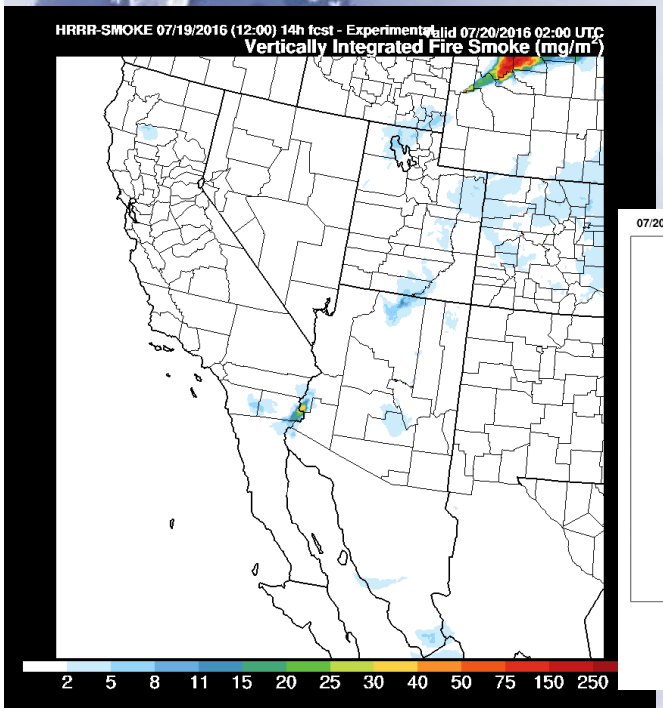
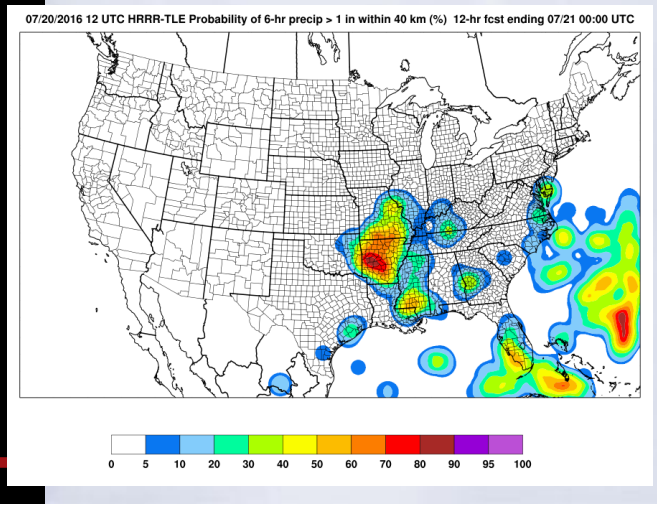
Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION
NCEP

Improvements in HRRRv2/RAPv3 for Aug 2016 Implementation at NCEP for More Accurate Warm-Season and Cold-Season NWP





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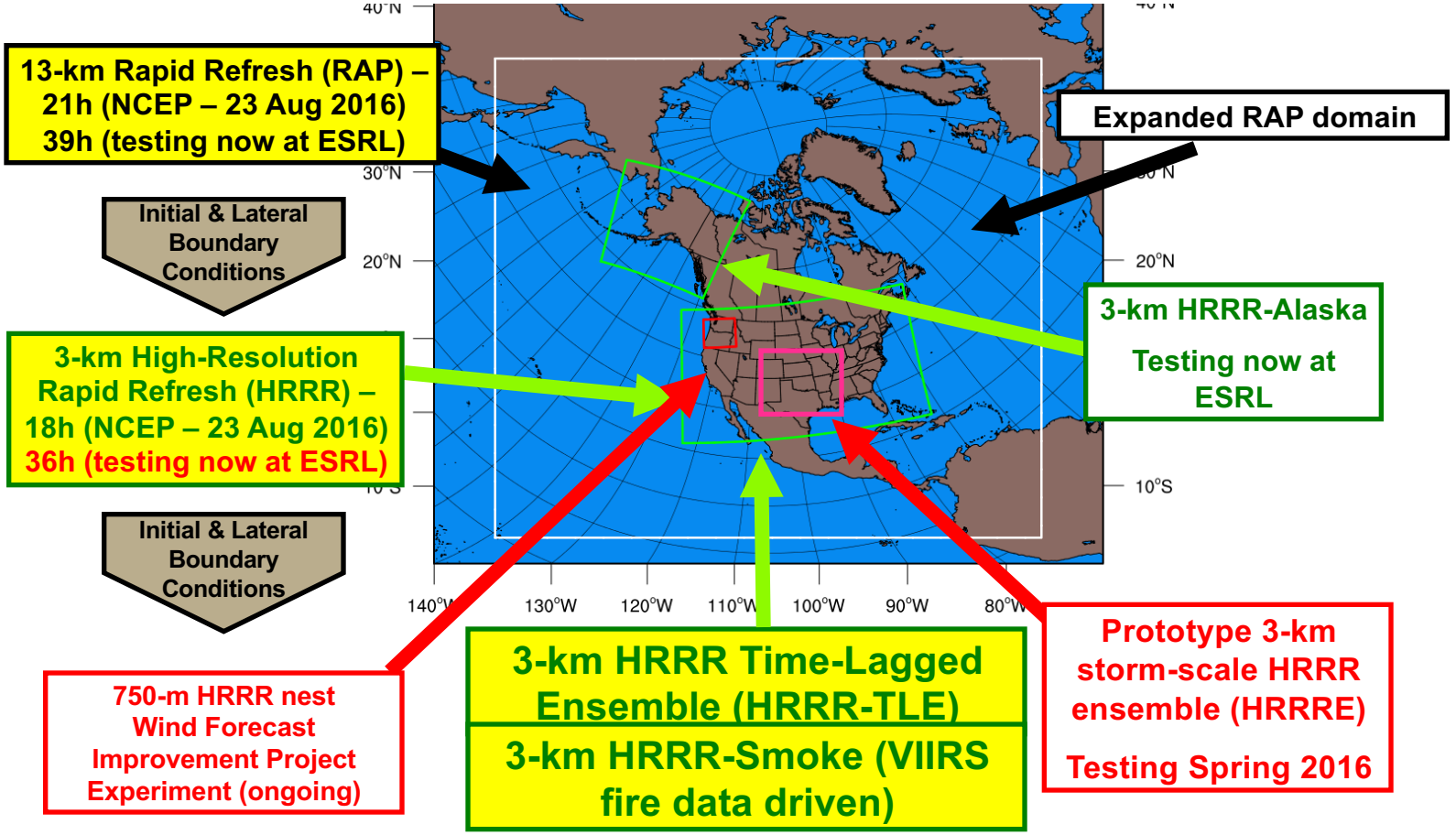
NWS-Western Region
Seminar, 20 July 2016
Updated 13 Sept 2016

RAP/HRRR Suite: Hourly-Updating Forecast Models



RAP/HRRR Implementation History

NCEP Operational Implementations

01 May 2012

- **RAPv1**: Adoption of GSI, WRF-ARW and unified post
- Enabled use of community-developed software

25 Feb 2014

- **RAPv2**: Hybrid EnKF-3DVar data assimilation
- Significant improvement in upper-air forecasts

30 Sep 2014

- **HRRRv1**: 3-km Radar DA in WRF-ARW
- Significant improvement in convective forecasts

23 Aug 2016

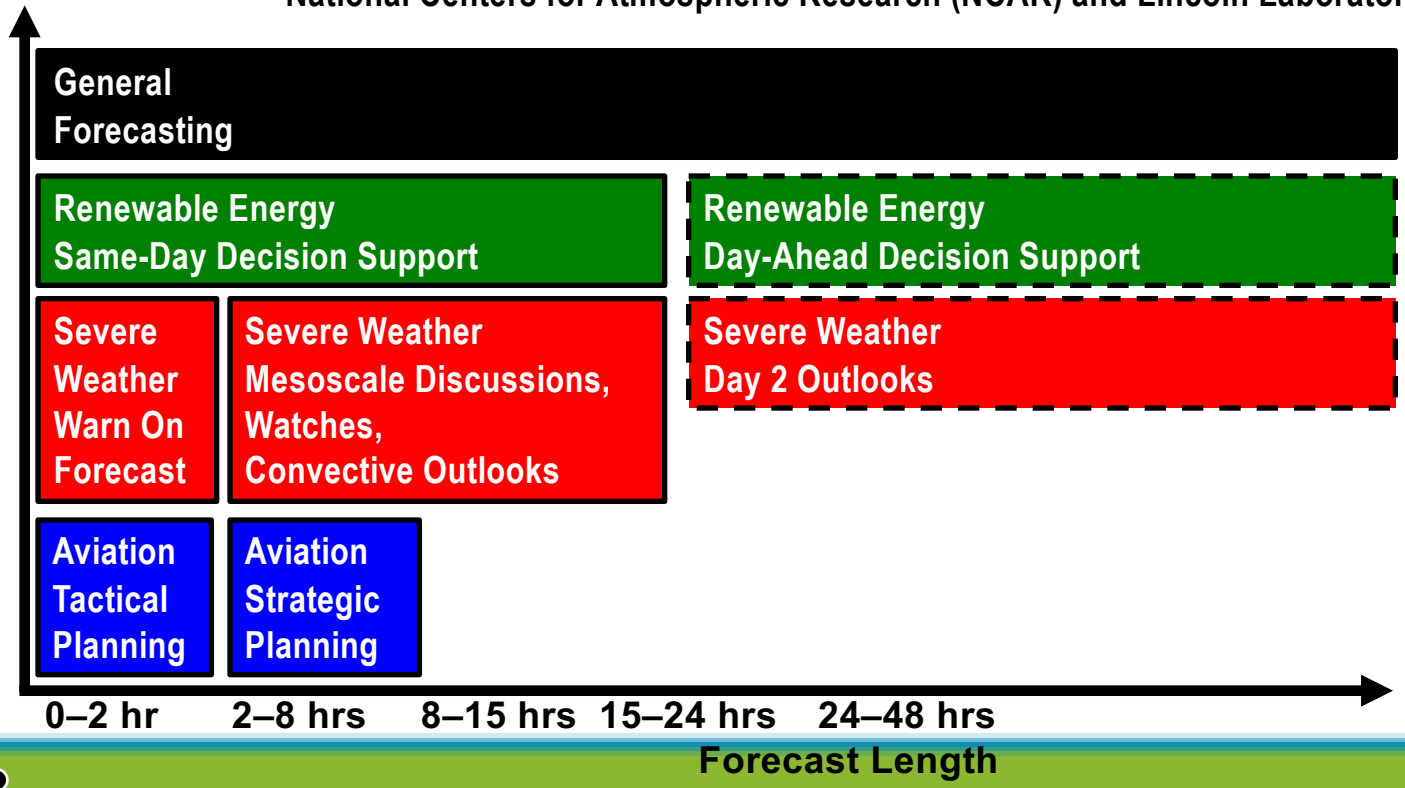
- **RAPv3/HRRRv2 (a.k.a. RAPX/HRRRX)**: Aerosol Thompson MP, improvements to MYNN PBL, RUC LSM, RRTMG Rad, Grell-Freitas cumulus
- Significant improvement in surface forecasts

History of hourly updated NWP models at NOAA

Model and assimilation system	Horizontal grid spacing	Number of vertical levels	Assim. frequency	Implementation (month/year)		Geographical domain
				NCEP	ESRL	
RUC1	60 km	25	3h	1994		CONUS
RUC2	40 km	40	1h	4/1998		CONUS
RUC20	20 km	50	1h	2/2002		CONUS
RUC13	13 km	50	1h	5/2005		CONUS
Rapid Refresh	13 km	51	1h	5/2012	2010	N. America
Rapid Refresh v2	13 km	51	1h	2/2014	1/2013	N. America
Rapid Refresh v3	13 km	51	1h	Est 23 Aug 2016	1/2015	N. America
HRRR	3 km	51	1h	9/2014	2010	CONUS
HRRR v2	3 km	51	1h	Est 23 Aug 2016	4/2015	CONUS
RAPv4/HRRRv3	13km/3km	51	1h	Early 2018?	Sep-Oct 16	N.Am / CONUS

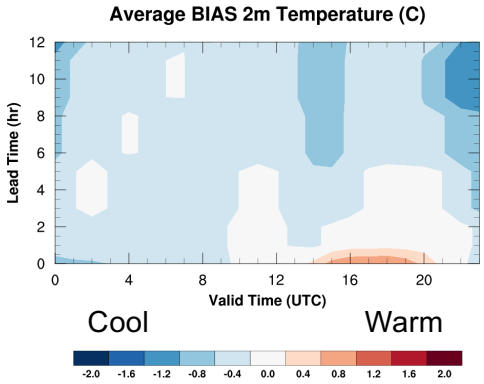
HRRR Users and Applications

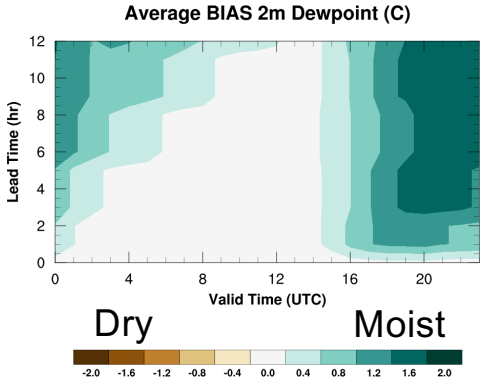
Example: National Weather Service including Storm and Weather Prediction Centers (SPC & WPC)
Aviation Weather Center (AWC) and FAA Command Center
National Severe Storms Laboratory (NSSL) and Air Resources Laboratory (ARL)
National Centers for Atmospheric Research (NCAR) and Lincoln Laboratory (LL)



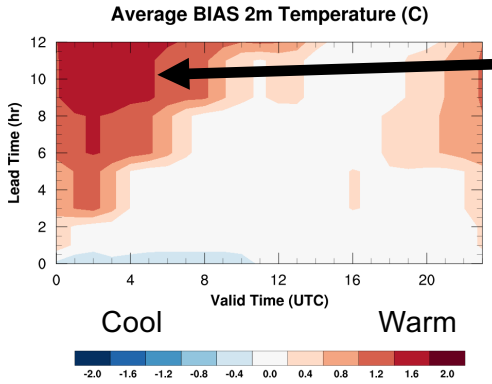
Operational RAPv2/HRRRv1 Forecast Biases

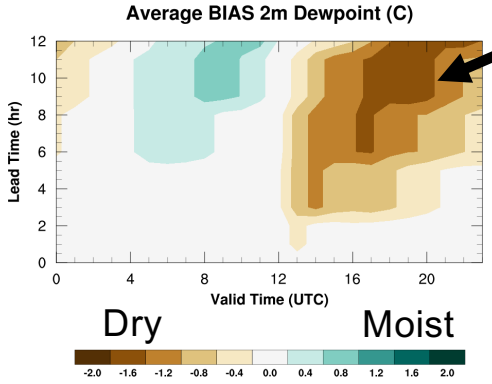
Winter (Jan-Mar)





Summer (Jul-Sep)



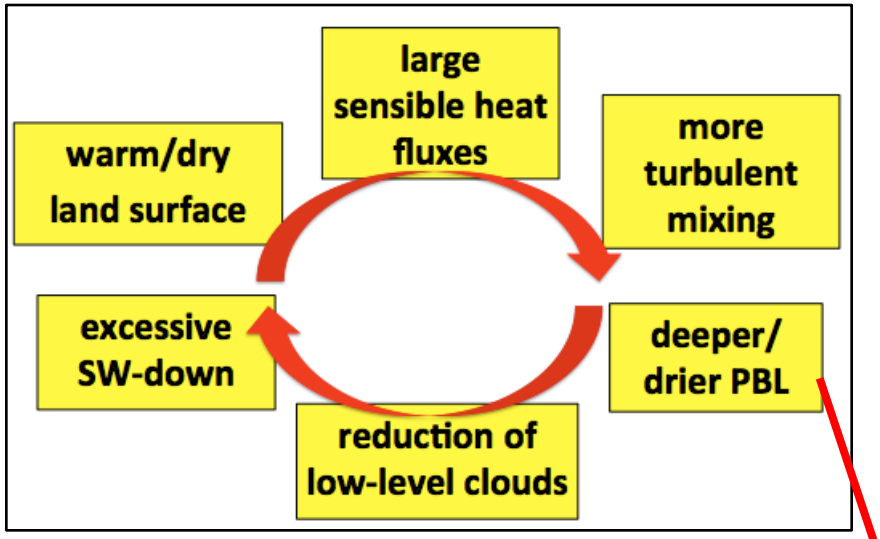


The RAP/HRRR has a daytime warm bias in the warm season.

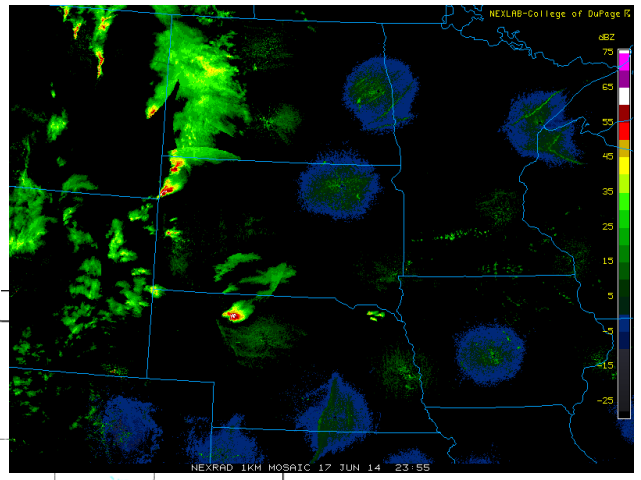
The RAP/HRRR has a daytime dry bias in the warm season.

