The High Resolution Rapid Refresh (HRRR): An hourly updating convection permitting forecast system nested in an hourly cycled mesoscale model with multi-scale data assimilation

Curtis Alexander, Steve Weygandt, Stan Benjamin, David Dowell, Tanya Smirnova, Ming Hu, John Brown, Patrick Hofmann, Eric James, and Haidao Lin

5 hr fcst valid 21z 29 May 2012

Canadian Meteorological and Oceanographic Society and American Meteorological Society
21st Conference on Numerical Weather Prediction
31 May 2012

Observations 21z 29 May 2012
High-Resolution Rapid Refresh

Experimental 3km nest inside RAP, hourly 15-h fcst

Replaced RUC at NCEP 05/01/12

WRF, GSI, RUC features

13km Rapid Refresh (RAP) (mesoscale)

13km RUC (mesoscale)

3km HRRR (storm-scale)
HRRR Users and Applications

Aviation Weather Center (AWC): 2-D grids
Federal Aviation Administration (FAA) Command Center
National Center for Atmospheric Research (NCAR): 2-D, 3-D, 15-min grids
  Operational evaluation in CoSPA
Storm Prediction Center (SPC): 2-D grids
  Operational severe weather forecasting and evaluation
National Severe Storms Laboratory (NSSL): 2-D, 3-D and 15-min grids
  Mesoscale analysis, Short-term precipitation forecasts
National Centers for Environmental Prediction (NCEP): 15-min grids
  Real Time Mesoscale Analysis (RTMA)
Department of Energy/NOAA Wind Forecast Improvement Project (WFIP)
  ~12 energy private sector companies via WFIP (WindLogics, 3Tier, AWS Truepower, Precision Wind, Weather Channel, etc.)
  Real-time forecasts of turbine-level wind and solar irradiance
Colorado State University (CSU/CIRA): 2-D grids
  Verification of solar irradiance forecasts at SURFRAD sites
Air Resources Laboratory (ARL): Tiled 3-D HRRR grids
  Dispersion forecasts, Local wind forecasts in complex terrain
National Weather Service (NWS): 2-D and 3-D grids
  Operational weather forecasting
United States Air Force (USAF): 2-D grids
  Operational weather forecasting
Evolution of the HRRR Domain

**Hourly frequency maintained**

**September 2007**
- Initial HRRR domain: northeastern United States
- Aviation corridor
- 745 x 383 grid points
- 200 processors

**March 2009**
- Domain expansion: Eastern 2/3 of the US
- 1000 x 700 grid points
- 568 processors

**October 2009**
- Domain expansion: CONUS
- 1800 x 1060 grid points
- 15 hour forecasts
- 1000 processors

**May – Oct 2010 HRRR run reliability**
- 94.5% HRRR completion rate
- 140 TB (including scheduled downtime)
- 2088 CPUs

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HRRR Milestones

- Inception over northeastern US  
  Sept 2007

- Integration into CoSPA: Aviation Users  
  Spring 2008

- Domain expansion to eastern US  
  Mar 2009

- HCPF time-lagged ensemble inception  
  May 2009

- HRRR WRF-ARW updated to v3.1.1  
  Oct 2009

- Domain expansion to CONUS  
  Oct 2009

- HRRR WRF-ARW updated to v3.2  
  Apr 2010

- Forecast period extended to 15 hrs  
  Apr 2010

- Real-time multi-scale reflect. verification  
  June 2010

- Parallel (shadow) retrospective system  
  Sept 2010

- Attained ~95% reliability  
  Jun 2010
### HRRR (and RAP) Milestones

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced latency to ~2 hrs</td>
<td>Dec 2010</td>
</tr>
<tr>
<td>Conversion of all output to GRIB2 format</td>
<td>Apr 2011</td>
</tr>
<tr>
<td>Transition from RUC to RAP parent model</td>
<td>Apr 2011</td>
</tr>
<tr>
<td>DOE-funded HRRR FTP site for energy industry</td>
<td>May 2011</td>
</tr>
<tr>
<td>Update to WRF-ARW v3.3.1</td>
<td>Feb 2012</td>
</tr>
<tr>
<td>Rapid Refresh operational at NCEP</td>
<td>May 2012</td>
</tr>
<tr>
<td>3-km data assimilation and cycling</td>
<td>2012-2013</td>
</tr>
<tr>
<td>HRRR operational at NCEP</td>
<td>2015?</td>
</tr>
<tr>
<td>Ensemble Rapid Refresh (NARRE) at NCEP</td>
<td>2016?</td>
</tr>
<tr>
<td>Ensemble HRRR (HRRRE) at NCEP</td>
<td>2017?</td>
</tr>
</tbody>
</table>
Model Configurations

