Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

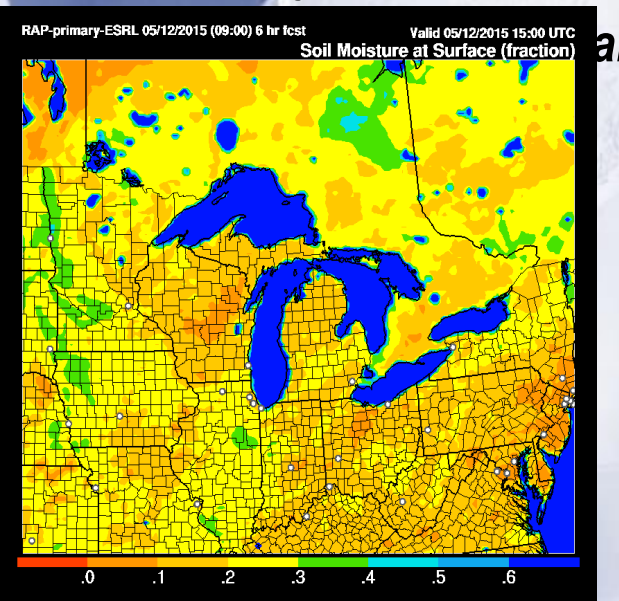
NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION
NCEP

Coupled-Model/Assimilation Development at Regional and Global Scales at ESRL

Stan Benjamin

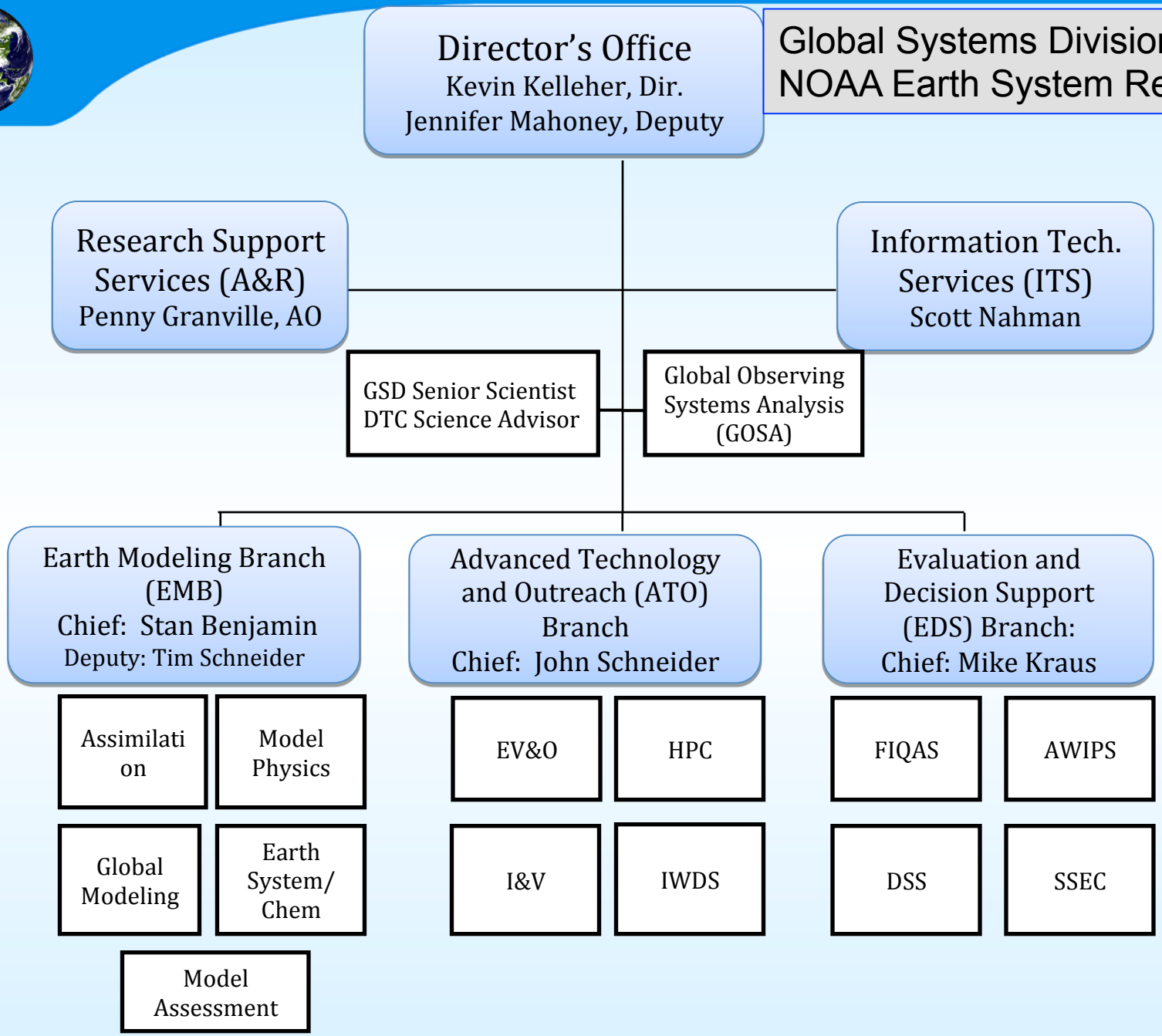
Curtis Alexander, Steve Weygandt, David Dowell, Ming Hu, Tanya Smirnova, Joe Olson, John Brown, Eric James, Jaymes Kenyon, etc. an Sun, Georg Grell, Jian-Wen Bao, Rainer Bleck. Jin Lee