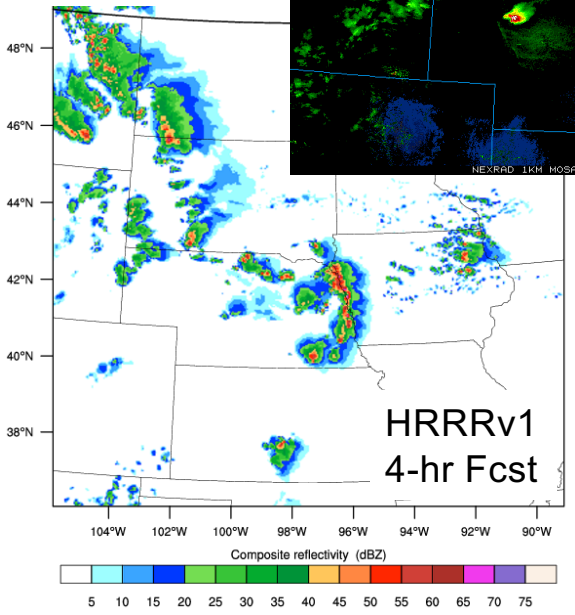
Experimental improvements to the model to remove bias have been made and will be implemented in RAPv3/HRRRv2.

Operational RAPv2/HRRRv1 Bias Conceptual Model



00 UTC
18 June 2014
Coleridge, NE

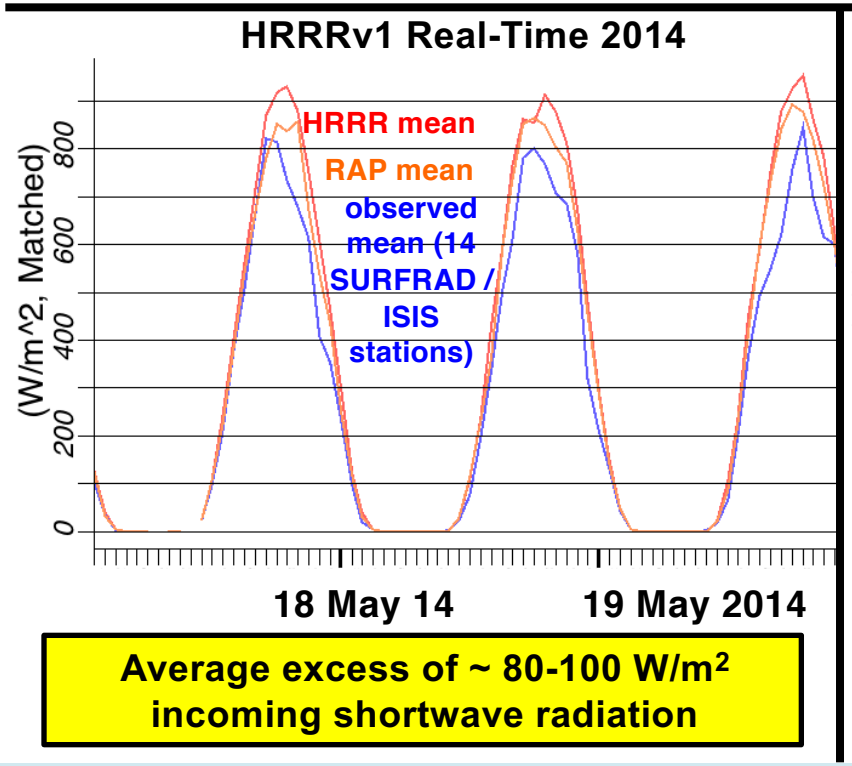




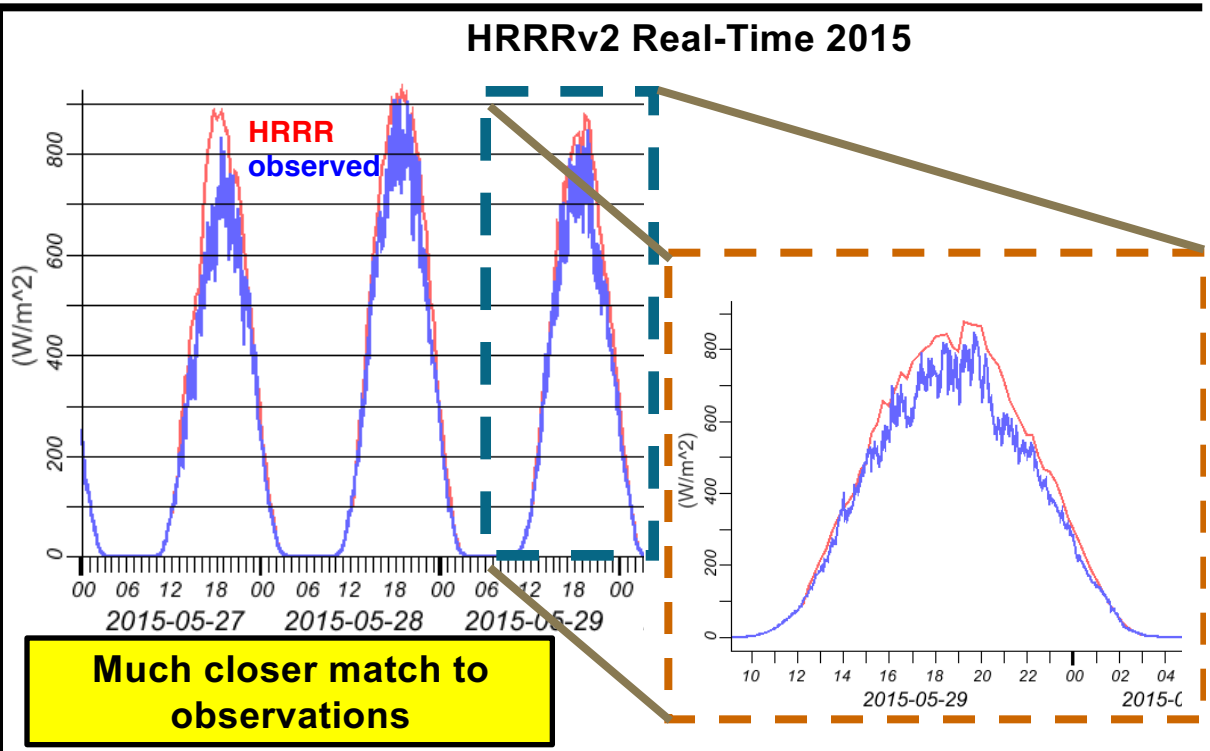
Led to occasional spurious high-based convective initiation in more weakly-forced diurnally-driven events

HRRRv2 Real-Time Case Study: Spring Radiation

Downward Shortwave Flux at Surface
12-hr Forecasts



Average excess of ~ 80-100 W/m^2 incoming shortwave radiation

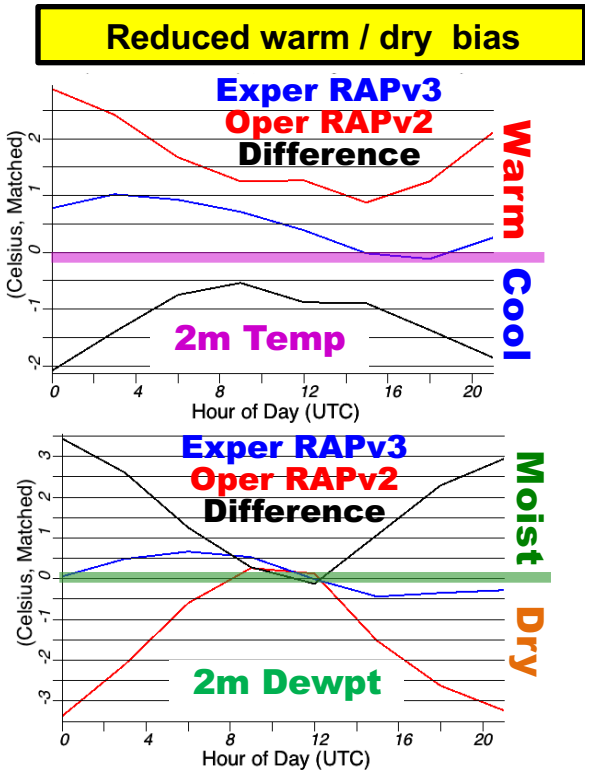


Much closer match to observations

RAPv3/HRRRv2 Model Forecast Improvements

HRRR component improvements to address warm/dry bias in RAPV2/HRRRv3

Component	Mitigating Items
GSI Data Assimilation	Canopy water cycling Temp pseudo-innovations thru model boundary layer More consistent use of surface temp/dewpoint data
GFO Convective Parameterization	Shallow cumulus radiation attenuation Improved retention of stratification atop mixed layer
Thompson Microphysics	Aerosol awareness for resolved cloud production Attenuation of shortwave radiation
MYNN Boundary Layer	Mixing length parameter changed Thermal roughness in surface layer changed Coupling boundary layer clouds to RRTMG radiation
RUC Land Surface Model	Reduced wilting point for more transpiration Keep soil moisture in croplands above wilting point



RAPv3/HRRRv2 Changes at NCEP (Aug 2016)

	Model	Data Assimilation
RAP (13 km)	WRF-ARWv3.6+ incl. physics changes Physics changes: Grell-Freitas-Olson convective scheme - non-local mixing in shallow cumulus Thompson MP -- Aerosol-aware MYNN PBL – subgrid-cloud rad feedback RUC LSM -- MODIS seasonal leaf-area index -- Reduced wilting point, irrigation for cropland RRTMG radiation scheme Direct and diffuse GHI components	Merge with GSI trunk Radial velocity assimilation Mesonet assimilation RARS data assimilation Radiance bias correction Pseudo-PBL obs for temperature Improved 2m temp/dewpoint background estimate, QC Low-reflectivity precip building Stronger ensemble weight in assimilation
HRRR (3 km)	WRF-ARWv3.6+ incl. physics changes Physics changes: Thompson MP - Aerosol-aware MYNN PBL – subgrid-cloud rad effect RUC LSM -- MODIS seasonal leaf-area index -- Reduced wilting point, irrigation for cropland RRTMG radiation scheme Direct and diffuse GHI components Numerics changes: 6th order slope-dependent diffusion	Merge with GSI trunk 3-km hybrid assimilation Hydrostatic rebalance after analysis Mesonet assimilation Pseudo-PBL obs for temperature Improved 2m temp/dewpoint background estimate, QC Low-reflectivity precip building Full cloud/precip hydrometeor assim Stronger ensemble weight in assimilation

Most important for improvements to convection, cloud, warm/dry bias correction

RAPv3/HRRRv2 Changes to Observations Assimilated

New in RAPv3/HRRRv2

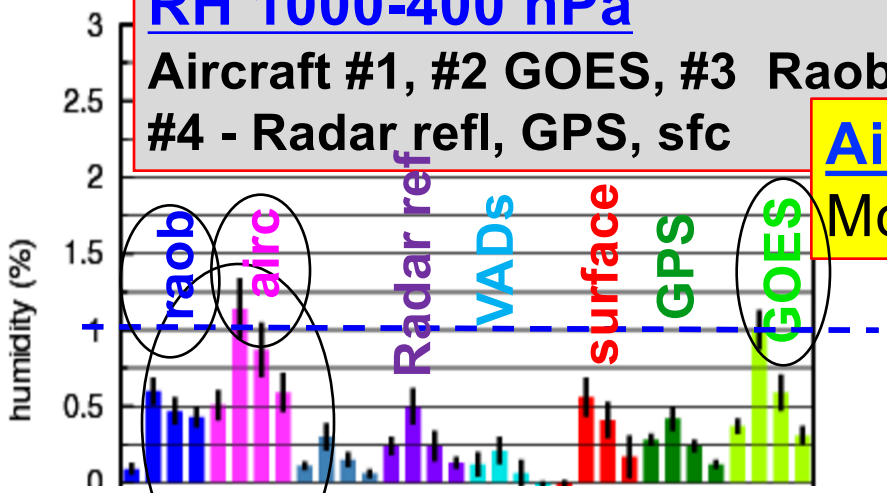
Radial Velocity (RAPv3)
Lightning (RAPv3)
Mesonet (RAPv3/HRRRv2)
RARS Radiances (RAPv3)

Hourly Observation Type	Variables Observed	Observation Count
Rawinsonde	Temperature, Humidity, Wind, Pressure	120
Profiler – 915 MHz	Wind, Virtual Temperature	20-30
Radar – VAD	Wind	125
Radar	**Radial Velocity**	**125 radars**
Radar reflectivity – CONUS	3-d refl ➔Rain, Snow, Graupel	1,500,000
Lightning	**(proxy reflectivity)**	**NLDN**
Aircraft	Wind, Temperature	2,000 -15,000
Aircraft - WVSS	Humidity	0 - 800
Surface/METAR	Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather	2200 - 2500
Surface/Mesonet	**Temperature, Moisture, Wind**	**~5K-12K**
Buoys/ships	Wind, Pressure	200 - 400
GOES AMVs	Wind	2000 - 4000
AMSU/HIRS/MHS **(RARS)**	Radiances	1K-10K
GOES	**Radiances**	**large**
GOES cloud-top press/temp	Cloud Top Height	100,000
GPS – Precipitable water	Humidity	260
WindSat Scatterometer	Winds	2,000 – 10,000

Obs Impact - N. America, 3h/6h/9h/12h, 12z+00z, RAP

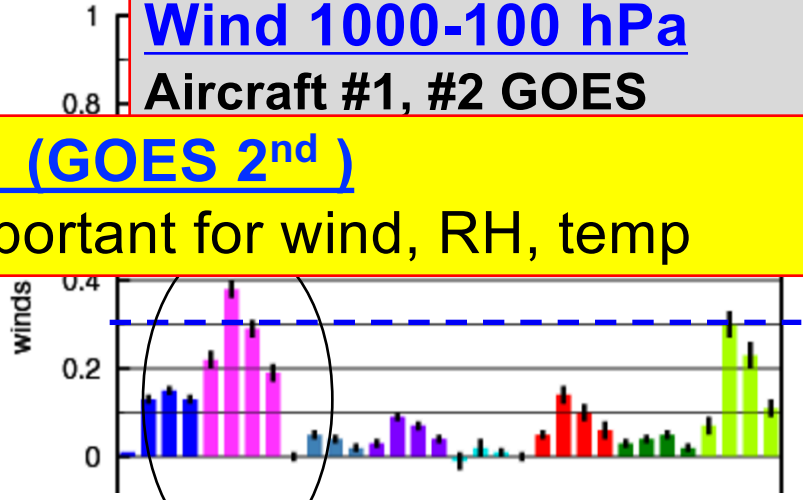
RH 1000-400 hPa

Aircraft #1, #2 GOES, #3 Raobs
#4 - Radar refl, GPS, sfc



Wind 1000-100 hPa

Aircraft #1, #2 GOES

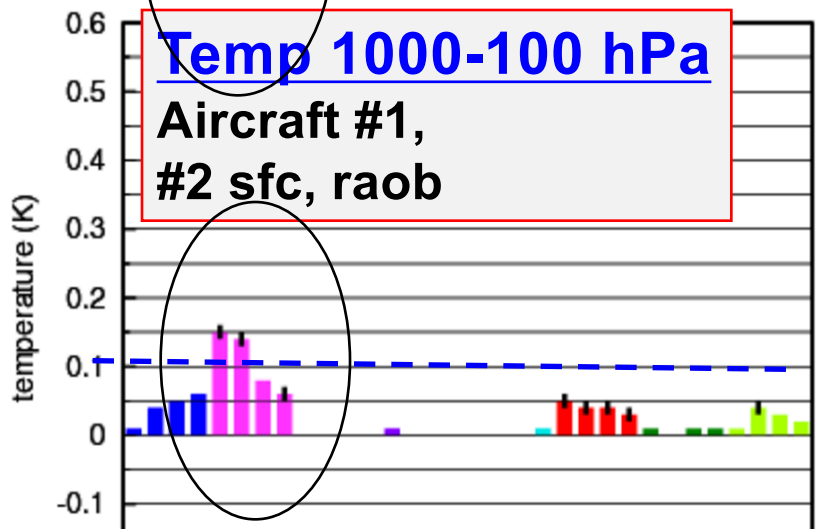


Aircraft (GOES 2nd)

Most important for wind, RH, temp

Temp 1000-100 hPa

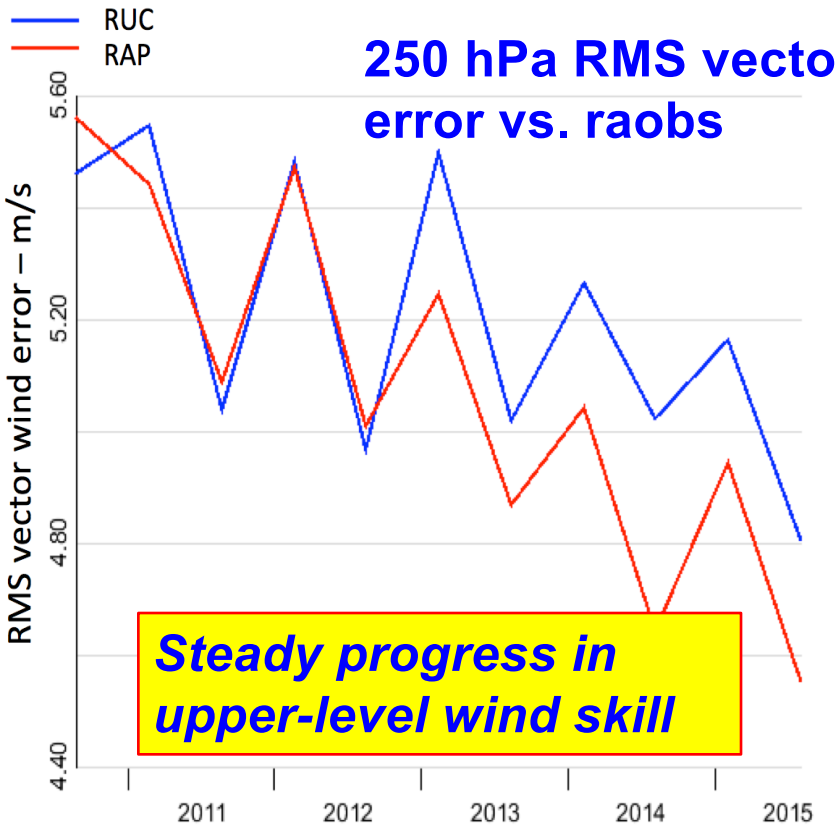
Aircraft #1,
#2 sfc, raob



A - withhold rawinsonde obs - Exp. raob - control
B - withhold aircraft obs - Exp. aircraft - control
C - withhold profiler obs - Exp. profiler - control
D - withhold radar reflectivity - Exp. radar - control
E - withhold VAD winds - Exp. vad - control
F - withhold surface obs including METAR cloud - Exp. surface - control
G - withhold GPS-Met precipitable water obs - Exp. gpsmet - control
H - withhold GOES satellite obs - Exp. goes - control

