladwig

Curtis Alexander, David Dowell, Ming Hu, Trevor Alcott, Isidora Jankov, Jeff Beck, Brian Jamison, Steve Weygandt, Stan Benjamin, John Brown, Tanya Smirnova, Joseph Olson, Jaymes Kenyon, Georg Grell, Eric James, Haidao Lin

NOAA/ESRL/GLOBAL SYSTEMS DIVISION

Special Thanks to Collaborators at NSSL, NCAR, and OU
RAP/HRRR: Hourly-Updating Weather Forecast Suite

13-km Rapid Refresh (RAPv4) – to 39h (Feb 2018)

Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRRv3) – to 36h (Feb 2018)

Initial & Lateral Boundary Conditions

750-m HRRR nest Scale-ware Physics Testing (ongoing)

3-km High-Resolution Time Lagged Ensemble (HRRR-TLE)

3-km HRRR-Smoke (VIIRS fire data)

3-km High-Resolution Rapid Refresh Alaska, Hawaii and Puerto Rico Testing (HRRR-AK, HRRR-HI, HRRR-PR) Experimental (ongoing)

3-km Storm-Scale Ensemble Analysis and Forecast (HRRRE) 55% CONUS HRRR Experimental (ongoing)
RAP/HRRR Performance History

- 2013 (v2)
- 2014
- 2015 (v3)
- 2016
- 2017 (v4)

Experimental RAP RMSE
6-hr Forecasts – June-July

~25% RMSE Reduction in 5 years

Temperature
Humidity
Wind

Kelvin (boxes show 95% confidence)
Pressure (hPa)
percent (boxes show 95% confidence)
m/s (boxes show 95% confidence)

More Skill
### RAPv4/HRRRv3 Summary of Changes

#### Upcoming RAPv4/HRRRv3 Implementation in early 2018

<table>
<thead>
<tr>
<th>Model</th>
<th>Run at:</th>
<th>Domain</th>
<th>Grid Points</th>
<th>Grid Spacing</th>
<th>Vertical Levels</th>
<th>Vertical Coordinate</th>
<th>Pressure Top</th>
<th>Boundary Conditions</th>
<th>Initialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>GSD, NCO</td>
<td>North America</td>
<td>953 x 834</td>
<td>13 km</td>
<td>50</td>
<td>Sigma-Isob Hybrid</td>
<td>10 mb</td>
<td>GFS</td>
<td>Hourly (cycled)</td>
</tr>
<tr>
<td>HRRR</td>
<td>GSD, NCO</td>
<td>CONUS</td>
<td>1799 x 1059</td>
<td>3 km</td>
<td>50</td>
<td>Sigma-Isob Hybrid</td>
<td>20 mb</td>
<td>RAP</td>
<td>Hourly (pre-forecast hour cycle)</td>
</tr>
</tbody>
</table>

#### Newer Model Version
- More Ensemble Weight
- Advanced “Physics Suite”

#### RAPv4/HRRRv3 Summary of Changes

<table>
<thead>
<tr>
<th>Model</th>
<th>Version</th>
<th>Assimilation</th>
<th>Radar DA</th>
<th>Radiation LW/SW</th>
<th>Microphysics</th>
<th>Cumulus Param</th>
<th>PBL</th>
<th>LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>WRF-ARW v3.8.1+</td>
<td>GSI Hybrid Ensemble to 0.85</td>
<td>13-km DFI, ½ Strength</td>
<td>RRTMG/RRTMG</td>
<td>Thompson Aerosol v3.8.1</td>
<td>GF + Shallow</td>
<td>MYNN v3.8.1</td>
<td>RUC v3.8.1</td>
</tr>
<tr>
<td>HRRR</td>
<td>WRF-ARW v3.8.1+</td>
<td>GSI Hybrid Ensemble to 0.85</td>
<td>3-km 15-min LH</td>
<td>RRTMG/RRTMG</td>
<td>Thompson Aerosol v3.8.1</td>
<td>None</td>
<td>MYNN v3.8.1</td>
<td>RUC v3.8.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Horiz/Vert Advection</th>
<th>Scalar Advection</th>
<th>Upper-Level Damping</th>
<th>Diffusion Option</th>
<th>6th Order Diffusion</th>
<th>SW Radiation Update</th>
<th>Land Use</th>
<th>MP Tend Limit</th>
<th>Time-Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>5th/5th Positive-Definite</td>
<td>w-Rayleigh 0.2</td>
<td>Full (2)</td>
<td>Yes 0.12</td>
<td>20 min</td>
<td>MODIS Seasonal</td>
<td>0.01 K/s</td>
<td>60 s</td>
<td></td>
</tr>
<tr>
<td>HRRR</td>
<td>5th/5th Positive-Definite</td>
<td>w-Rayleigh 0.2</td>
<td>Full (2)</td>
<td>Yes 0.25</td>
<td>15 min with SW-dt</td>
<td>MODIS Seasonal</td>
<td>0.07 K/s</td>
<td>20 s</td>
<td></td>
</tr>
</tbody>
</table>
HRRR Improved Convective Forecasts

Experimental HRRRv3 13 hr fcst
Valid 00 UTC 17 May 2017

Composite Reflectivity Observations
00 UTC 17 May 2017

Operational HRRRv2 13 hr fcst
Valid 00 UTC 17 May 2017

More Accurate
Convection Along
Weakly-Forced Dryline
HRRR CSI/BIAS Reflectivity Spring (Three Weeks May 2017)

**CSI 25 dBZ 40 km**

**CSI 30 dBZ**

**CSI 35 dBZ**

**Improved CSI**

**More Optimal Bias**

HRRRv3

HRRRv2 (ops)

HRRRv2 (ops)