NOAA Earth System Research Laboratory
Global Systems Division
Earth Modeling Branch
Boulder, Colorado USA



GLERL, Ann Arbor, Michigan - Seminar, 20 May 2015

Global Systems Division
NOAA Earth System Research Lab



Earth Modeling Branch (EMB) staff – May 2015

Chief – Stan Benjamin
Deputy – Tim Schneider

Sections	Assimilation	Model physics	Global modeling	Model assessment	Chem/earth system
Leads	Steve Weygandt	John Brown	Stan Benjamin	Tim Schneider	Georg Grell
	Ming Hu Curtis Alexander David Dowell Eric James Haidao Lin Tracy Smith Terra Ladwig Yuanfu Xie Steve Albers Dan Birkenheuer Craig Hartsough Xin Zhang Jun Zhou	Tanya Smirnova Joe Olson Jaymes Kenyon Isidora Jankov Ligia Bernadet Christina Holt Jeff Beck Hongli Jiang Jim Frimel	Shan Sun Rainer Bleck Haiqin Li Ning Wang Ed Szoke Kevin Brundage Jin Lee Esther Kim Kayee Wong Man Zhang Gerard Ketefian	Bill Moninger Xue Wei Brian Jamison Jeff Hamilton Judy Henderson Mike Fiorino Bonny Strong Scott Gregory	Steven Peckham Mariusz Pagowski Pallavi Marrapu Li Zhang Saulo Freitas Karla Longo

Administrative staff
- Mary Gutierrez

Budget analyst from GSD Director's Office
- Bernie Johnson

Systems administrators
- Scott Buennemeyer
- Gary Fisher

Full EMB staff listing including visitors and phone numbers
http://www.esrl.noaa.gov/gsd/staff/EMB.html

Earth Modeling Branch

Key mission – what we need to accomplish in EMB:

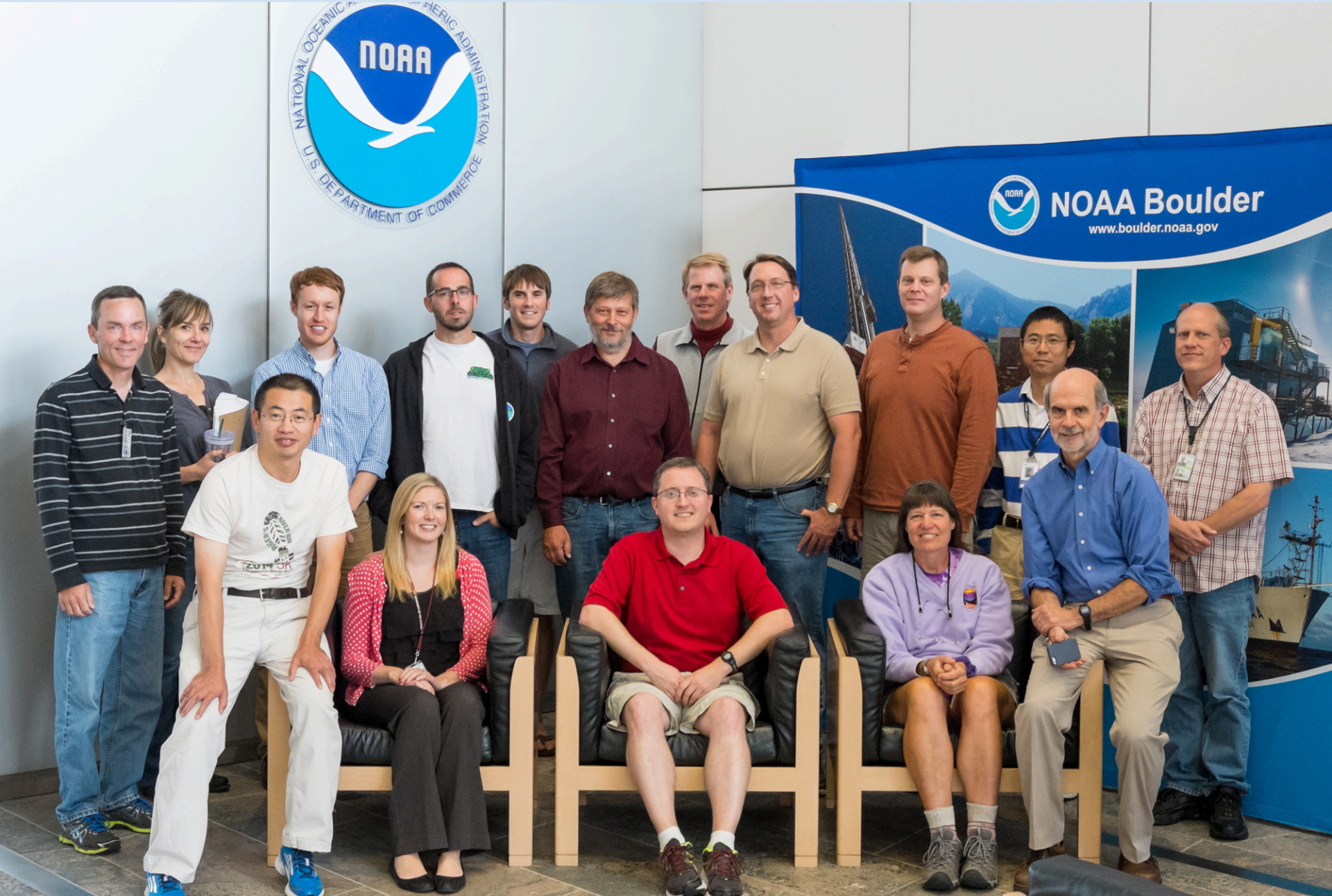
- **Develop** research modeling/assimilation suitable for operations (the GSD R2O theme) – **applied** R&D.
- Accomplish transfer from research to operations **primarily within NOAA**.
- Collaborate with **community modeling/assimilation efforts**. Work with NCEP, NCAR, other ESRL divisions and OAR laboratories, universities, international community toward these efforts. **Innovate** within community efforts.
- Address both global and regional modeling efforts with same scientific expertise/techniques/code where possible.
- Broaden atmospheric modeling **into earth system** (with chemistry, ocean, biosphere, etc.). Work with other ESRL divisions (and GSD branches) toward this.