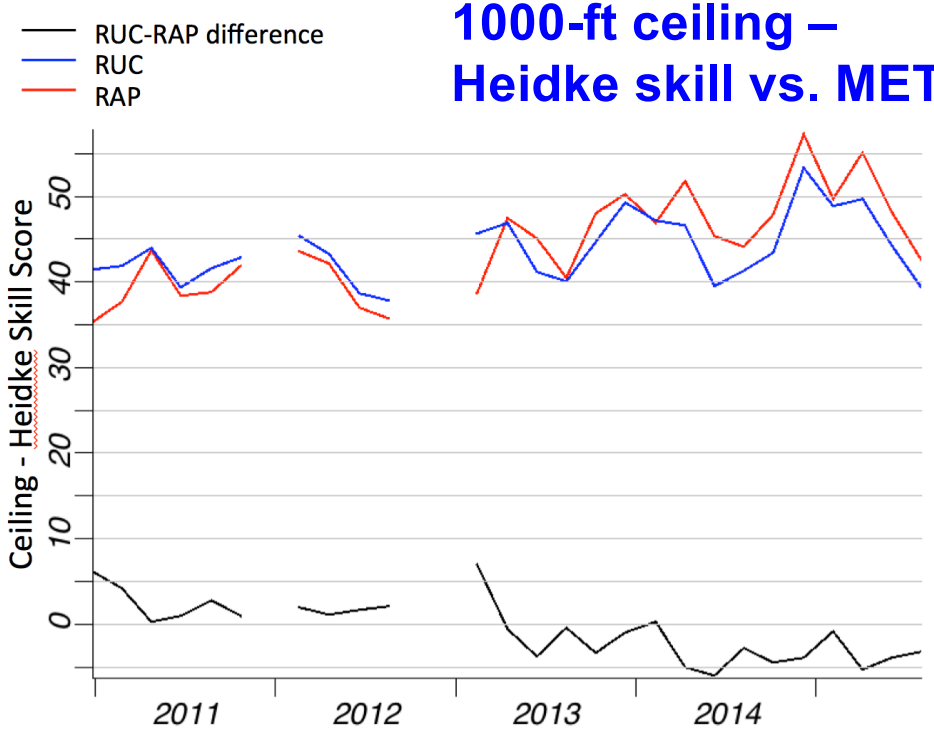
6h F – 0h A for normalizing
V – 1.5 m/s, T – 0.6K
RH – 5%

RUC / RAP 2009-2015 – 6h forecasts over CONUS



250 hPa RMS vector error vs. raobs

Steady progress in upper-level wind skill



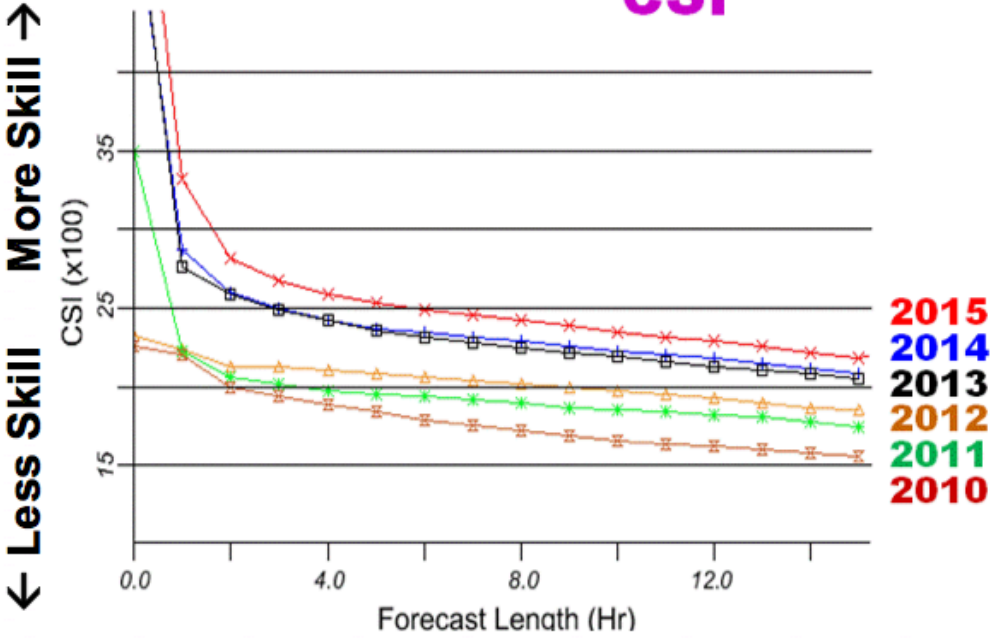
1000-ft ceiling – Heidke skill vs. METARs

HRRR reflectivity verification by year

CONUS
1 Jan – 31 Dec
Each year

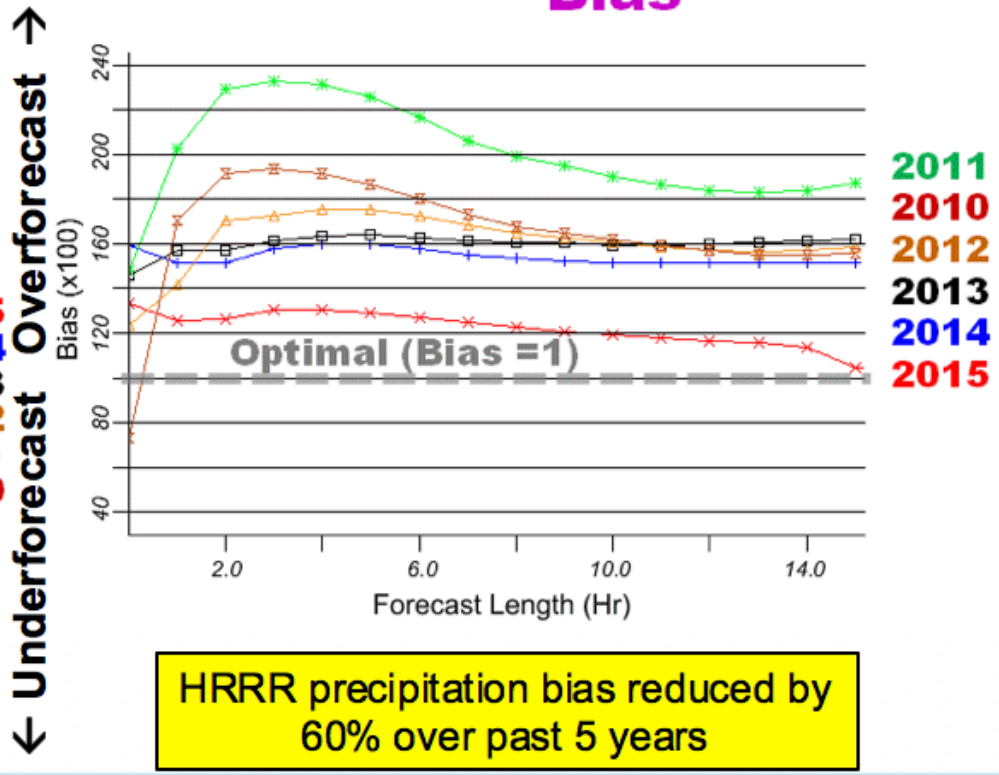
20 dbz 20 km -- score vs. forecast length

CSI



HRRR precipitation location skill improves by 50% over past 5 years

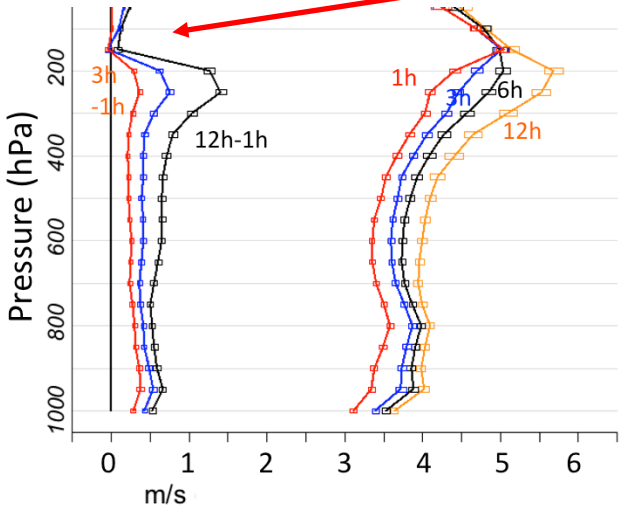
Bias



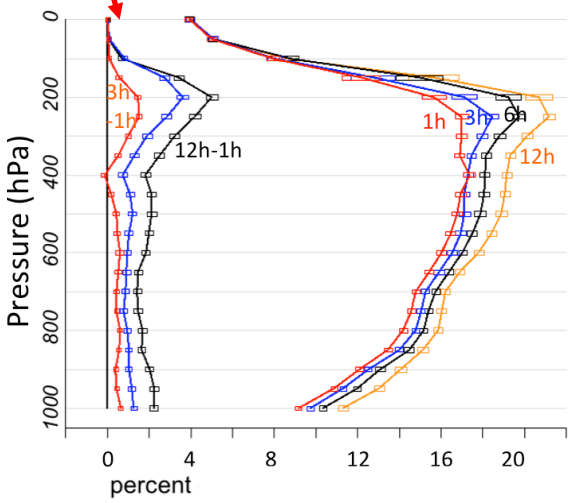
HRRR precipitation bias reduced by 60% over past 5 years

RAP (RAPv3) 2015 – 1-12h forecast skill over CONUS vs. raobs

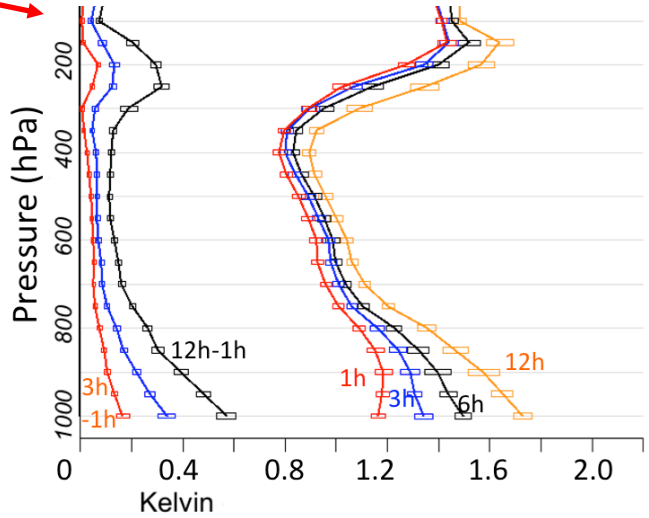
Skill improvement w/ 1h fcst



Winds – RMS vector error



RH – RMS error



Temp – RMS error

RAPv3/HRRRv2 Summary of Changes

Operational RAPv2/HRRRv1

Model	Run at:	Domain	Grid Points	Grid Spacing	Vertical Levels	Pressure Top	Boundary Conditions	Initialized
RAP	GSD, NCO	North America	758 x 567	13 km	50	10 mb	GFS	Hourly (cycled)
HRRR	GSD, NCO	CONUS	1799 x 1059	3 km	50	20 mb	RAP	Hourly (pre-forecast hour cycle)

Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.4.1+	GSI Hybrid 3D-VAR/Ensemble	13-km DFI	RRTM/ Goddard	Thompson v3.4.1	G3 + Shallow	MYNN	RUC
HRRR	WRF-ARW v3.4.1+	GSI 3D-VAR	3-km 15-min LH	RRTM/ Goddard	Thompson v3.4.1	None	MYNN	RUC

Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	6th Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	$5^{th}/5^{th}$	Positive-Definite	w-Rayleigh 0.2	Yes 0.12	10 min	MODIS Fractional	0.01 K/s	60 s
HRRR	$5^{th}/5^{th}$	Positive-Definite	w-Rayleigh 0.2	No	5 min	MODIS Fractional	0.07 K/s	20 s

RAPv3/HRRRv2 Summary of Changes – Model / Assim

Implementation RAPv3/HRRRv2

Larger RAP domain

Newer WRF version

More ensemble weight, more complete use of radar reflect. all seasons

Advanced physics

Seasonal Vegetation Fraction/Leaf Area Index

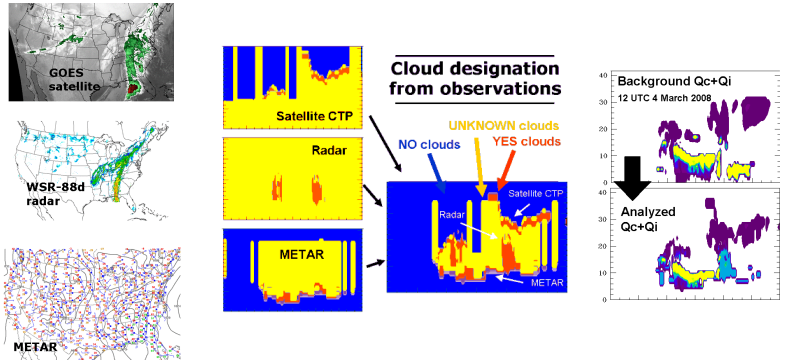
Model	Run at:	Domain	Grid Points	Grid Spacing	Vertical Levels	Pressure Top	Boundary Conditions	Initialized
RAP	GSD, NCO	North America	953 x 834	13 km	50	10 mb	GFS	Hourly (cycled)
HRRR	GSD, NCO	CONUS	1799 x 1059	3 km	50	20 mb	RAP	Hourly (pre-forecast hour cycle)

Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.6+	GSI Hybrid Ensemble to 0.75	13-km DFI + low reflect	RRTMG/ RRTMG	Thompson Aerosol v3.6	GF + Shallow	MYNN v3.6	RUC v3.6
HRRR	WRF-ARW v3.6+	GSI Hybrid Ensemble to 0.75	3-km 15-min LH + low reflect	RRTMG/ RRTMG	Thompson Aerosol v3.6	MYNN sub-grid clouds for radiation	MYNN v3.6	RUC v3.6

Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	6th Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	5th/5th	Positive-Definite	w-Rayleigh 0.2	Yes 0.12	20 min	MODIS Seasonal	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	Yes 0.25 (flat terr)	15 min with SW-dt	MODIS Seasonal	0.07 K/s	20 s

Rapid Refresh Specific Analysis Features

Cloud and hydrometeor analysis



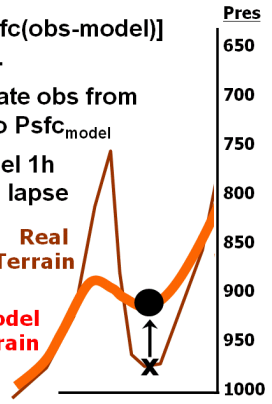
Special treatments for surface observations

Elevation correction

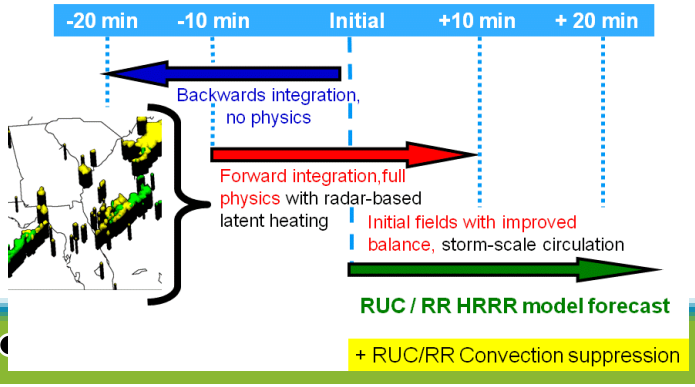
If abs[Psfc(obs-model)] < 70 hPa.

Extrapolate obs from $Psfc_{obs}$ to $Psfc_{model}$

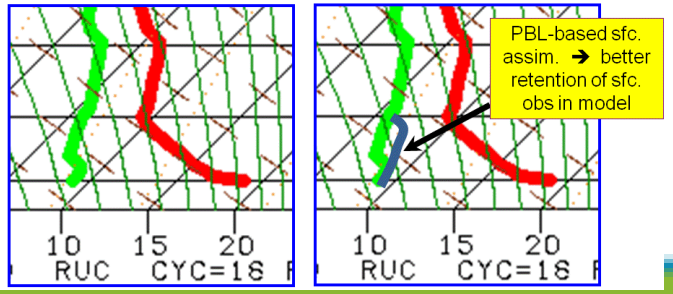
Use model 1h low-level lapse rate.