ESRL/GSD/AMB

Retrospective

RAP Retro

HRRR Retro

Real-Time

RAP Dev2

RAP Dev

RAP Primary

HRRR Dev

HRRR Primary

NCEP

RAP NCO

FAA-CoSPA

NWS-AWIPS

DOE-WFIP

AMB RAP/HRRR verification system

CMOS/AMS 21st NWP  •  High-Resolution Rapid Refresh  •  31 May 2012
Hourly HRRR Initialization from RAP

**Hourly HRRR**
- Use 1-h old LBC to reduce latency

**Lateral Boundary Conditions**
- Interp to 3 km grid
- 15-h fcst

**Hourly RAP**
- Use most recent IC (post-DFI) to get latest radar info

**18-h fcst**
- Initial Condition Fields
- DDFI
- Analysis Fields
- 1-h old LBC

**3DVAR**
- Obs

**Reduced Latency:** ~2h for 2011-12

**Time (UTC)**
- 11 z
- 12 z
- 13 z
# RAP and HRRR Configurations

<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>Boundary Conditions</th>
<th>Initialized</th>
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<tbody>
<tr>
<td>RAP</td>
<td>GSD, NCO</td>
<td>North America</td>
<td>758 x 567</td>
<td>13 km</td>
<td>50</td>
<td>Sigma</td>
<td>GFS</td>
<td>Hourly (cycled)</td>
</tr>
<tr>
<td>HRRR</td>
<td>GSD</td>
<td>CONUS</td>
<td>1799 x 1059</td>
<td>3 km</td>
<td>50</td>
<td>Sigma</td>
<td>RAP</td>
<td>Hourly (no-cycle)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Version</th>
<th>Assimilation</th>
<th>Radar DFI</th>
<th>Radiation</th>
<th>Microphysics</th>
<th>Cum Param</th>
<th>PBL</th>
<th>LSM</th>
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<tbody>
<tr>
<td>RAP</td>
<td>WRF-ARW v3.3.1+</td>
<td>GSI-3DVAR</td>
<td>Yes</td>
<td>RRTM/Goddard</td>
<td>Thompson</td>
<td>G3 + Shallow</td>
<td>MYJ</td>
<td>RUC</td>
</tr>
<tr>
<td>HRRR</td>
<td>WRF-ARW v3.3.1+</td>
<td>None: RAP I.C.</td>
<td>No</td>
<td>RRTM/Goddard</td>
<td>Thompson</td>
<td>None</td>
<td>MYJ</td>
<td>RUC</td>
</tr>
</tbody>
</table>
CoSPA Operational Evaluation Periods

Development and Upgrade Periods

HRRR Reliability

HRRR 12 hr fcst availability
Includes all missed/ incomplete runs

CoSPA Operational Evaluation Periods

Development and Upgrade Periods

3 month running average

CMOS/AMS 21st NWP • High-Resolution Rapid Refresh • 31 May 2012
HRRR Reliability

HRRR 12 hr fcst availability
Excludes non-consecutive missed/ incomplete runs

CoSPA Operational Evaluation Periods
Development and Upgrade Periods

3 month running average

CMOS/AMS 21st NWP • High-Resolution Rapid Refresh • 31 May 2012
HRRR Reliability

HRRR 12 hr fcst availability
Excludes two (or fewer) consecutive missed/ incomplete runs

CoSPA Operational Evaluation Periods
Development and Upgrade Periods

3 month running average
HRRR Reliability

HRRR 12 hr fcst availability
Excludes three (or fewer) consecutive missed/ incomplete runs

CoSPA Operational Evaluation Periods
Development and Upgrade Periods

3 month running average

GSD Program Review • High-Resolution Rapid Refresh • 13 March 2012
CoSPA: Collaborative effort: ESRL/GSD, NCAR/RAL, MIT/LL
Provide 0-8 hr thunderstorm intensity and echo top guidance to aviation community

HRRR 15 UTC 08 July 2011
6 hr forecast valid 21 UTC

CoSPA 17 UTC 08 July 2011
4 hr forecast valid 21 UTC

Observation
Valid 21 UTC 08 July 2011

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TC improvement: RAP † HRRR

Comparison of HRRR forecast reflectivity (with 15-min output frequency) and observed reflectivity for Hurricane Irene
Radar Reflectivity Assimilation

00z init
00z 12 Aug 2011

Convergence Cross-Section

RAP
HRRR
no radar

RAP
HRRR
RADAR

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Radar Reflectivity Assimilation

+1h fcst
01z 12 Aug 2011

Convergence Cross-Section

RAP HRRR no radar

RAP HRRR RADAR
Differences large enough to affect convective forecasts
HRRR Forecast Behavior