October 2014

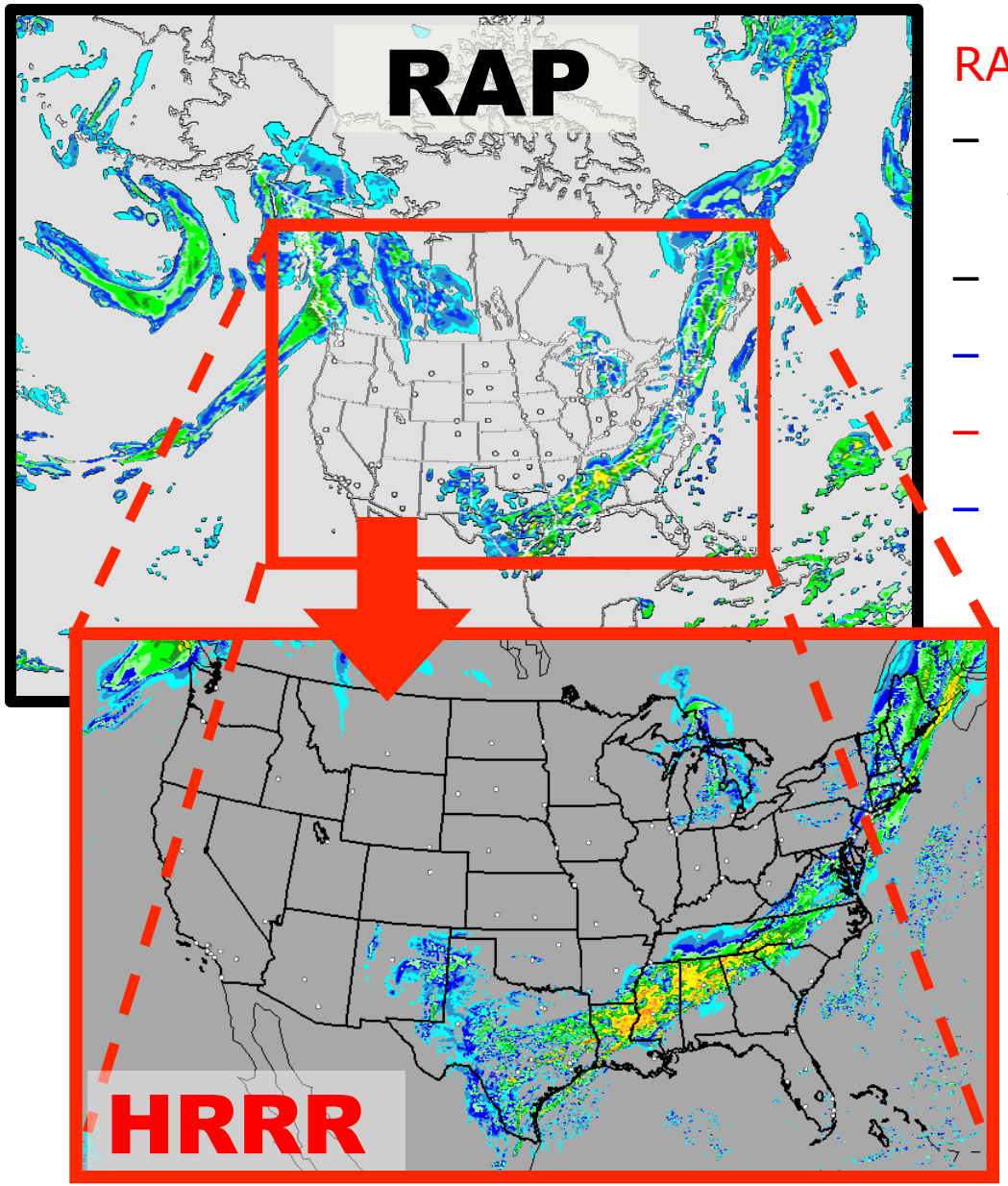
EMB grand challenges

- Storm-scale CONUS-wide 3km ens-based data assimilation and ensemble forecast modeling
- Earth-system global modeling capability with atmosphere, ocean, chemistry, ice, and land-surface components for research and potential operational applications.