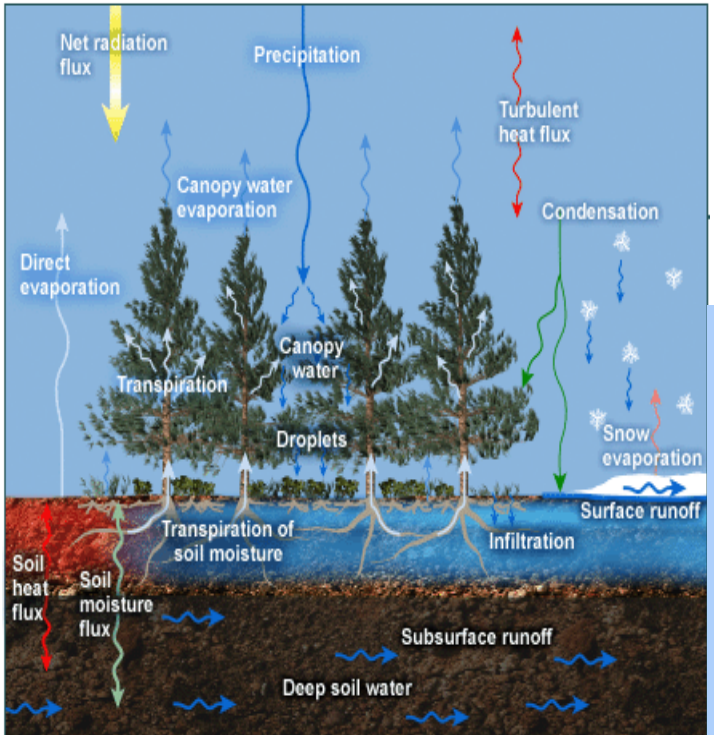
Digital filter-based reflectivity assimilation (DDFI)



PBL-based pseudo-observations



Updates to RUC Land Surface Model



OLD ~ 8 m	NEW ~ 8 m
0 (cm)	0 (cm)
	1
	4
5	
	10
20	
	30
40	60
	100
160	160
300	300

Thinner soil layer in energy / moisture budgets
Potential for increased near-surface diurnal cycle
Reduced warm bias at night, cold bias in day

RAP improvements

Version 2

Increased number of levels in soil domain – 9 levels

- Increased roughness Z_0 for forests, cropland, urban
- New formulation to compute effective roughness length Z_{0eff} in the grid box (exponential)

==========

Version 3 (partial list)

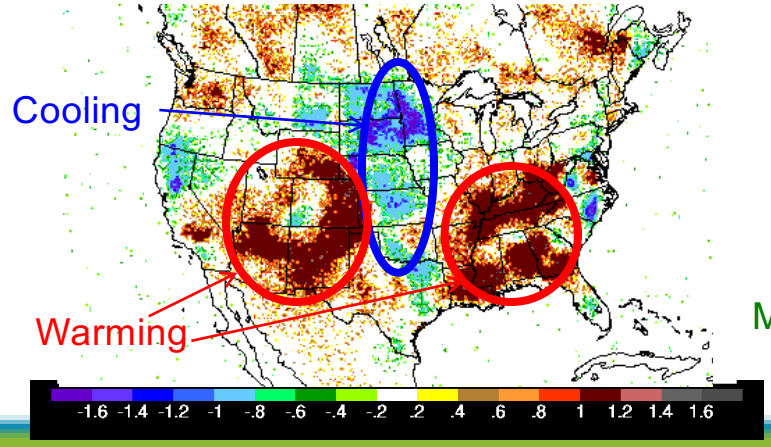
- Seasonal variations of Z_0 for MODIS cropland category
- Seasonal variations of LAI based on the current vegetation fraction and variability of this parameter for different vegetation types

What is unique about the Land Surface Model (LSM) for HRRR/RAP?

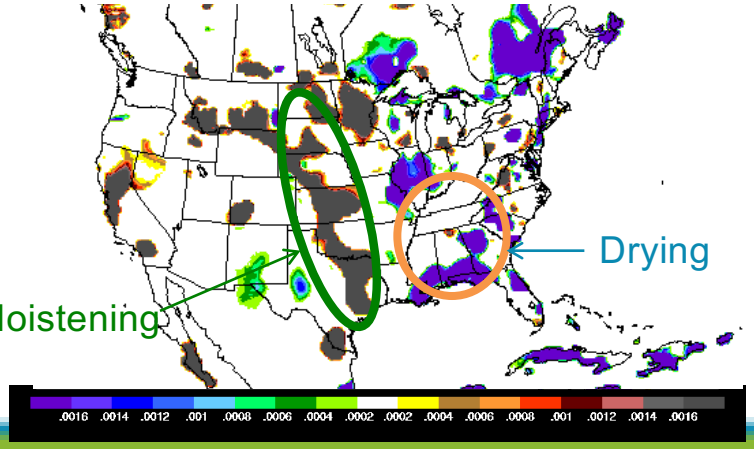
- 9 soil layers, 2 snow layers
- Surface observations are used to update the LSM through the data assimilation step. For example, the soil temperature is decreased and soil moisture is increased where the model is too warm and too dry compared to the surface observations.

Example Soil Adjustments
20 UTC
03 June 2013

Soil Temperature



Soil Moisture

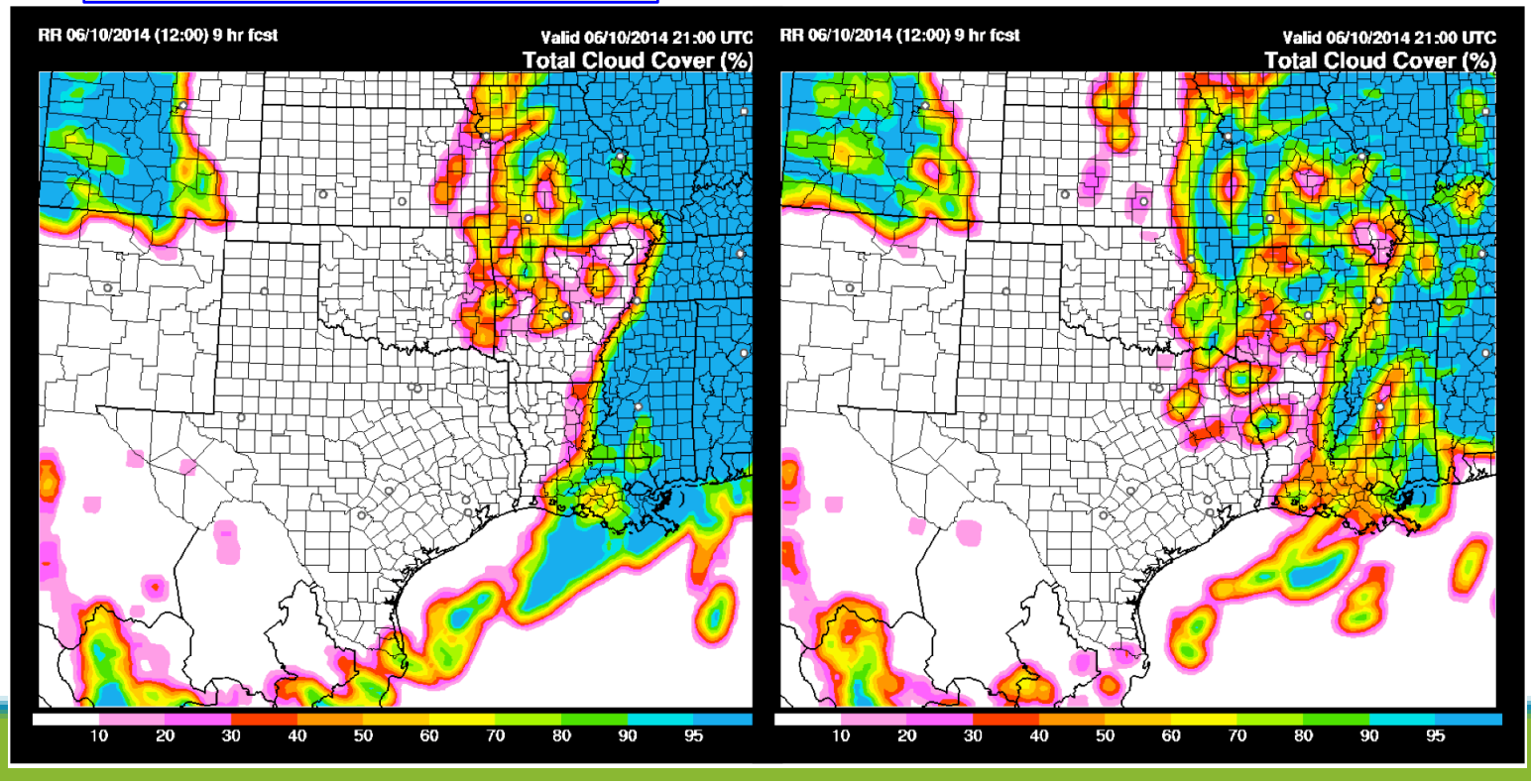


NCEP RAPv3/HRRRv2-2015 Changes

Use of forecast aerosol fields to have prognostic cloud-condensation nuclei (CCN).

Example: RAP cold-start tests without/with aerosol-aware cloud microphysics

WRFv3.6 Aerosol-aware

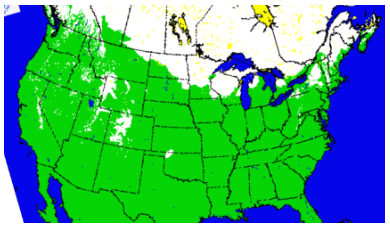


What about snow cover?

The snow water equivalent is cycled. So, model frozen precipitation is remembered.

The Interactive Multisensor Snow/Ice Mapping System (IMS) is used to update the snow cover in the model when it is available (once a day).

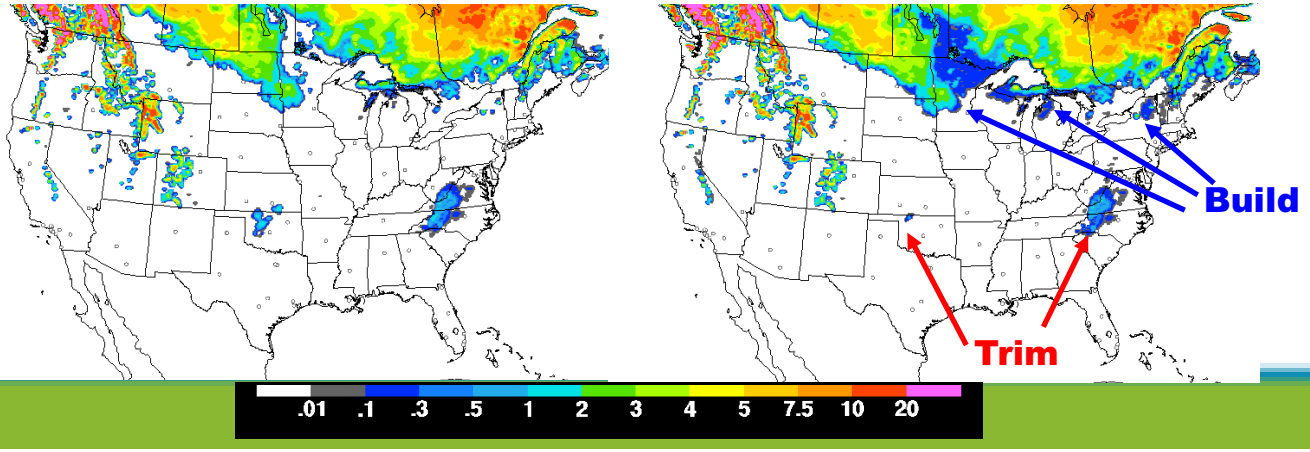
IMS Surface Snow Water Equivalent
Valid 0000 UTC



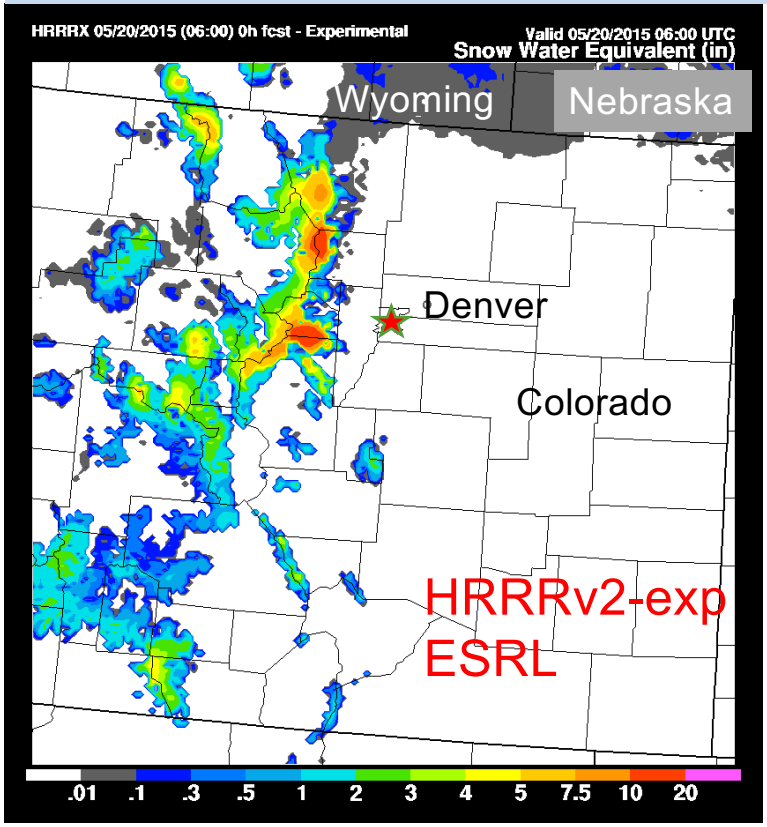
Model Surface Snow Water Equivalent
Valid 0000 UTC

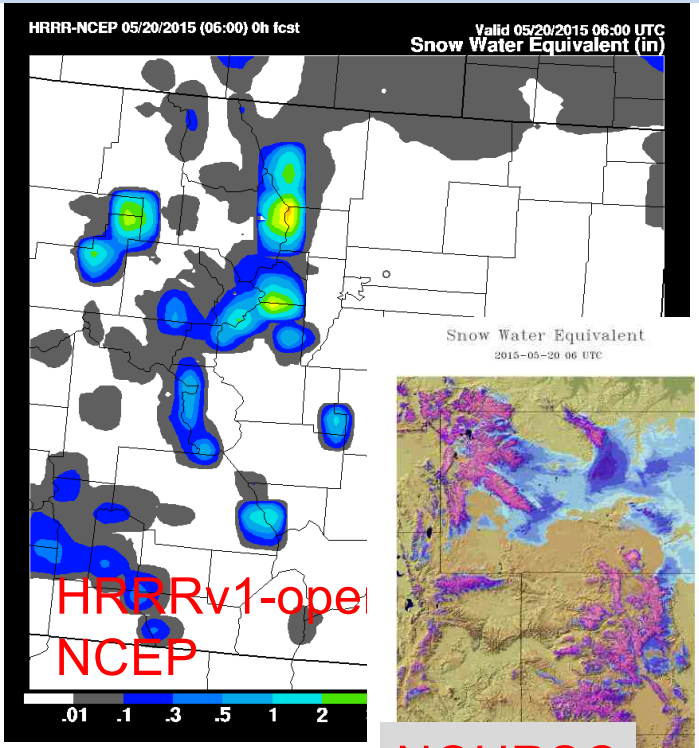
Before NOAA IMS snowcover update

After NOAA IMS snowcover update



Snow-cover updating
HRRRv2 – full land-sfc/snow cycling





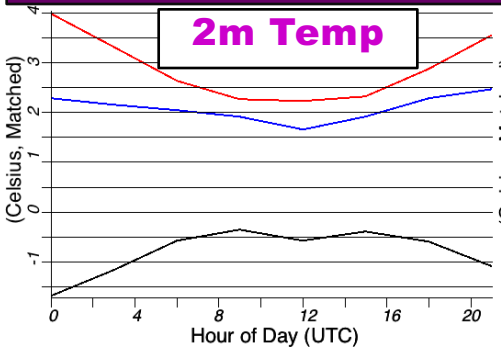
Snow water equivalent – 06z 20 May 2015 – inches