2011

(1) High bias in convection over eastern US
(2) False alarms
(3) Lead in convective initiation (early AM runs)
(4) Difficulty maintaining mesoscale convective systems
(5) Reflectivity biases in snow and convective storms

RAP/HRRR Model Development and Evaluation

2012 Targets

(1) Lower peak bias in convection over eastern US
(2) Fewer false alarms
(3) Improved timing of convective initiation
(4) More success maintaining mesoscale convective systems
(5) More realistic reflectivity
## RAP and HRRR Changes 2011-2012

<table>
<thead>
<tr>
<th>Model</th>
<th>Data Assimilation</th>
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<tbody>
<tr>
<td><strong>RAP-ESRL</strong></td>
<td><strong>Soil adjustment</strong></td>
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<tr>
<td><strong>WRFv3.3.1+</strong></td>
<td><strong>Temp-dep radar-hydrometeor building</strong></td>
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<tr>
<td><strong>Physics changes</strong></td>
<td><strong>PW assim mods</strong></td>
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<tr>
<td></td>
<td><strong>Cloud assim mods</strong></td>
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<tr>
<td></td>
<td><strong>Tower/nacelle/sodar observations</strong></td>
</tr>
<tr>
<td></td>
<td><strong>GLD360 lightning</strong></td>
</tr>
<tr>
<td></td>
<td><strong>GSI merge with trunk</strong></td>
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<tr>
<td></td>
<td><strong>Radial wind assim</strong></td>
</tr>
<tr>
<td><strong>Numerics changes</strong></td>
<td><strong>30‡ 10 min shortwave radiation</strong></td>
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<tr>
<td></td>
<td><strong>New reflectivity diagnostic</strong></td>
</tr>
<tr>
<td><strong>30‡ 10 min</strong></td>
<td></td>
</tr>
<tr>
<td><strong>RAP-ESRL</strong></td>
<td><strong>30‡ 05 min shortwave radiation</strong></td>
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<tr>
<td><strong>(13 km)</strong></td>
<td><strong>New reflectivity diagnostic</strong></td>
</tr>
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<td></td>
<td></td>
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<tr>
<td><strong>HRRR (3 km)</strong></td>
<td><strong>3 km/15 min reflect assim</strong></td>
</tr>
<tr>
<td><strong>WRFv3.3.1+</strong></td>
<td><strong>3 km radial wind assim</strong></td>
</tr>
<tr>
<td><strong>Physics changes</strong></td>
<td><strong>3 km cloud cycling</strong></td>
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<tr>
<td></td>
<td><strong>3 km land-surface cycling</strong></td>
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<tr>
<td><strong>Numerics changes</strong></td>
<td><strong>3 km cloud cycling</strong></td>
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</table>

**CMOS/AMS 21st NWP  •  High-Resolution Rapid Refresh  •  31 May 2012**
Reflectivity Forecast Verification

Reflectivity ≥ 30 dBZ

03km Eastern US 135 Cases from August 2011

2011 Real-Time HRRR

2012 HRRR run retrospectively
Reflectivity Forecast Verification

Reflectivity $\geq 30$ dBZ

40km Eastern US 135 Cases from August 2011

2011 Real-Time HRRR

2012 HRRR run retrospectively

CMOS/AMS 21st NWP  High-Resolution Rapid Refresh  31 May 2012
Composite Reflectivity
Derived From Mosaic3D

observed reflectivity

HRRR 08/11/2011 (16:00) 12 hr forecast

real-time 2011 HRRR 12-h forecast

CMOS/AMS 21st NWP • High-Resolution Rapid Refresh • 31 May 2012
HRRR 2012 Upgrade

Composite Reflectivity
Derived From Mosaic3D

observed reflectivity

HRRR 08/11/2011 (16:00) 12h fcst - Experimental
Composite Reflectivity (dBZ)

prototype 2012 HRRR
12-h forecast

CMOS/AMS 21st NWP • High-Resolution Rapid Refresh • 31 May 2012
Reflectivity Diagnostic Upgrade

HRRR 14-h forecast
initialized 1500 UTC 28 Feb 2012
WRF 3.2
old reflectivity diagnostic

CMOS/AMS 21st NWP  •  High-Resolution Rapid Refresh  •  31 May 2012
Reflectivity Diagnostic Upgrade