ESRL/GSD HRRR/RAP Development Team



Current Status - NOAA Hourly Updated Models



RAP - Rapid Refresh

- NOAA "situational awareness" model for high-impact weather
- New 18-hour forecast each hour
- NOAA/NCEP operational – 1 May 2012
- RAPv2 implementation – 25 Feb 2014
- Hourly use by National Weather Service, SPC/AWC/WPC, FAA, private sector

HRRR – High-Resolution Rapid Refresh

- Storm/energy/aviation guidance
- Real-time operational – NCEP, and *experimental*- ESRL supercomputer
- NCEP implementation HRRRv1 - 30 September 2014

RAP and HRRR: *Hourly-Updated* Weather Forecast Models

13-km Rapid Refresh (RAP)

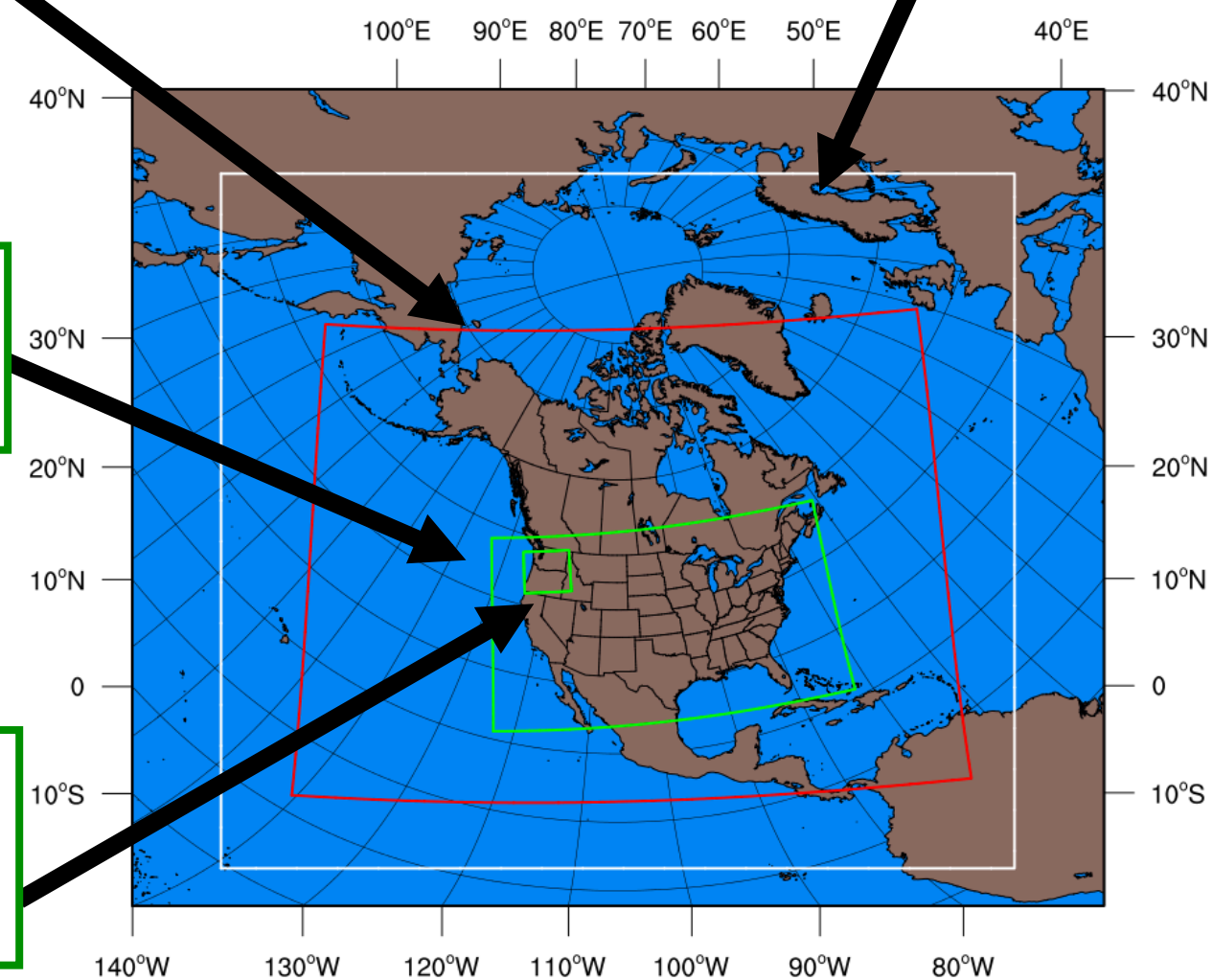
Expanded RAP (Summer 2015)

Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRR)

Initial & Lateral Boundary Conditions

750-m HRRR nest (WFIP2, experimental)



History of hourly updated NWP models at NOAA

Model/assimilation system	Horizontal resolution	Number of vertical levels	Assimilation frequency	Implemented at NCEP	Geographical domain
RUC1	60 km	25	3h	Sept 1994	CONUS
RUC2	40 km	40	1h	April 1998	CONUS
RUC20	20 km	50	1h	April 2002	CONUS
RUC13	13 km	50	1h	May 2005	CONUS
Rapid Refresh	13 km	50	1h	May 2012	N. America
Rapid Refresh v2	13 km	50	1h	Feb 2014	N. America
Rapid Refresh v3	13km	50	17	Sept 2015 - planned	N. America
HRRR	3 km	50	1h	Sept 2014	CONUS
HRRR v2	3 km	50	1h	Sept 2015 - planned	CONUS