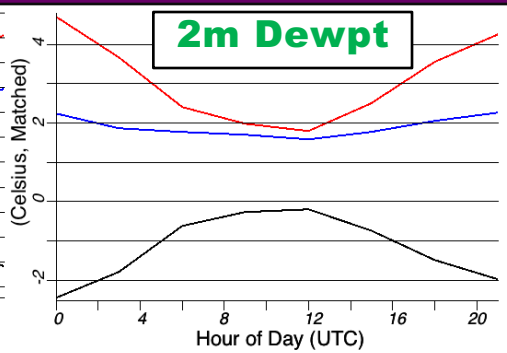
RAPv3 Retrospective Tests: Surface

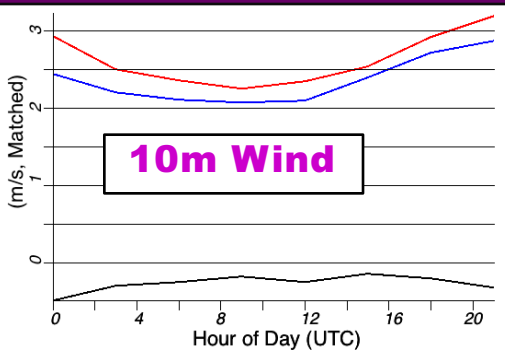
Eastern US
15 Jul – 15 Aug 2014

Exper RAPv3
Oper RAPv2
RAPv3 - RAPv2 Difference

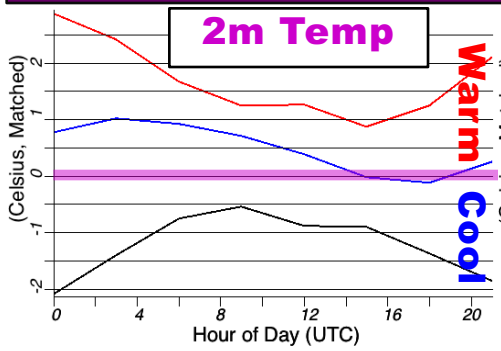
RAP Surface 12-hr Forecast RMSE

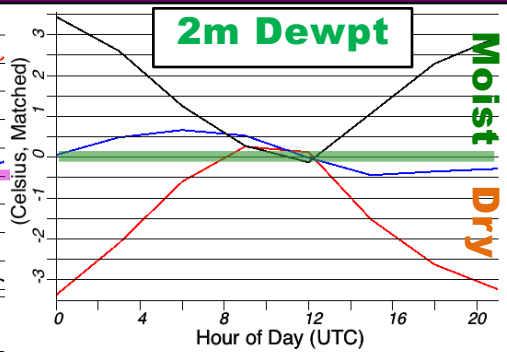


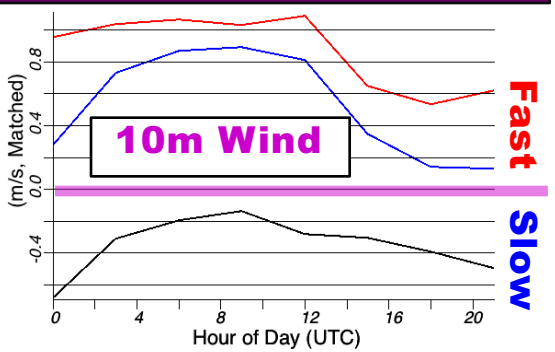




RAP Surface 12-hr Forecast Bias





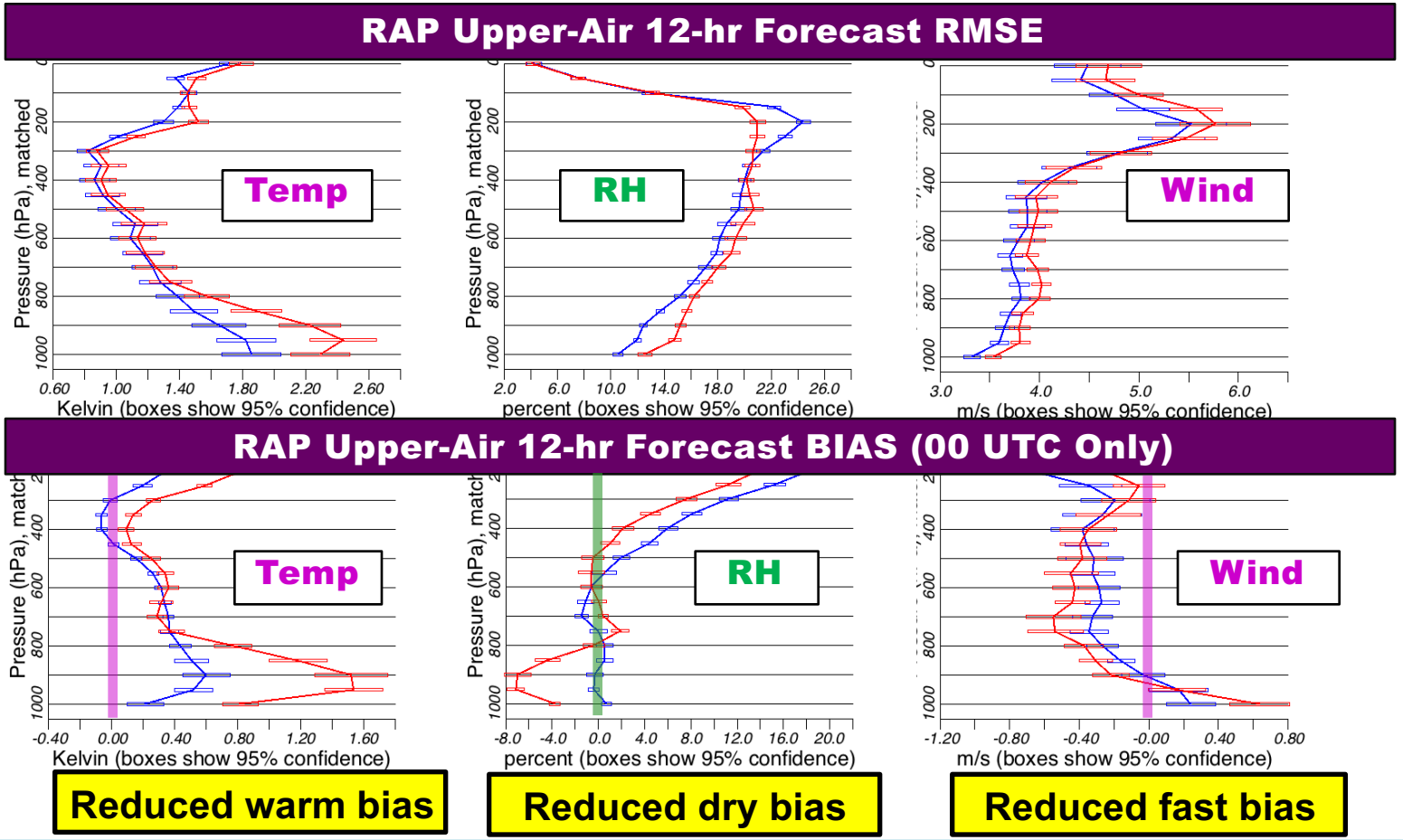


Reduced warm bias | **Reduced dry bias** | **Reduced fast bias**

RAPv3 Retrospective Tests: Upper-Air

Eastern US
15 Jul – 15 Aug 2014

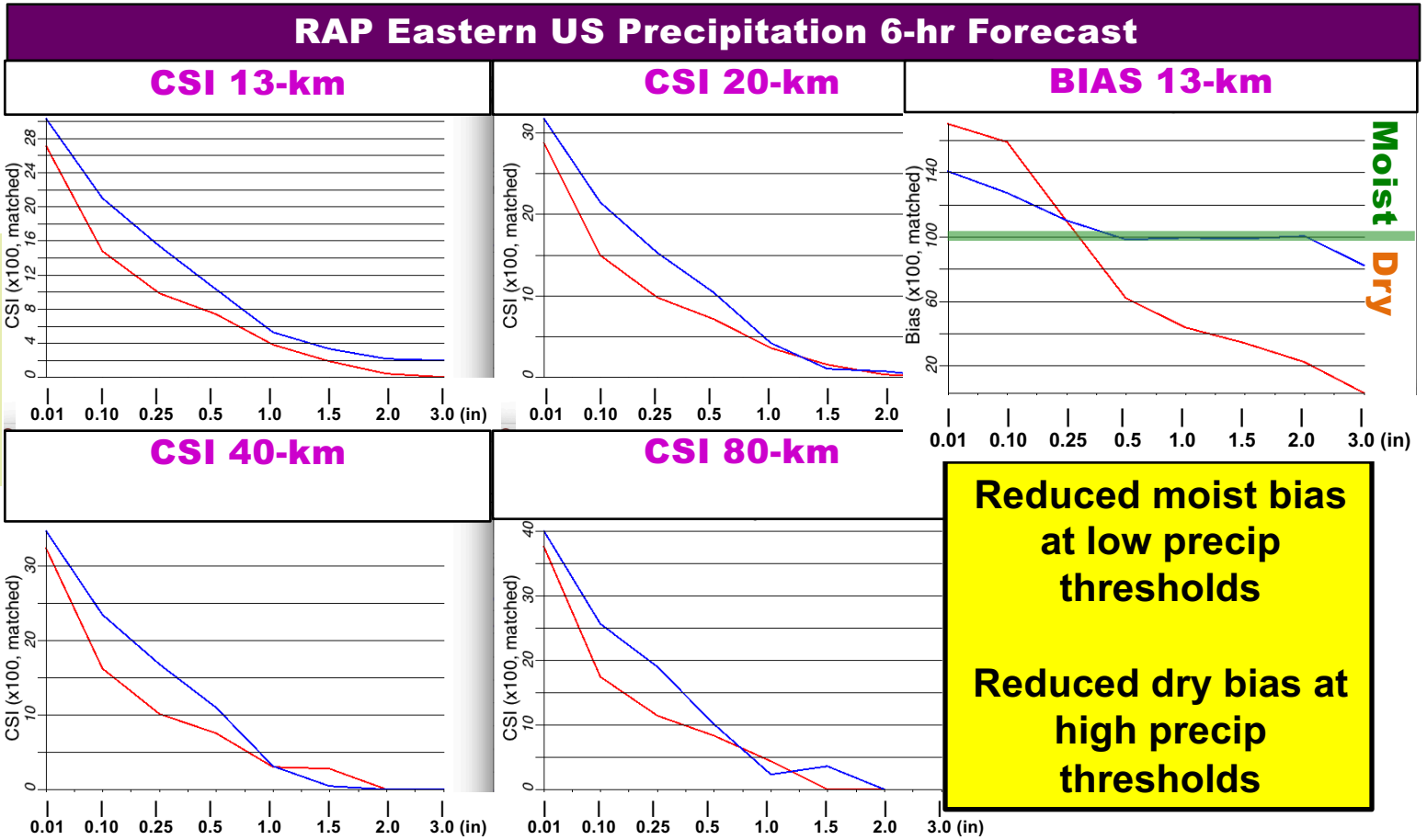
Exper RAPv3
Oper RAPv2
RAPv3 - RAPv2
Difference



RAPv3 Retrospective Tests: Precipitation

Eastern US
15 Jul – 15 Aug 2014

Exper RAPv3
Oper RAPv2



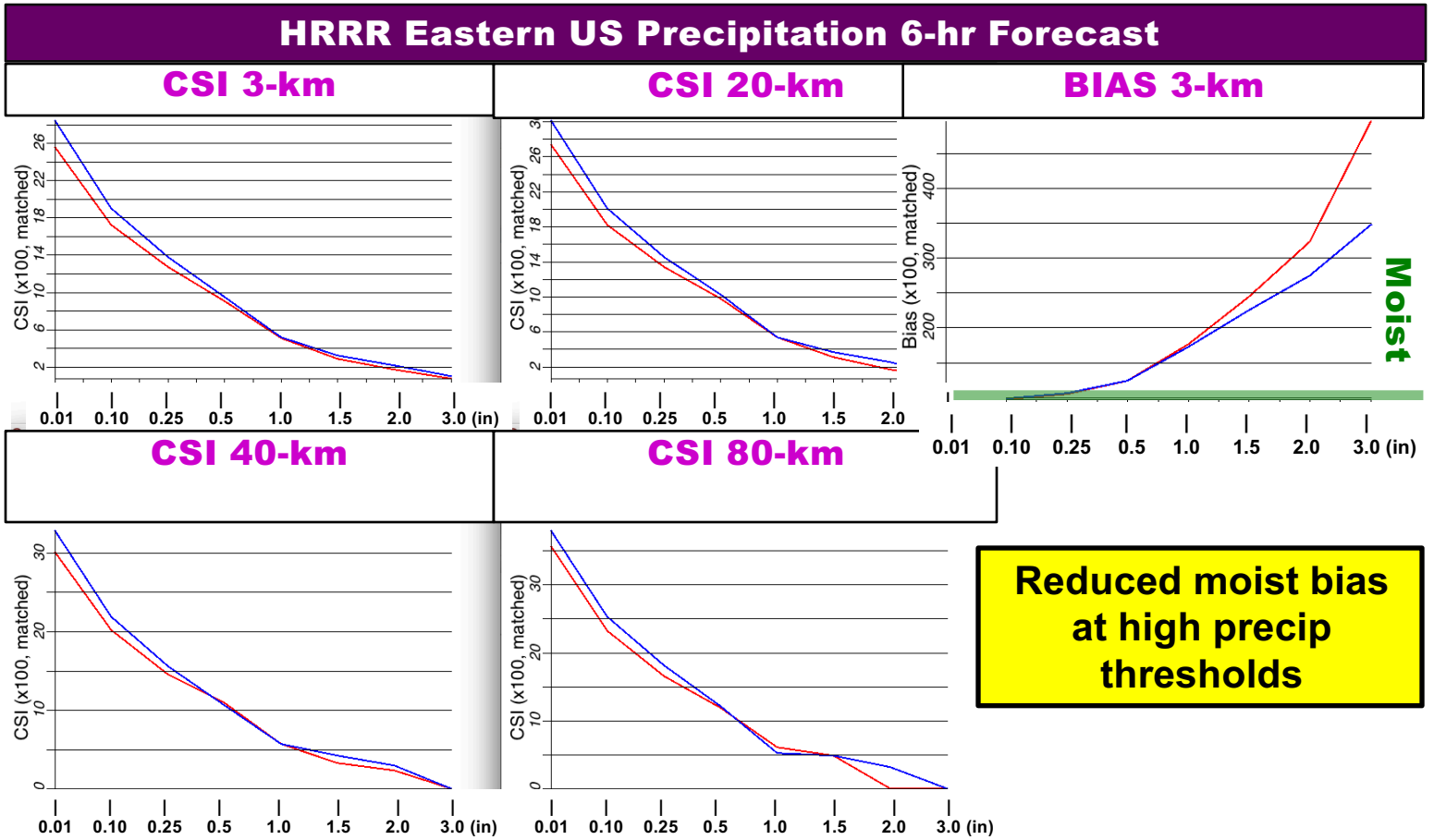
Reduced moist bias at low precip thresholds

Reduced dry bias at high precip thresholds

HRRRv2 Retrospective Tests: Precipitation

Eastern US
15 Jul – 15 Aug 2014

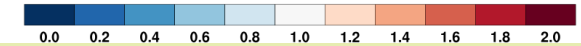
Exper HRRRv2
Real-Time HRRRv1



Reduced moist bias at high precip thresholds

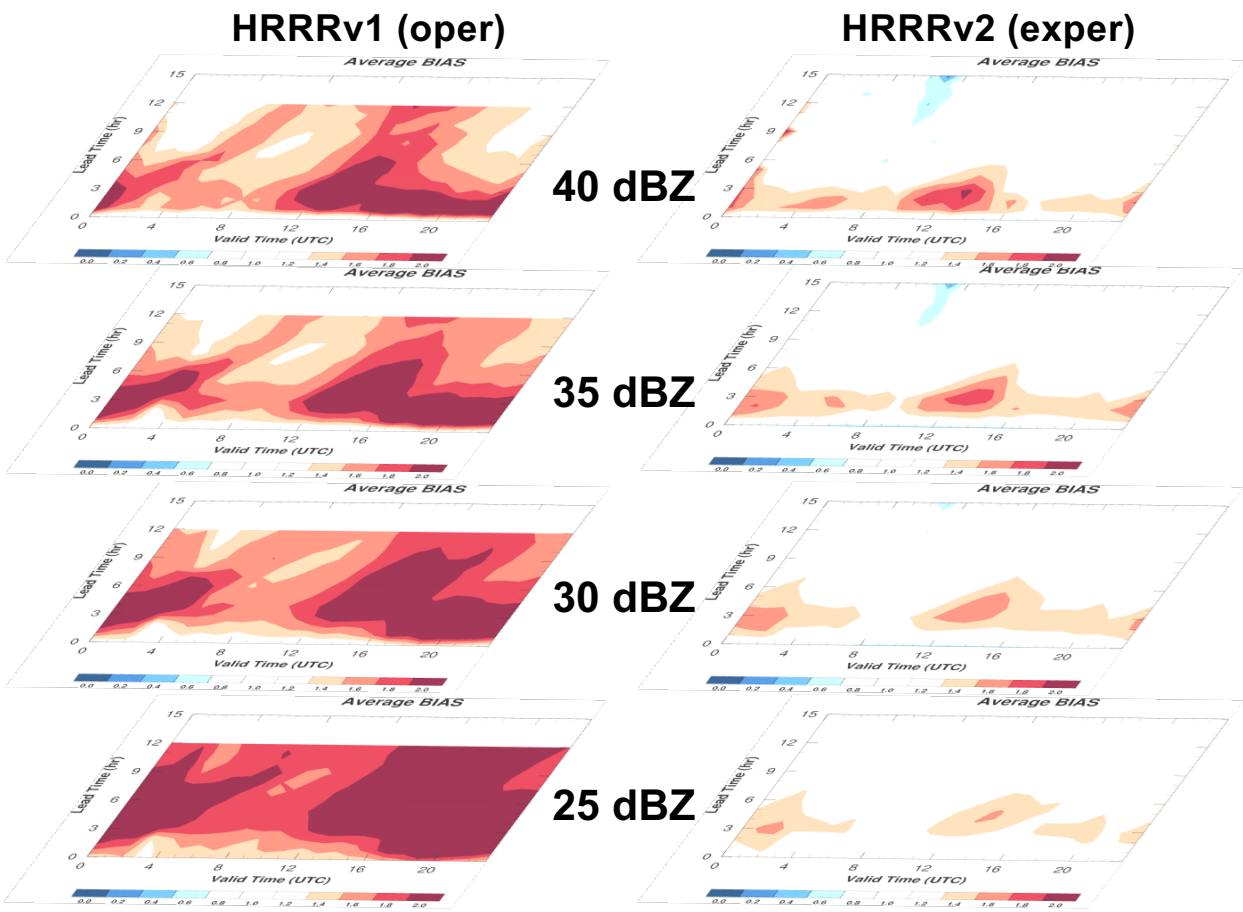
HRRRv2 Real-Time Evaluation: Reflectivity

Eastern US
May – June 2015



←Low Bias CREF High Bias→

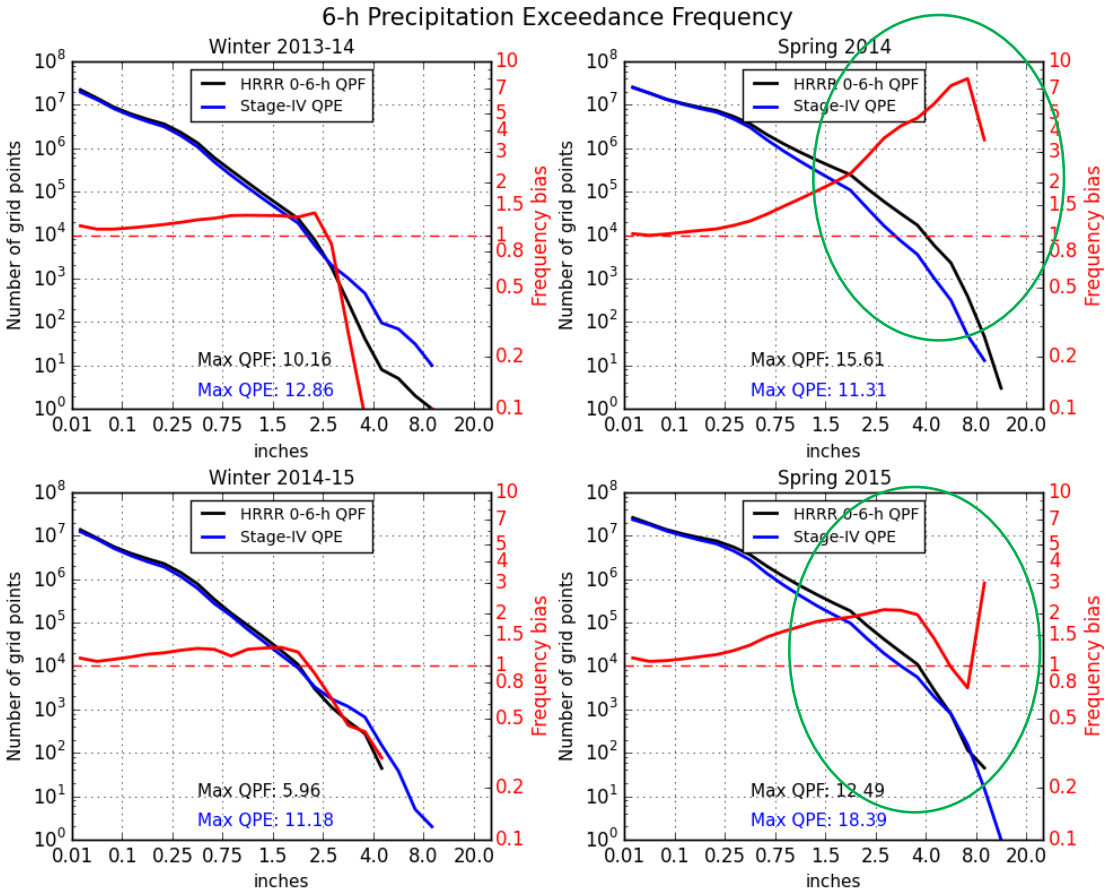
High afternoon bias in HRRRv1 improved in HRRRv2



HRRRv2 Real-Time Evaluation: Precipitation

Statistical Improvement in QPF skill.