HRRR 12-h forecast
initialized 1700 UTC 28 Feb 2012

WRF 3.3.1
new reflectivity diagnostic
### Verification of RAP-ESRL vs HRRR

#### Cold Season (29 Jan 2012 – 10 Mar 2012)

<table>
<thead>
<tr>
<th>Lead Time</th>
<th>Clouds</th>
<th>Precip (13 km)</th>
<th>Reflectivity (40 km)</th>
<th>Upper-Air</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ceiling &lt; 500 ft</td>
<td>Vis &lt; 0.5 mile</td>
<td>&gt; 0.1 inch</td>
<td>&gt; 1.0 inch</td>
<td>25 dBZ</td>
</tr>
<tr>
<td>3-hr</td>
<td>Equal</td>
<td>HRRR</td>
<td>N/A</td>
<td>Equal</td>
<td>HRRR</td>
</tr>
<tr>
<td>6-hr</td>
<td>HRRR</td>
<td>Equal</td>
<td>N/A</td>
<td>HRRR</td>
<td>HRRR</td>
</tr>
<tr>
<td>12-hr</td>
<td>HRRR</td>
<td>HRRR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Warm Season (15 April 2012 – 31 May 2012)

<table>
<thead>
<tr>
<th>Lead Time</th>
<th>Clouds</th>
<th>Precip (13 km)</th>
<th>Reflectivity (40 km)</th>
<th>Upper-Air</th>
<th>Surface</th>
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<td></td>
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<td>&gt; 1.0 inch</td>
<td>25 dBZ</td>
</tr>
<tr>
<td>3-hr</td>
<td>HRRR</td>
<td>HRRR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-hr</td>
<td>HRRR</td>
<td>Equal</td>
<td>HRRR</td>
<td>Equal</td>
<td>HRRR</td>
</tr>
<tr>
<td>12-hr</td>
<td>HRRR</td>
<td>RAP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Forecast skill comparable at lower thresholds, RAP superior at higher thresholds.
**12 hr fcsts 10m wind rms difference from METARs**

(3-day running mean, verified every hour)

**Eastern US**

**Western US**

HRRR more accurate than RAP, more so in western US, especially since Oct 2011
Time-lagged Ensemble

Forecasts valid 21-22z 27 April 2011
10-11 hr fcst
HRRR 11z Init
09-10 hr fcst
HRRR 12z Init
08-09 hr fcst
HRRR 13z Init

Forecasts valid 22-23z 27 April 2011
11-12 hr fcst
HRRR 11z Init
10-11 hr fcst
HRRR 12z Init
09-10 hr fcst
HRRR 13z Init

All six forecasts combined to form probabilities valid 22z 27 April 2011
Spatial radius 45 km
Time radius 1 hr
UH threshold 25 m²/s²

CMOS/AMS 21st NWP • High-Resolution Rapid Refresh • 31 May 2012
Example: 27 April 2011

13z + 09hr fcst
Valid 22z 27 April 2011

1630z SPC Tornado Probability
Valid 1630-1200 UTC 28 Apr

27 April 2011 Storm Reports
Valid 1200-1200 UTC 28 Apr

Tornadic Storm Probability (%)
Example: 27 April 2011

13z + 09hr fcst
Valid 22z 27 April 2011

Tornadic Storm Probability (%)

Reflectivity (dBZ)

Observed Reflectivity
22z 27 April

27 April 2011 Storm Reports
Valid 1200-1200 UTC 28 Apr

Tornado = Red Dots
HRRR Websites

HRRR Web Pages:
Hourly Plan-View Forecast Fields
Sub-Hourly Plan-View Forecast Fields
Sounding Forecasts

http://rapidrefresh.noaa.gov/hrrrconus/
http://rapidrefresh.noaa.gov/hrrrconus15min/
http://rapidrefresh.noaa.gov/soundings/
**HRRR Transition to NCEP**

- **Current – 1 computer running HRRR**
  - NOAA/ESRL – Boulder
  - Current reliability: 97% for last 12h months (allowing up to 3h gaps)

- **2012-14 – 2 computers running HRRR – interim solution**
  - Boulder – computer 1
  - Fairmont, WV – computer 2
  - Expected reliability to increase further to 98.5-99% via coordination of downtimes for Boulder vs. Fairmont computers

- **2015 – NCEP running HRRR**
  - NOAA/NCEP computing budget – will allow no increase before 2015

**Conclusion:** *Interim HRRR computing for 2012-14 on 2 sites to provide “research regular” HRRR from NOAA for NWS, FAA, DOE/energy users*
Summary and Plans

• Moist bias reduced in 2012 RAP and HRRR
  – Reduced false alarms, lower precipitation bias
  – GSI enhancements and WRF upgrade to v3.3.1
  – Reflectivity diagnostic consistent with microphysics

• Focus on cycled 3-km assimilation for 2013
  – 3-km variational analysis
  – 3-km non-variational cloud analysis
  – 3-km radar reflectivity data assimilation

• Reduced latency for 2013 (currently 2-3 hrs)
  – Approximate 1-hr reduction in execution time
  – Faster post-processing with parallelization
  – Direct GRIB2 generation