RAP vs. RUC - hourly updated NWP models at NOAA

Model	Domain	Grid Points	Grid Spacing	Vertical Levels	Vertical Coordinate	Pressure Top	Lateral Boundary Conditions
RUC	CONUS	451 x 337	13 km	50	Sigma/ Isentropic	~50 hPa	NAM
RAP	North America	758 x 567	13 km	50	Sigma	10 hPa	GFS

Model	Assimilation	DFI	Cloud Analysis	Micro-physics	WRF version	Radiation LW/SW	Cumulus parm	PBL	LSM
RUC	RUC-3DVAR	Yes w/radar	Yes	Thompson et al (2004)	N/A	RRTM/ Dudhia	Grell-Devenyi	Burk-Thompson	RUC 2003
RAP	GSI w/ radiances	Yes w/radar reflectivity	Yes	Thompson (2008) w/ enhancements	V3.2.1+	RRTM/ Goddard	Grell-3d	MYJ	RUC 2010
RAP v2	GSI with hybrid ensemble/var (0.5/0.5) assimilation	Yes w/ radar refl	Yes	Ditto, w/ minor adjustments	V3.3.1+	RRTM/ Goddard	Grell-3d	MYNN	RUC 2014
RAP v3	GSI-hybrid ens/var (0.75/0.25) assimilation	Yes w/ radar refl and lightning	Yes	Thompson and Eidhammer (2015)	V3.6.1+	RRTMG	Grell-Freitas (2014) w/enhancements	MYNN	RUC 2015

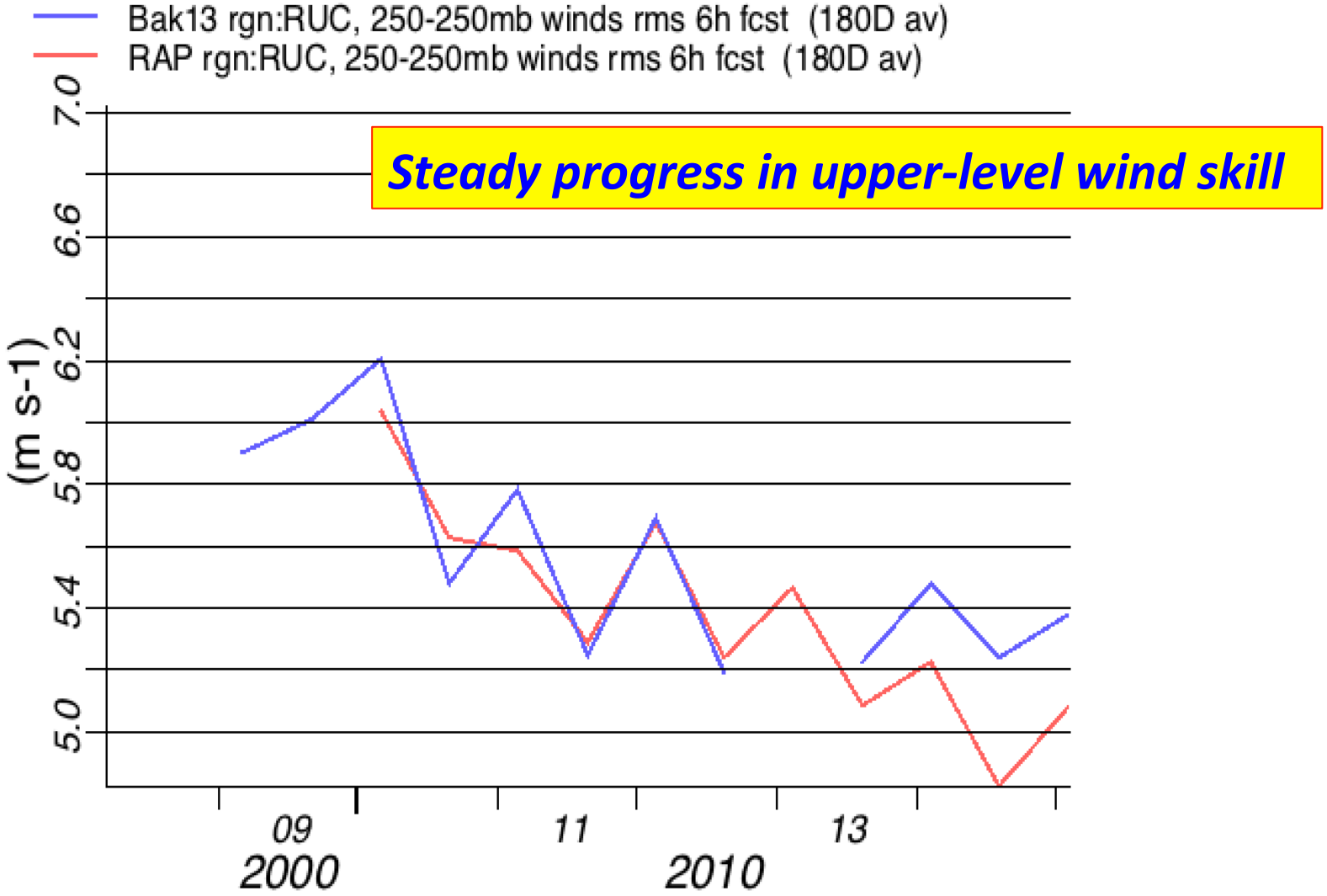
RAP/HRRR – variables updated in data assimilation