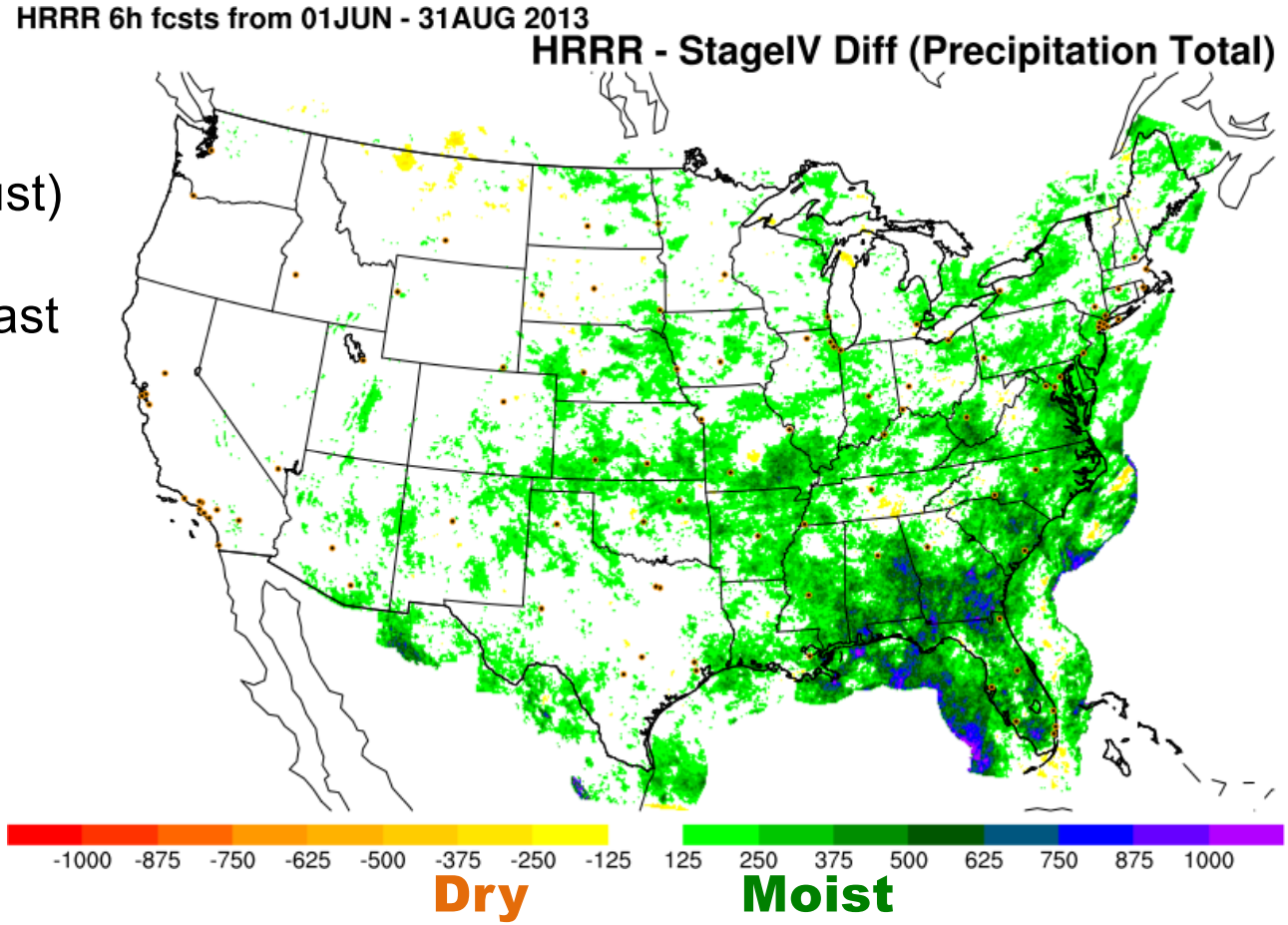
Reduction in bias from 2014 to 2015 particularly at higher thresholds



HRRRv2 Real-Time Evaluation: Precipitation

2013 Warm Season (June-August)

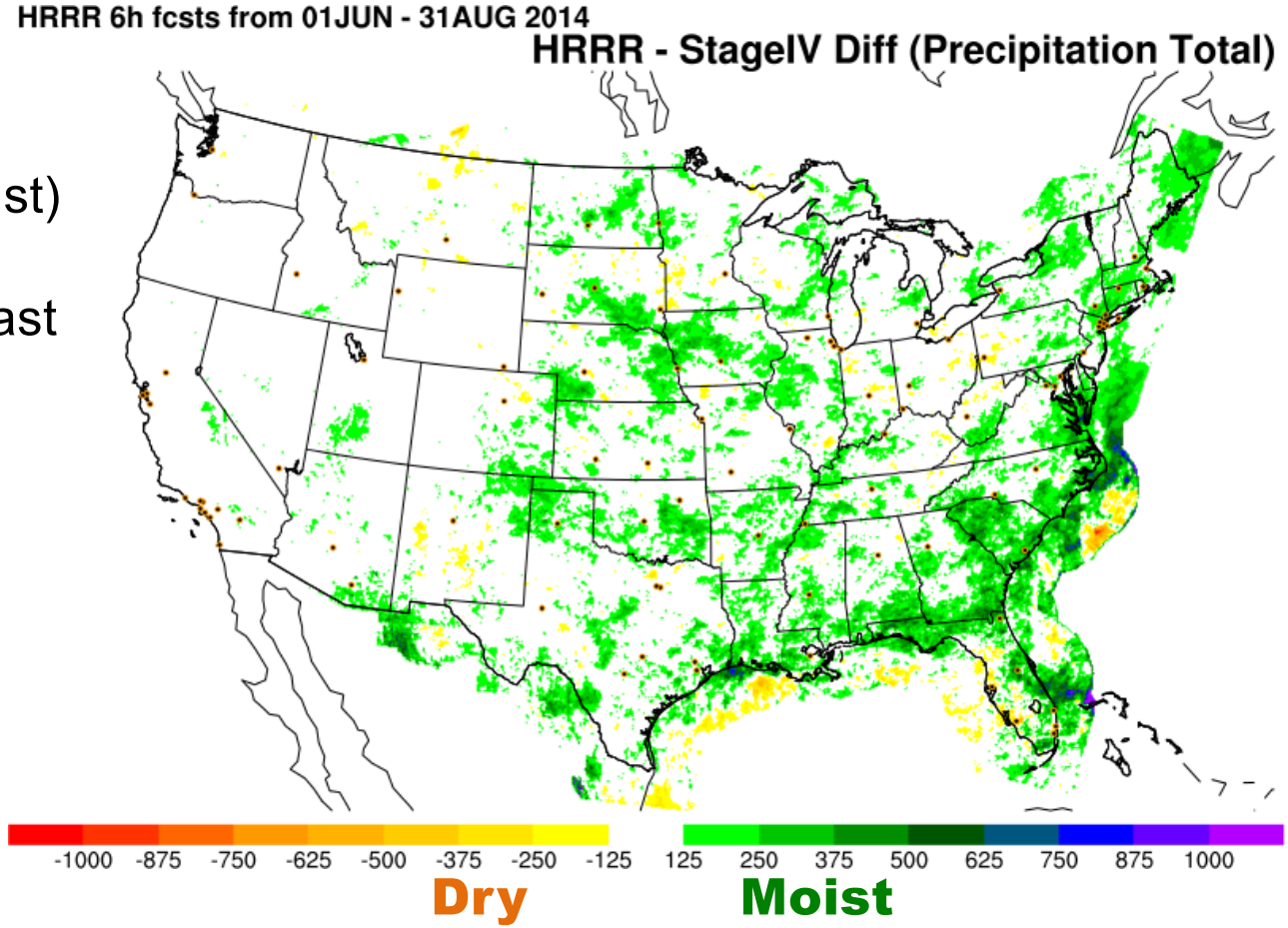
HRRR 0-6 hr precipitation forecast
Difference against Stage IV



HRRRv2 Real-Time Evaluation: Precipitation

2014 Warm Season (June-August)

HRRR 0-6 hr precipitation forecast
Difference against Stage IV

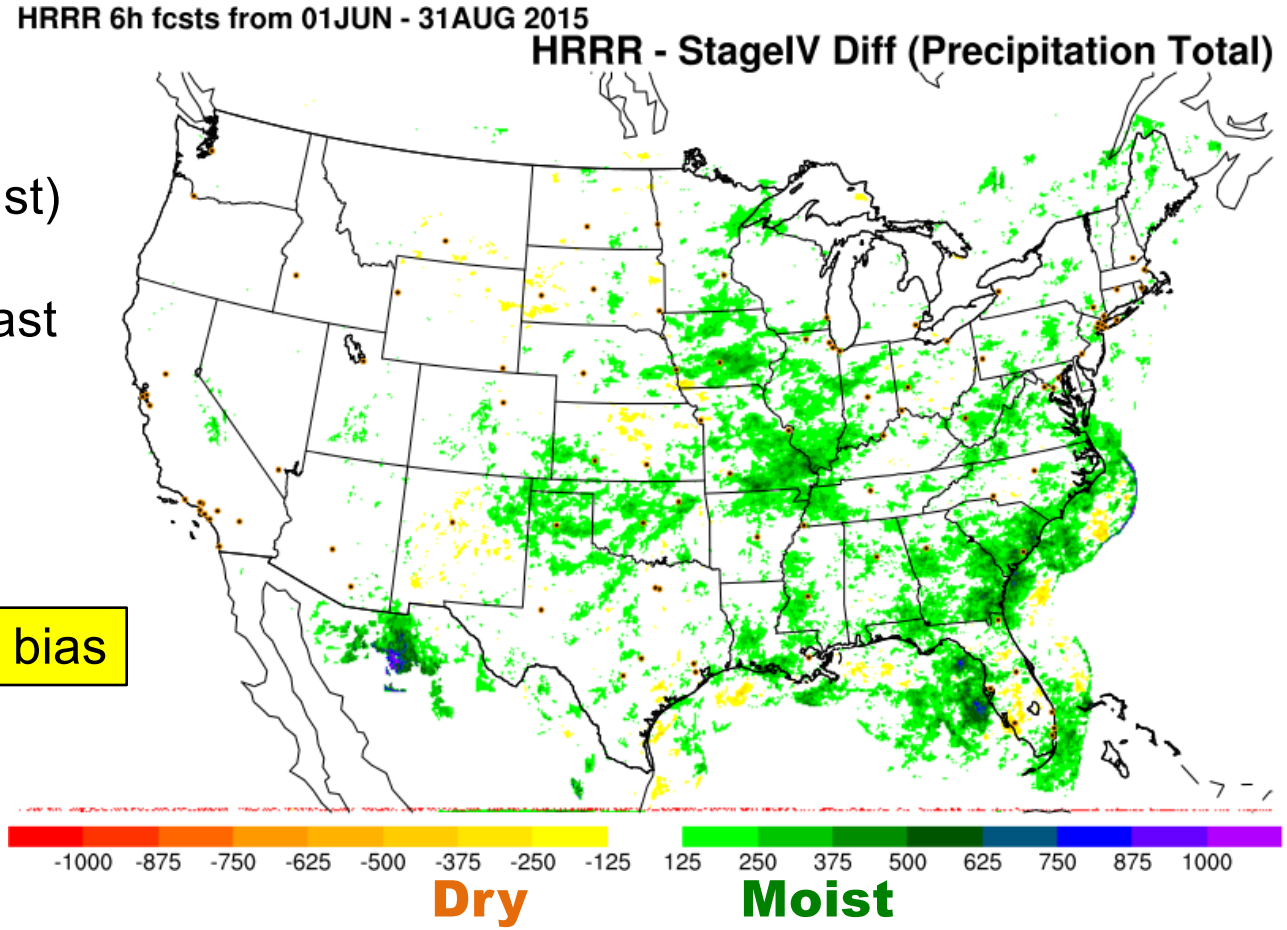


HRRRv2 Real-Time Evaluation: Precipitation

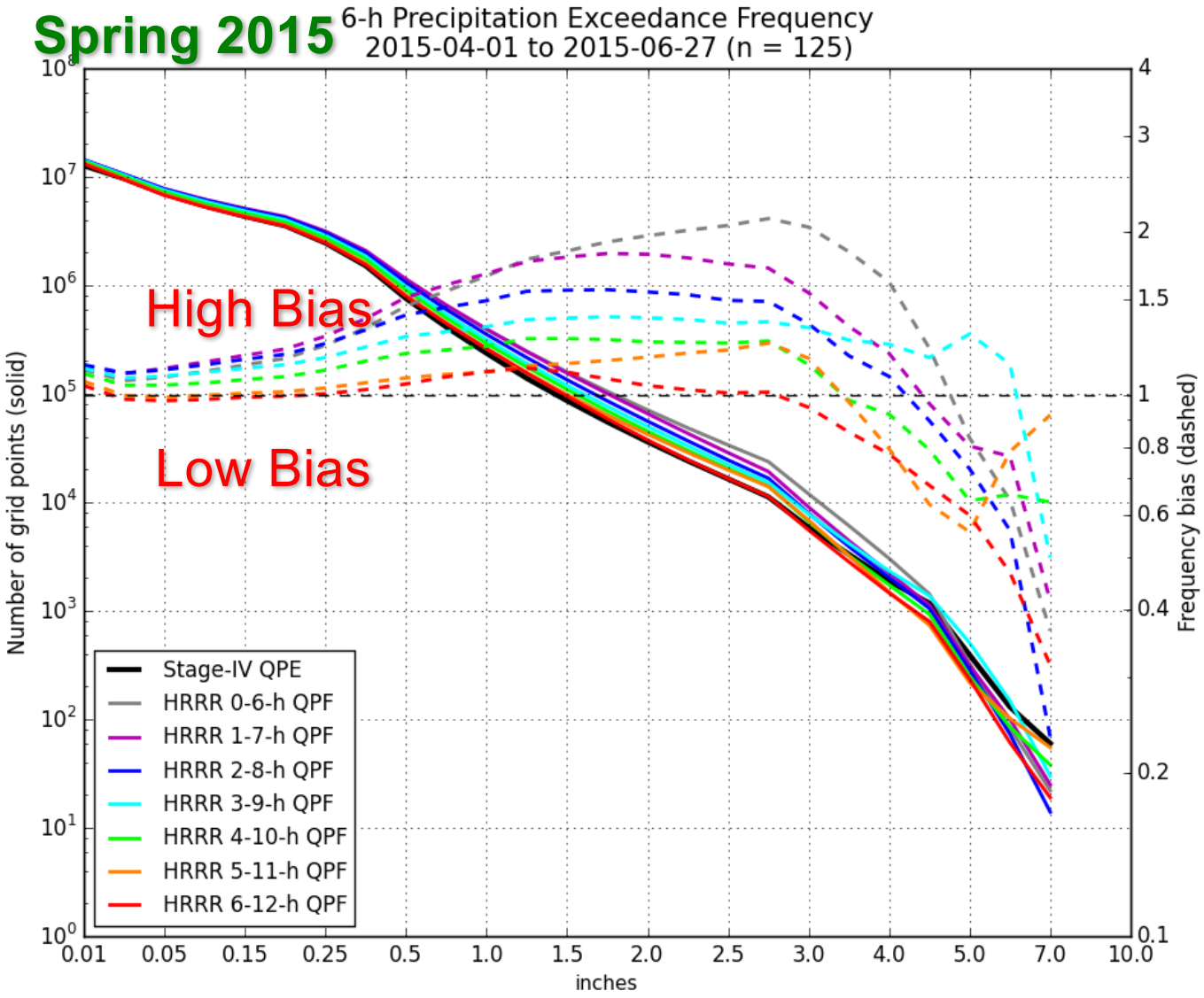
2015 Warm Season (June-August)