HRRRv3
• Why do we want ensemble forecasts?
  • Challenging forecasts have uncertainty, want get information about range of possibilities
• Why do we want ensemble forecasts?
  • Challenging forecasts have uncertainty, want get information about range of possibilities

<table>
<thead>
<tr>
<th>Inches of snow</th>
<th>0</th>
<th>5</th>
<th>15</th>
<th>20</th>
<th>20</th>
<th>10</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>5</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>
**Why do we want ensemble forecasts?**
- Challenging forecasts have uncertainty, want get information about range of possibilities

**How do they help?**
- Quantify likelihood of different outcomes
• **Why do we want ensemble forecasts?**
  • Challenging forecasts have uncertainty, want get information about range of possibilities
• **How do they help?**
  • Quantify likelihood of different outcomes
  • Additional benefit of improved deterministic forecast

---

**HRRRE Vision:** High Resolution and Rapidly Updating Probabilistic Forecast Guidance for Weather Hazards
HRRRE 2017 Design

Ensemble Initialization

- Same grid characteristics, physics, and initialization from the RAP as in the HRRR

- Sources of Spread
  - GFS Perturbations
  - Stochastic Parameter Perturbations to soil moisture
  - Model integration (No physics differences; Single core WRF-ARW)
HRRRE 2017 Design

Ensemble Initialization

- RAP Mean
- 36 GDAS Members
- 3-km interp
- 36 HRRRE members
- HRRR Soil Moisture Perts

Ensemble Data Assimilation Cycles

- 36 HRRRE Initial Conditions
- Ensemble Kalman Filter
- GSI Soil Adj + Cloud Anal

- Radar Conv Obs
- Sat Conv Obs

- 50,000 – 100,000 conventional observations per hour
- 100,000 MRMS 3D reflectivity observations per hour
- Adaptive, multiplicative posterior Inflation is used to help maintain ensemble spread
HRRRE 2017 Design

0hr
- RAP Mean
- 36 GDAS Members
- 3-km interp

36 HRRRE members

HRRR Soil Moisture Perts

1hr
- Ensemble Kalman Filter
- 36 HRRRE Initial Conditions
- 36 1-hr fcsts

1hr fcsts to 2hr fcsts
- Radar Conv Obs
- Sat Conv Obs

2hr
- Ensemble Kalman Filter
- 36 HRRRE Initial Conditions
- 36 1-hr fcsts

2hr fcsts to 3hr fcsts
- Radar Conv Obs
- Sat Conv Obs

3hr
- Ensemble Kalman Filter
- 36 HRRRE Initial Conditions

Additional processes:
- GSI Soil Adj + Cloud Anal
Computational limitations prevent us from running forecasts for all members. 

~10 members is manageable for viewing each members output.

Inclusion of Stochastic Parameter Perturbations in the PBL scheme during forecasts are being evaluated, however computational cost is prohibitive.
• Same grid characteristics, physics, and initialization from the RAP as in the HRRR
• Key differences of HRRRE from the HRRR, with goal of improving 0-6 hour forecasts
  • Cycling for 3+ hours in HRRRE
  • Pure Ensemble Kalman Filter (EnKF) data assimilation
  • Direct assimilation of radar reflectivity
• Ensemble forecast spread and skill are still a work in progress.

• HRRRE is used for initial and boundary conditions for a proof-of-concept real-time demonstration of “Warn-on-Forecast” (WoF) at NSSL. The prototype NSSL Experimental Warn-on-Forecast System for ensembles, NEWS-e assimilates radar and cloud observations every 15 minutes on an event dependent domain.
Assessing likelihood

HRRR 05/17/2017 (18:00) 6h fcst - Experimental  Valid 05/18/2017 00:00 UTC

Composite reflectivity

4-hour Wind Probability

HRRR-TLE post-processing development can be applied to HRRRE

Observations

Storm Reports (24 - hours)
Ensemble Forecast Challenge: Spread vs Error

Low Spread
Higher Certainty/Predictability?

High Spread
Lower Certainty/Predictability?

Ensemble Spread
Ensemble Mean Error

Observation

Forecast Value

Observation

Forecast Value
Ensemble Forecast Challenge: Spread vs Error

Underdispersive:
Observations frequently fall outside range of ensemble forecasts

Overdispersive:
Ensemble frequently forecasts a very large range of forecasts

Probability of Forecast

Forecast Value

Ensemble Mean

Observation

Ensemble Spread

Ensemble Mean Error

Forecast Value

Ensemble Mean

Observation

Ensemble Spread

Ensemble Mean Error
Ensemble Forecast Challenge: Spread vs Error

Isolated Supercell
00z 15 April 2017

Deterministic HRRR 6-hr Forecast

HRRRE 04/14/2017 (18:00) 6h fcst - Experimental  Valid 04/15/2017 00:00 UTC

Composite reflectivity dB
CSI 30-dBz Threshold
Eastern US
0000 UTC Forecasts

HRRR and HRRRE Member Reflectivity Forecast Skill

3-h cycling before forecast

15-h cycling before forecast

Forecast Length (Hr)

CSI (×100, matched)
Hurricane Harvey

10 Member, 35-hour reflectivity forecast
Probability of 6-hour Rainfall > 3.0 inches 
Valid 0600-1200 UTC

Hurricane Harvey

Observed Stage IV 24-hour Accumulation 
Valid 1200 UTC

Ensemble Max Value of 24-hour 
Accumulated Rainfall 
Valid 1200 UTC

Ensemble Max Value of Accumulated Rainfall (inches)

Probability of 6-hr Rainfall >= 3.0 in within 40 km (%)
https://rapidrefresh.noaa.gov/hrrr/HRRRE/
email: Terra.Ladwig@noaa.gov