Updated variables in native GSI/RAP /HRRR analysis	Updating from observations in GSI/RAP / HRRR analysis
Atmospheric variables (3-d)	
P pressure	GSI hybrid ensemble/var analysis
T_v virtual temperature	GSI hybrid ensemble/var analysis
u,v horizontal wind components	GSI hybrid ensemble/var analysis
q_v water vapor mixing ratio	GSI hybrid ensemble/var analysis
q* hydrometeor mixing ratios (cloud water, ice, rain water, snow, graupel)	Non-variational hydrometeor analysis with GOES cloud-top data, METAR cloud data, radar reflectivity
N* number concentrations for cloud droplets, water droplets, and ice particles	Adjusted based on q* modifications
Land-surface variables	
soil temperature	Adjusted using near-surface temperature and moisture increment
soil moisture	Same as above
snow water equivalent	Same as above
snow temperature	Same as above

250 hPa RMS vector error vs. raobs over CONUS

RUC / RAP

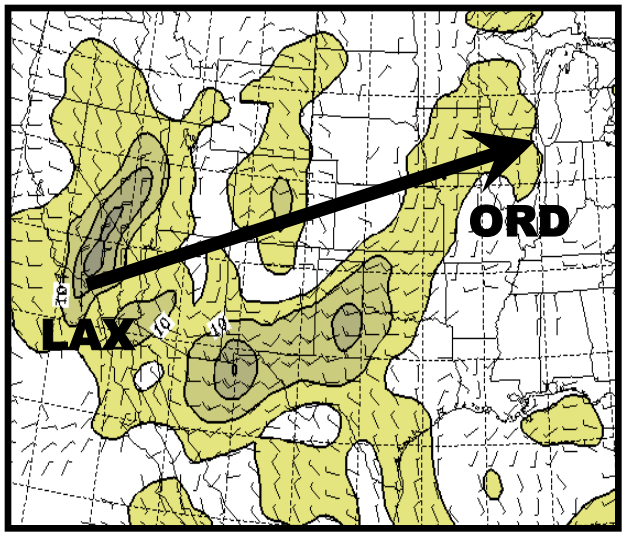
2009-2015 – 6h forecasts



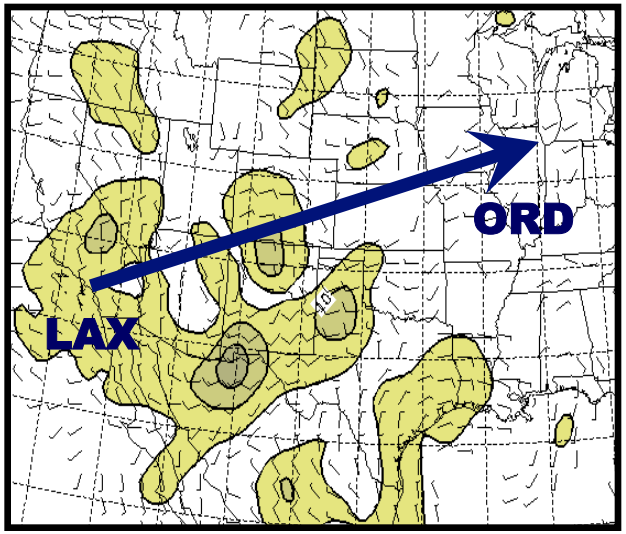
Benefits of Rapid Cycling NWP

Rapid update cycling with latest observations improves short-range forecasts (including upper-level winds)