HRRR 0-6 hr precipitation forecast
Difference against Stage IV

Reduction in high precipitation bias

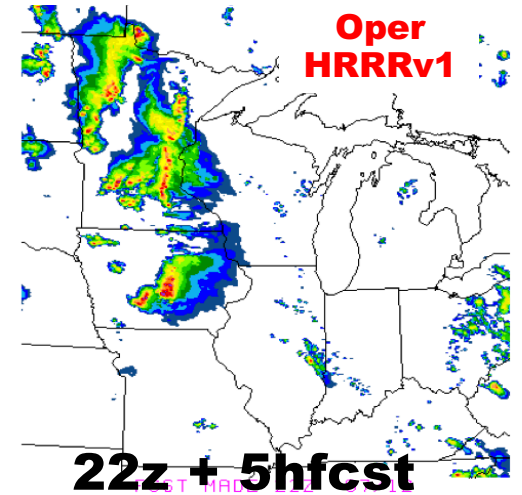


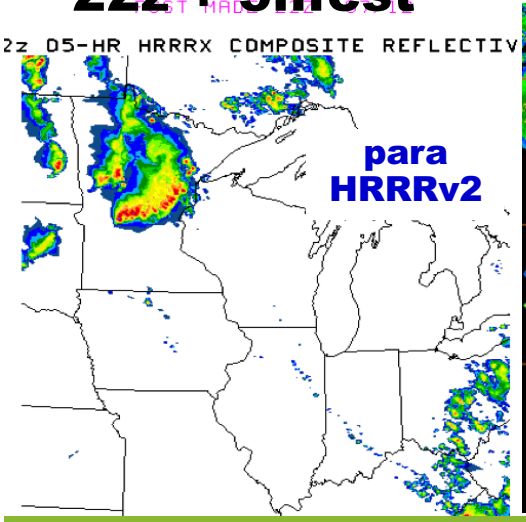
Spring 2015



HRRRv2 - little QPF bias after 4h. (high bias for 1-3h)

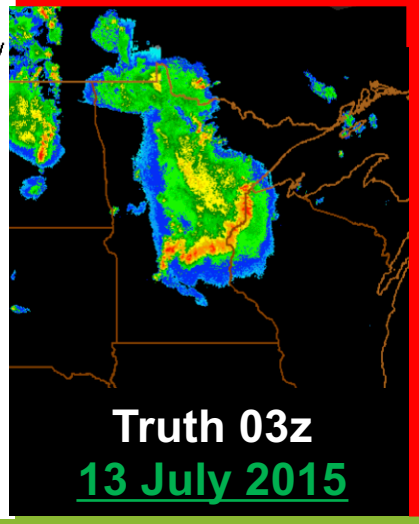
3 Case Studies: HRRRv2 Improved Convective Forecasts

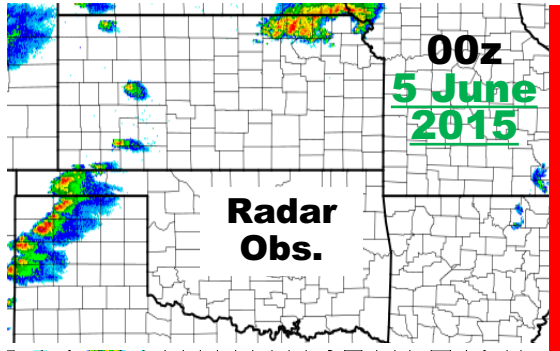


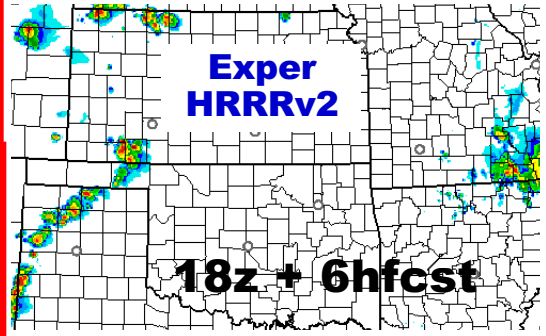


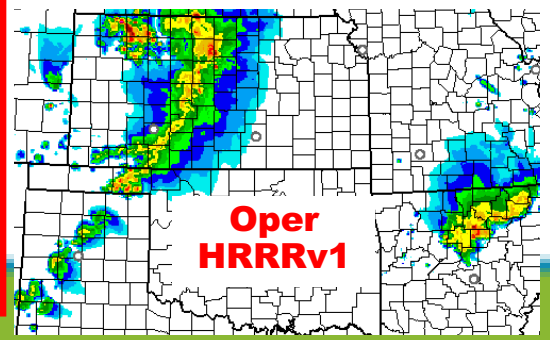
Improved convection (reduced over-prediction, better location)

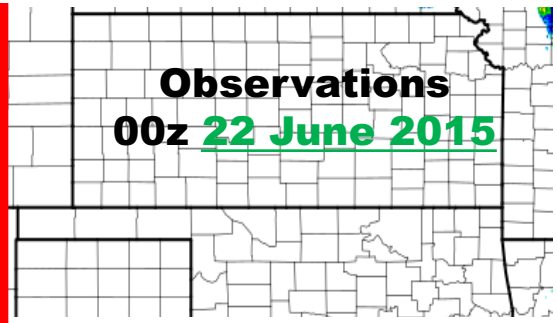
Better storm Environment from physics improvements

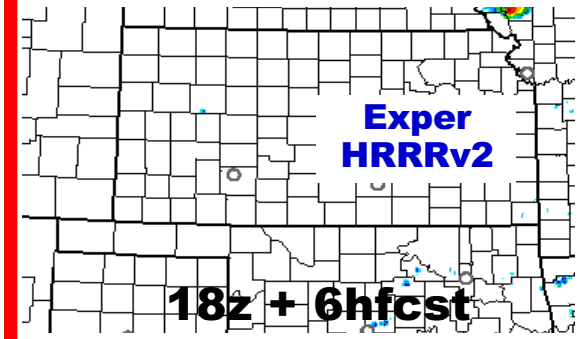


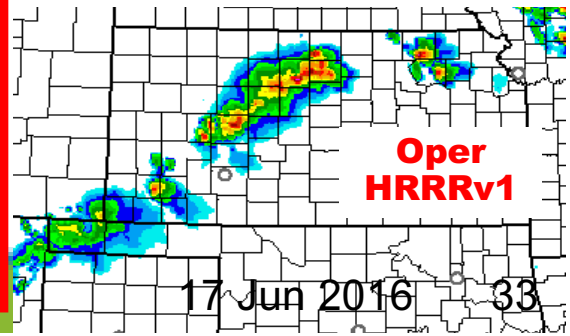






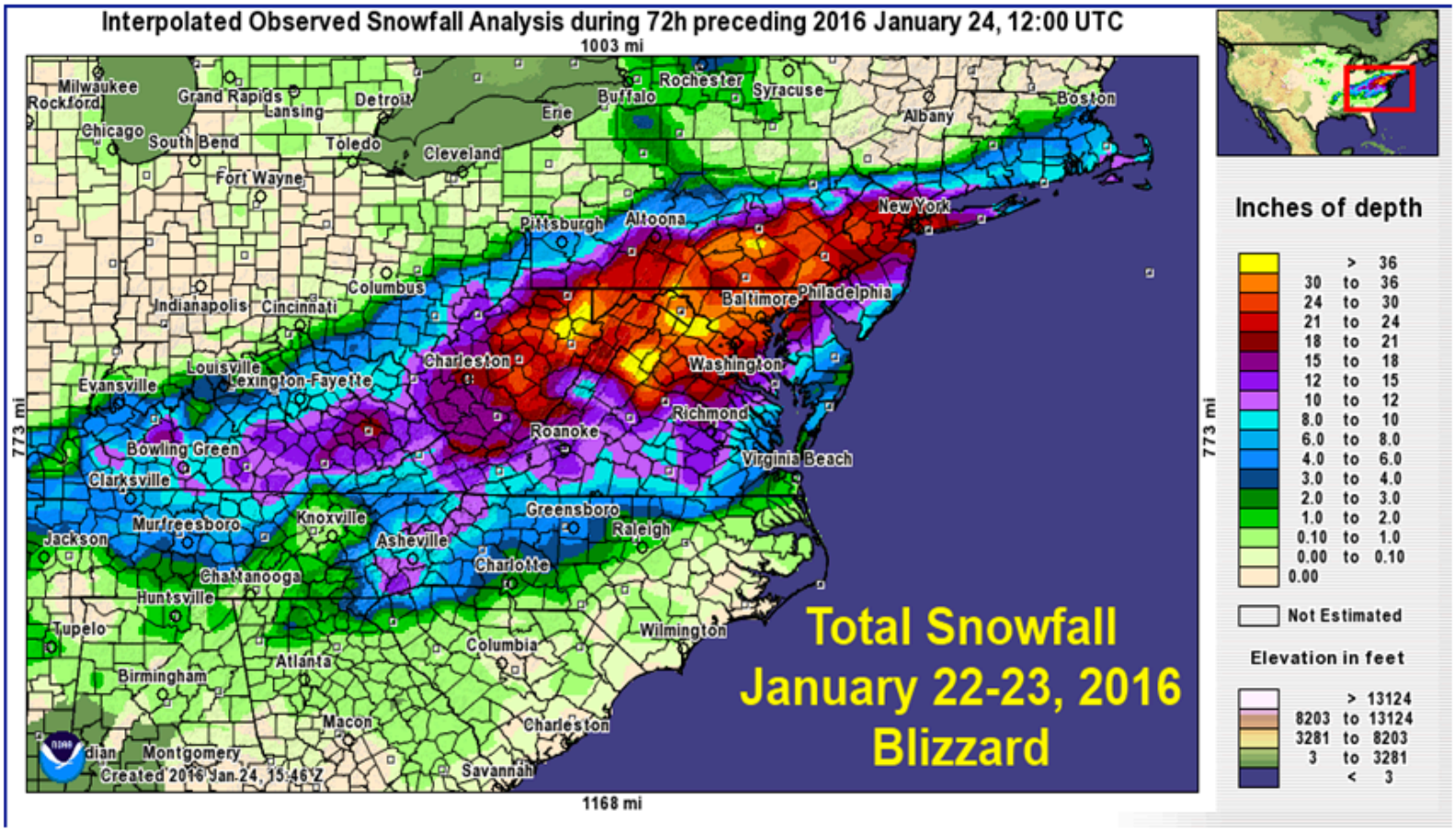




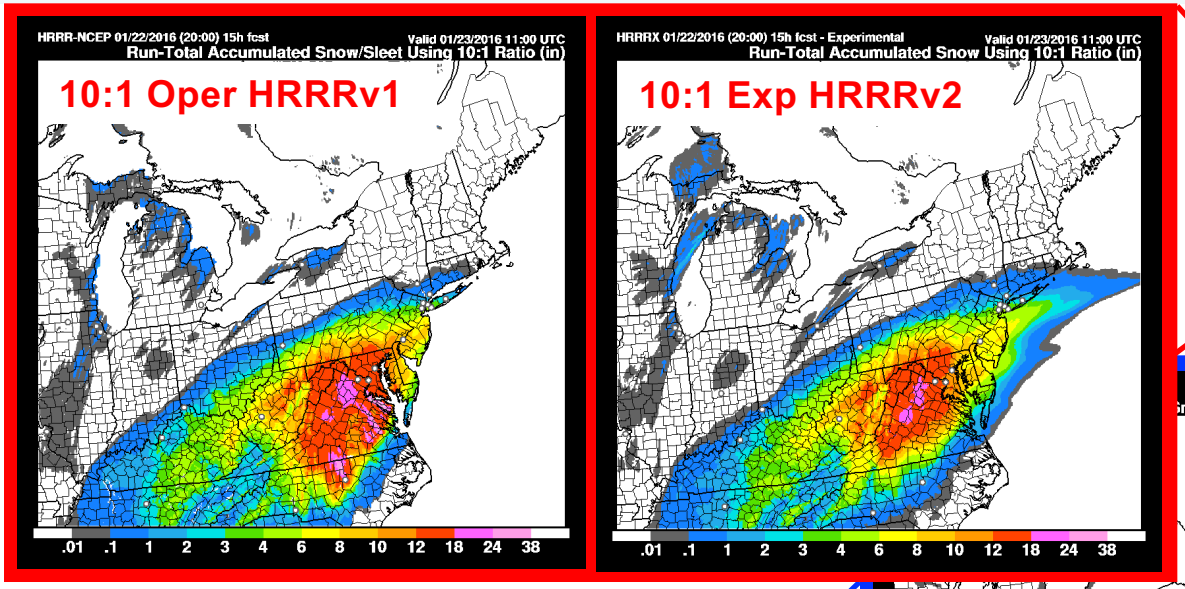


HRRRv2 Case Studies: Winter Precipitation

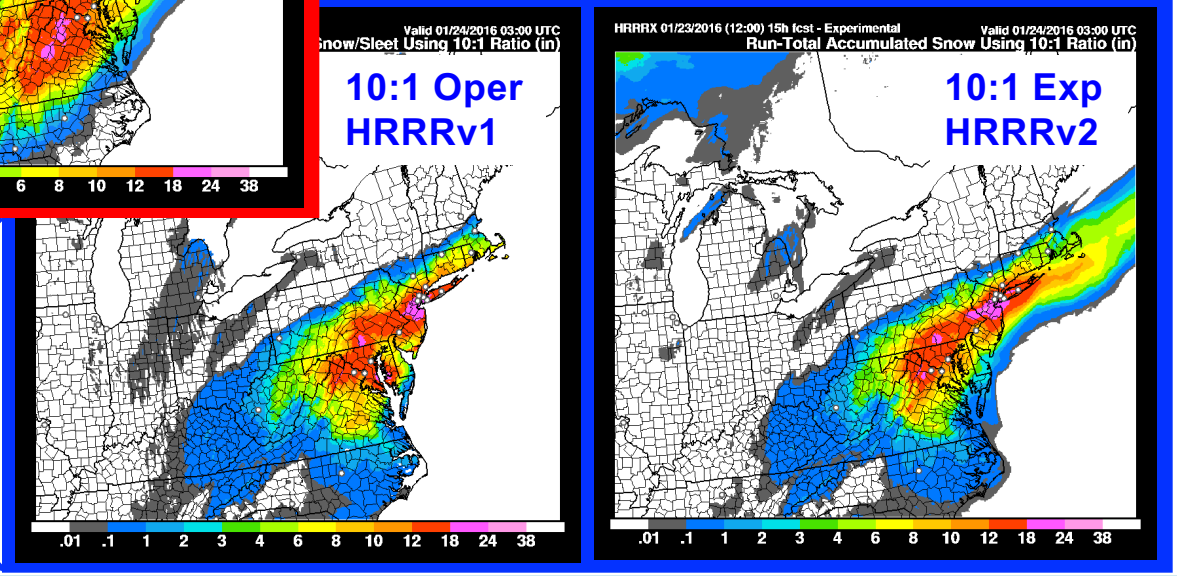
WPC



HRRRv2 Studies: Winter Precipitation



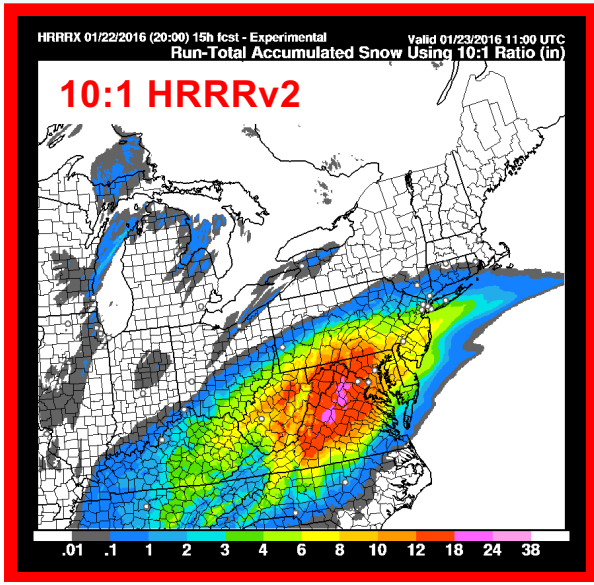
Early Snowfall Accumulation Period
15-hr forecasts valid from
20z 22 Jan – 11z 23 Jan 2016

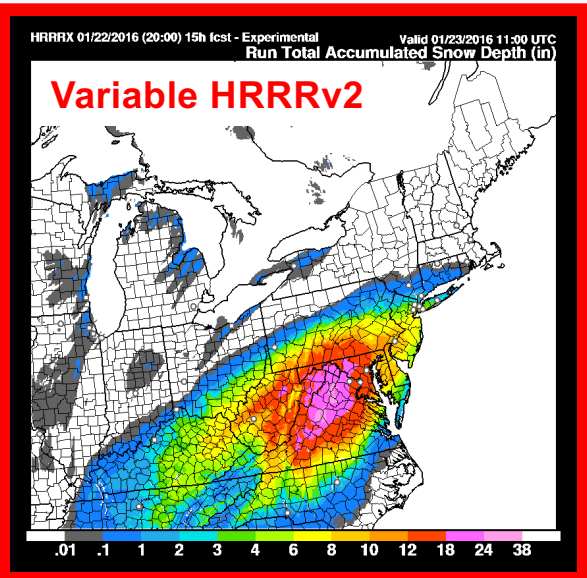


Late Snowfall Accumulation Period
15-hr forecasts valid from
12z 23 Jan – 03z 24 Jan 2016

Reduction of precip SE of DCA-PHL axis

HRRRv2 Case Studies: Winter Precipitation





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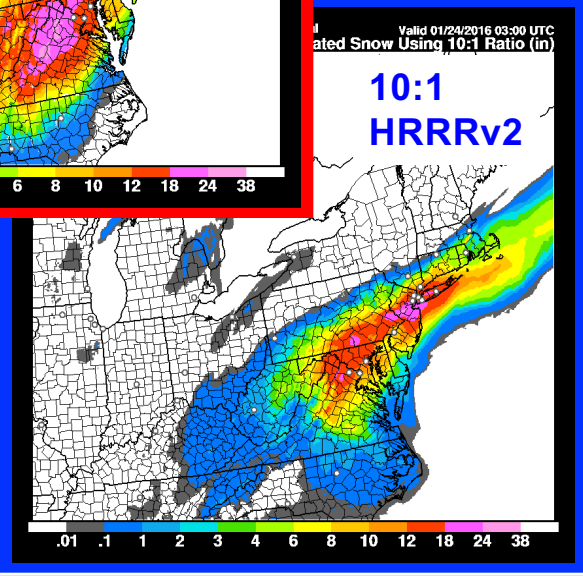
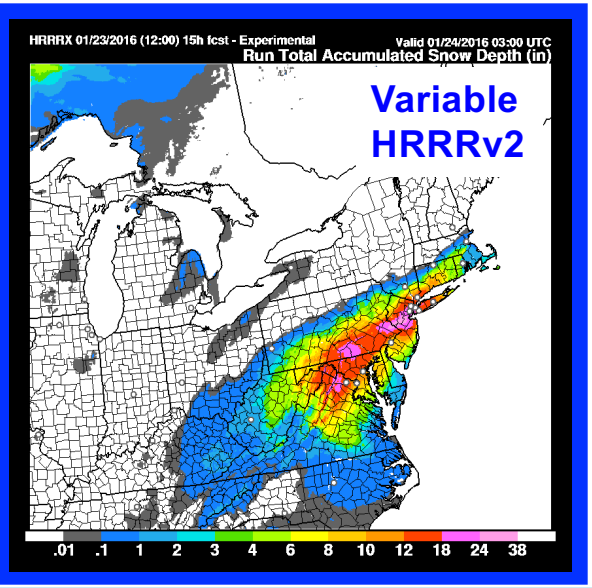