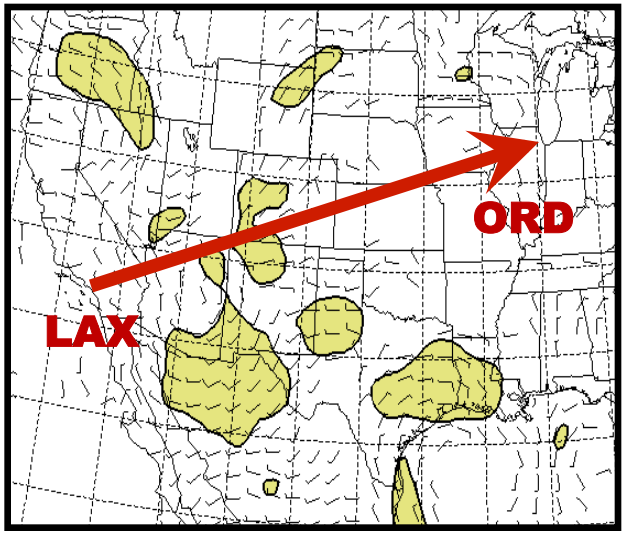
12-h fcst wind errors



6-h fcst wind errors



3-h fcst wind errors

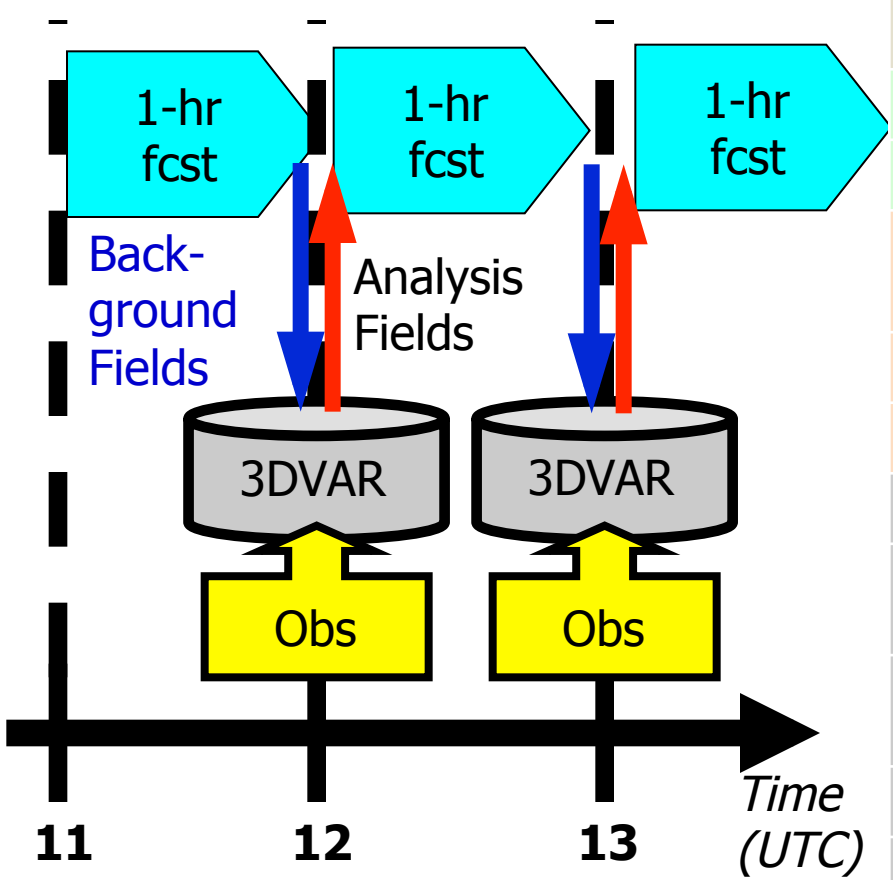


Jet-level (35 kft) wind forecast errors

Rapid Refresh
Hourly Update Cycle

Partial cycle atmospheric fields – introduce GFS information 2x/day

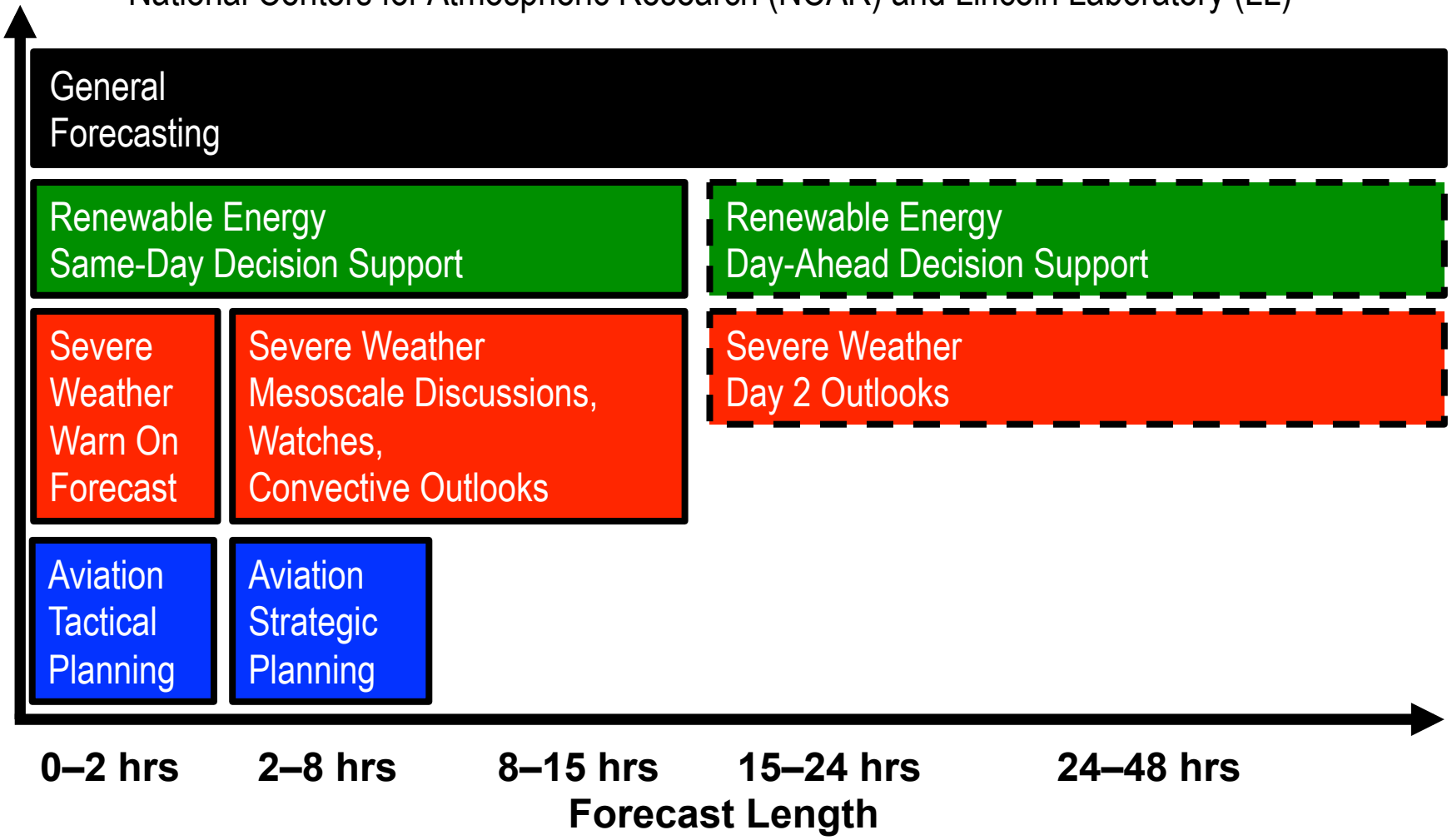
Fully cycle all land-sfc fields



Hourly Observations	RAP 2012 N. Amer
Rawinsonde (T,V,RH)	120
Profiler – NOAA Network (V)	21
Profiler – 915 MHz (V, Tv)	25
Radar – VAD (V)	125
Radar reflectivity - CONUS	2km
Lightning (proxy reflectivity)	NLDN, GLD360
Aircraft (V,T)	2-15K
Aircraft - WVSS (RH)	0-800
Surface/METAR (T,Td,V,ps,cloud, vis, wx)	2200- 2500