Late Snowfall Accumulation Period
15-hr forecasts valid from
12z 23 Jan – 03z 24 Jan 2016

Reduction of precip SE of DCA-PHL axis

RAPv3/HRRRv2: New Model Forecast Fields

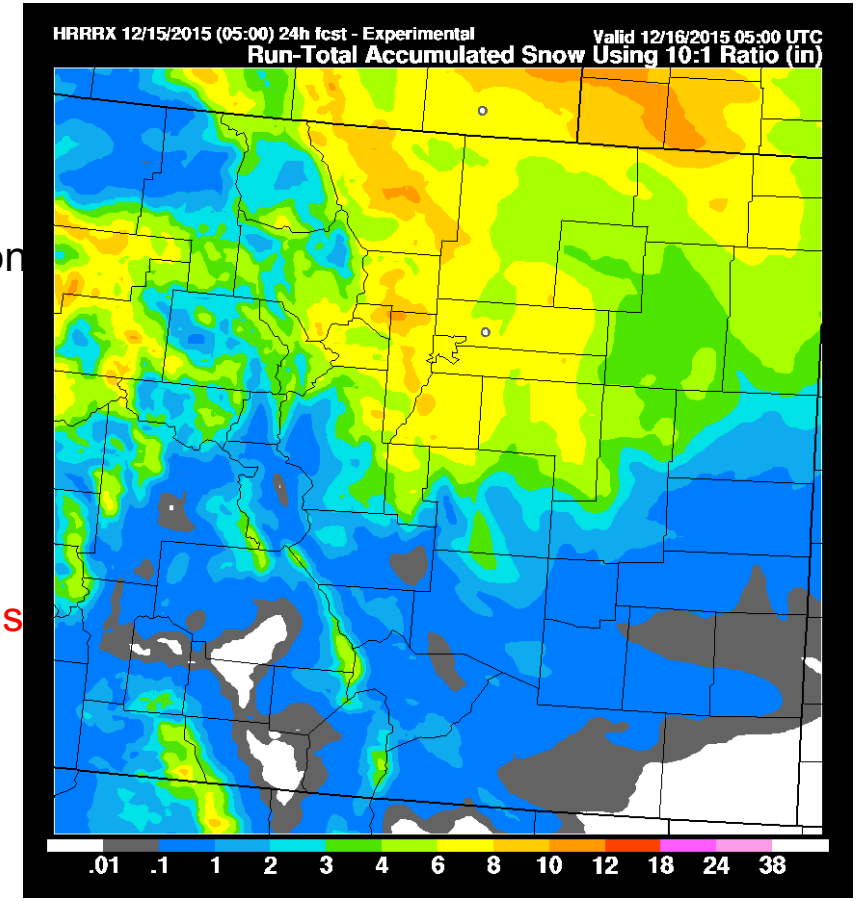
Highlights:

➢ 3-D
- Rain, cloud water and cloud ice number concentration
- Ice-friendly and water-friendly aerosol number concentration
- Cloud fraction (includes sub-grid scale cloud contributions)

➢ 2-D
- Downward direct-normal incident shortwave radiation flux
- Downward diffuse shortwave radiation flux

- Separate graupel and snow-water equivalent accumulations

- Run-total accumulated snow depth with variable-density microphysical contributions (no 10:1 assumption)
  - Deeper snow accumulations in colder regions
  - Shallower snow accumulations in warmer regions



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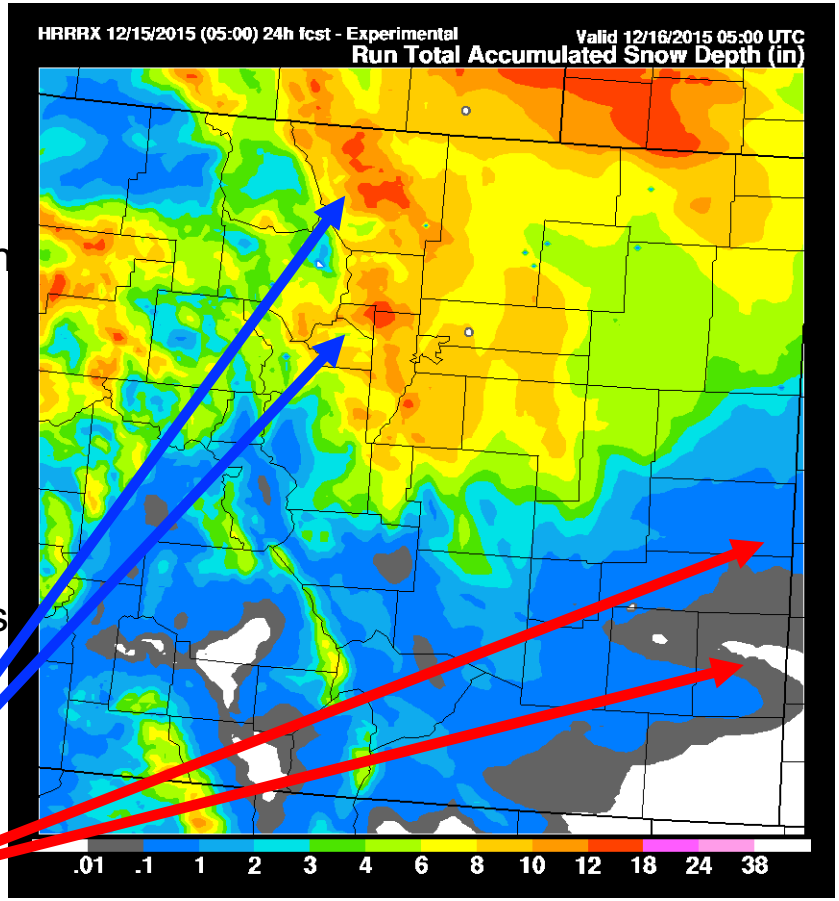
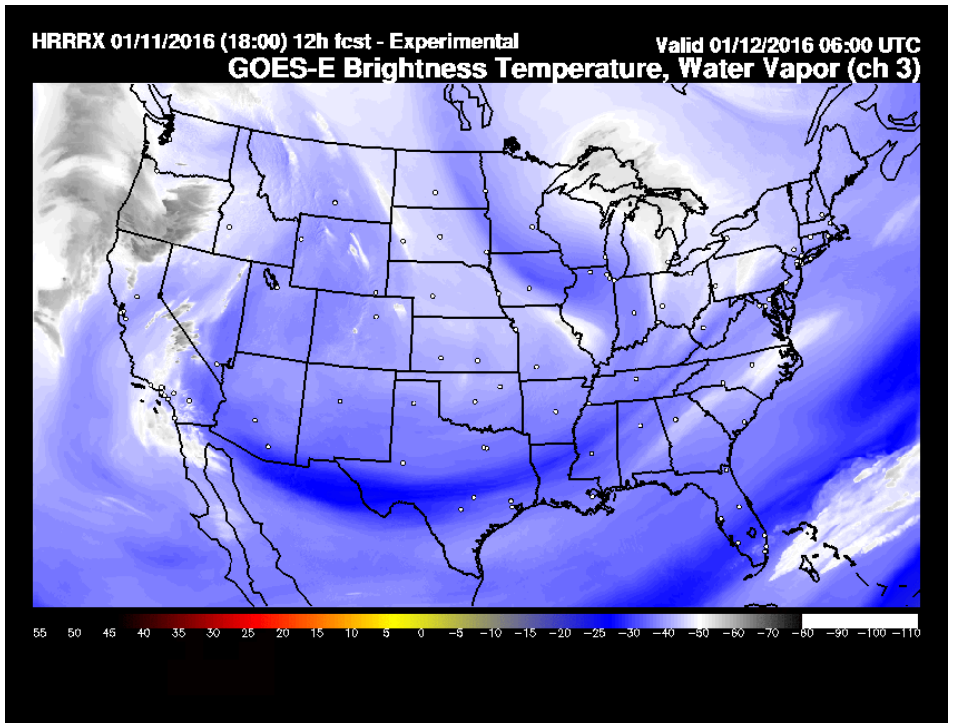


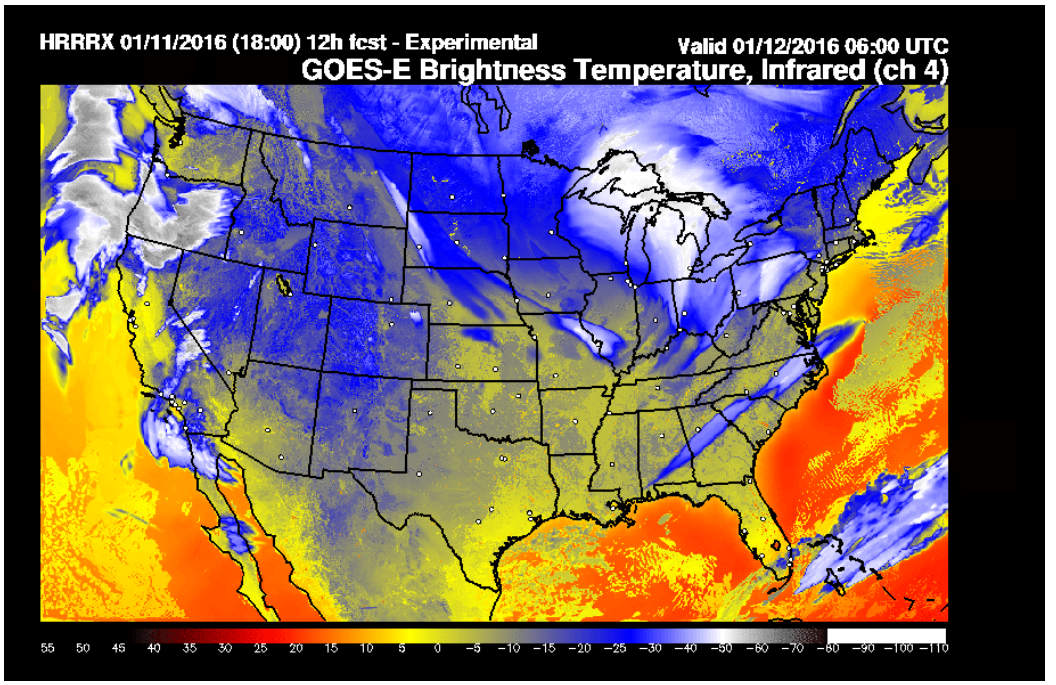
RAPv3/HRRRv2: New Model Forecast Fields

HRRRv2: Simulated Satellite Imagery (GOES-East and GOES-West)

Water Vapor

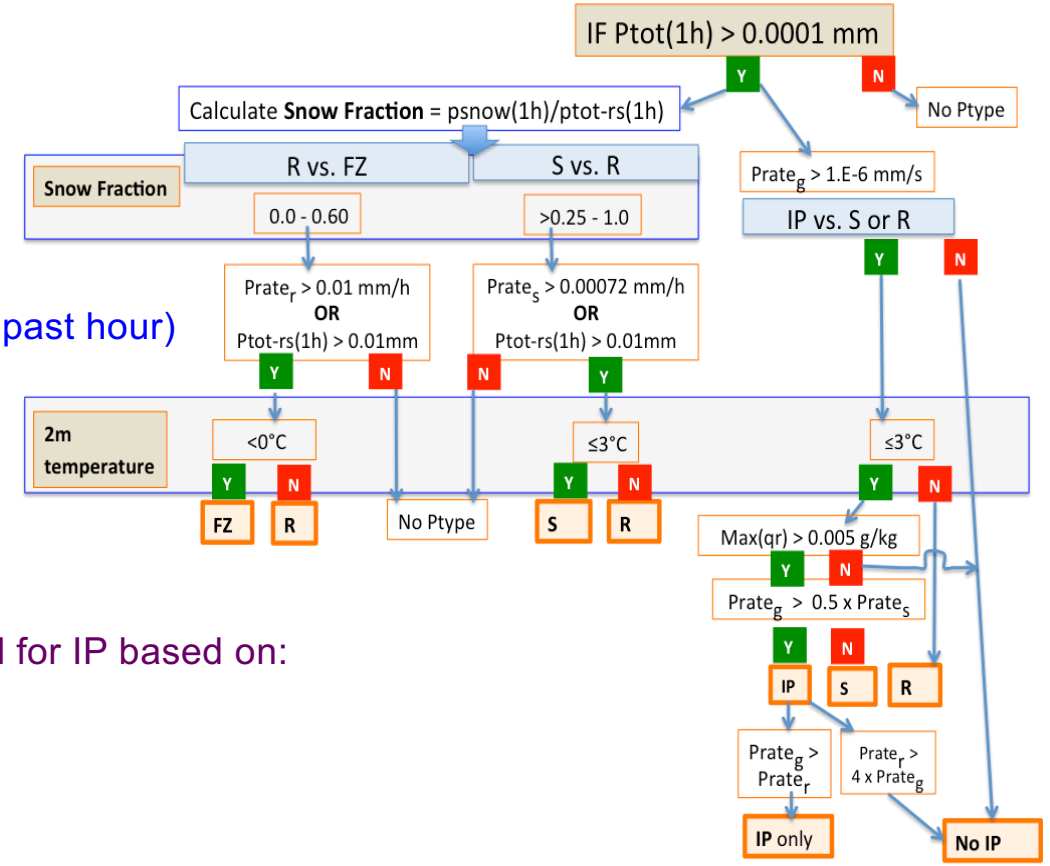


Infrared



RAPv3/HRRRv2: Precip Type Diagnostic

- Starts by computing snow fraction =
  - Fallen snow in past hour/(total snow + rain over past hour)
- Determine potential for S/R/ZR based on:
  - Fall rates for rain and snow
  - Amount of rain and snow over previous hour
  - 2m Temp
- Also check fall rate for graupel to determine potential for IP based on:
  - Fall rates for rain and snow
  - Max rain mixing ratio
  - 2m Temp



Can overlap one or more types (not exclusive)

RAPv3/HRRRv2: Forecast Performance Summary

RAPv3/HRRRv2 Enhancements

Operational Upgrade: Scheduled 23 Aug 2016

- **Winds -- Consistent RAPv3 improvement for both upper-air and surface, for all seasons**
- **Temperature – Reduced low-level warm bias for warm season afternoon / evening. Improved upper-level temperature forecasts**
- **Moisture – Reduced low-level dry bias for warm season afternoon / evening. Improved upper-level relative humidity forecast**
- **Precipitation – Slight improvement, reduced low thresh high bias / increased high thresh low bias, more accurate synoptic feature placement**
- **Convection – HRRRv2 reduces spurious convection in capped warm-sectors, permits more accurate convective evolutions**

RAPv4/HRRRv3 ESRL Development – (ESRL 39/36 hr Runs)

	Model	Data Assimilation
RAPv4 (13 km) Large impact Too early to tell	WRF-ARW v3.8+ incl. physics changes **Physics changes:** Thompson microphysics – improved upper-level clouds MYNN PBL update – better sub-grid clouds, meso env LSM update – 15" MODIS data – better lower boundary VIIRS-based real-time greenness vegetation fraction **Numerics changes:** Improved terrain (cell avg) – better winds /turbulence Hybrid vertical coordinate from NCAR (upcoming)	Merge with GSI trunk – last updated in Jan 2016 **New Observations for assimilation:** NCEP new VAD wind retrievals Add AMVs over land and TAMDAR GOES-R lightning mapper – convection proxy **Assimilation Methods:** Revised PBL pseudo-obs – reduce RH bias More ensemble weight in hybrid DA (0.9/0.1) METAR and GOES cloud building now consistent Aircraft temperature bias correction
HRRRv3 (3 km)	WRF-ARW v3.8+ incl. physics changes **Physics changes:** Thompson microphysics – improved upper-level clouds MYNN PBL update – better sub-grid clouds, meso env LSM update – 15" MODIS data – better lower boundary VIIRS-based real-time greenness vegetation fraction Add smoke with VIIRS fire radiative power? **Numerics changes:** Hybrid vertical coordinate from NCAR (upcoming)	**New Observations for assimilation:** GOES cloud-top cooling rates – convection proxy Add new VAD wind, AMVs over land and TAMDAR GOES-R lightning mapper – convection proxy Radar radial velocity at 3km – better convection METAR and GOES cloud building now consistent **DA Methods:** More ens weight in hybrid DA (.9/.1) – better winds Full atmospheric cycling – better 0-4 hr convection Variational/hybrid cloud analysis – better C/V

RAP/HRRR Development and Implementation Timeline

ESRL Experimental Versions	NCEP Operational Versions
➢ **RAPv3 – GSD testing in 2014-15** – Is initializing 2015 ESRL-HRRR(v2) – Improved PBL, LSM, cu-parm, DA – WRFv3.6.1 w/ Thompson/NCAR aerosol-aware microphysics	→ Aug 2016
➢ **HRRRv2 – GSD testing in 2014-15** – Initialized by 2015 RAP (v3) – Improved radar assimilation, hybrid assimilation, PBL/cloud physics	→ Aug 2016
➢ **RAPv4 – GSD testing in mid-2016** – Improved 13km physics – Hourly RAP ensemble data assimilation	→ Early 2018?
➢ **HRRRv3 – GSD testing in mid-2016** – Improved 3km physics, 3km ens assim – Full 3-km hourly cycling w/radial vel	→ Early 2018?

RAP/HRRR Suite: Hourly-Updating Forecast Models