Buoys/ships (V, ps)	200-400
Mesonet (T, Td, V, ps)	flagged
GOES AMVs (V)	2000- 4000
AMSU/HIRS/MHS radiances	Used
GOES cloud-top pressure/temp	13km
GPS – Precipitable water	~250
WindSat scatterometer	2-10K

HRRR Users and Applications

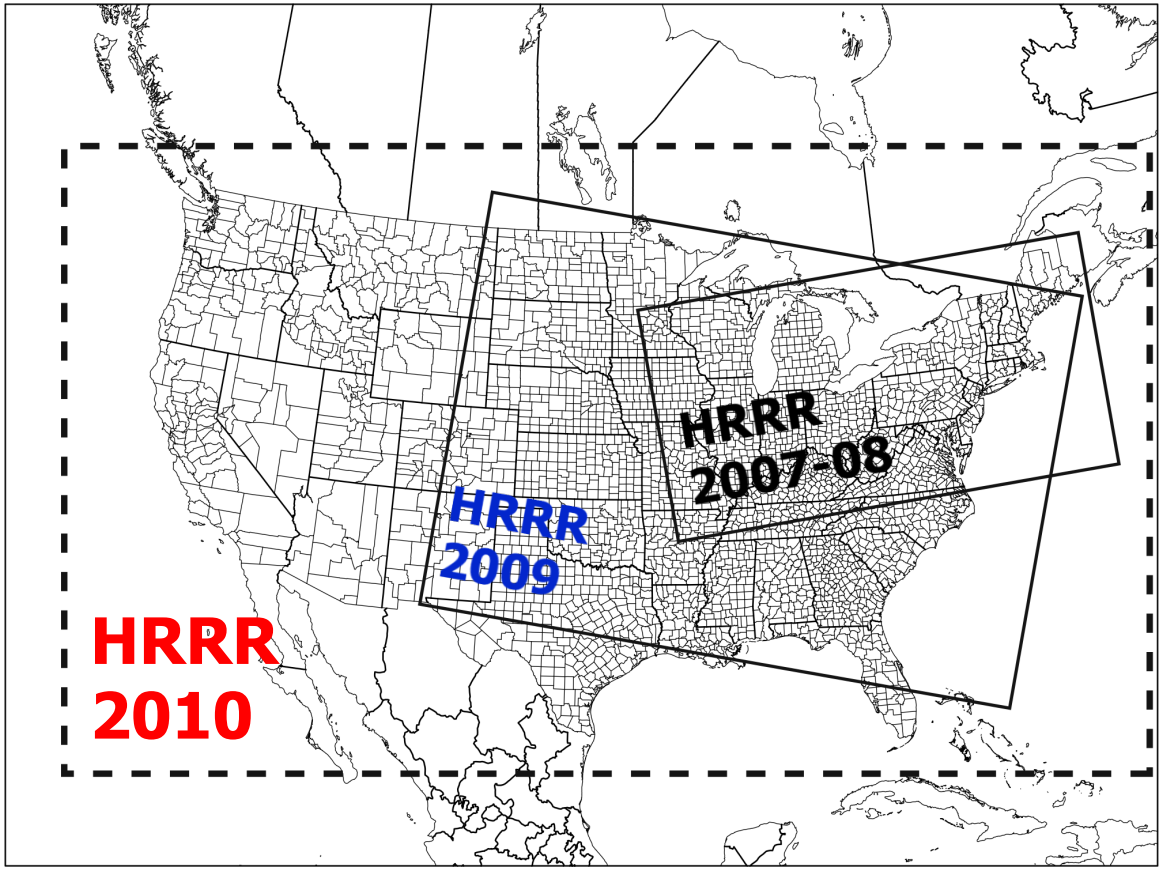
Example: National Weather Service including Storm and Weather Prediction Centers (SPC & WPC)
Aviation Weather Center (AWC) and FAA Command Center
National Severe Storms Laboratory (NSSL) and Air Resources Laboratory (ARL)
National Centers for Atmospheric Research (NCAR) and Lincoln Laboratory (LL)



Evolution of the HRRR Domain

Hourly frequency maintained

RUC Domain



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

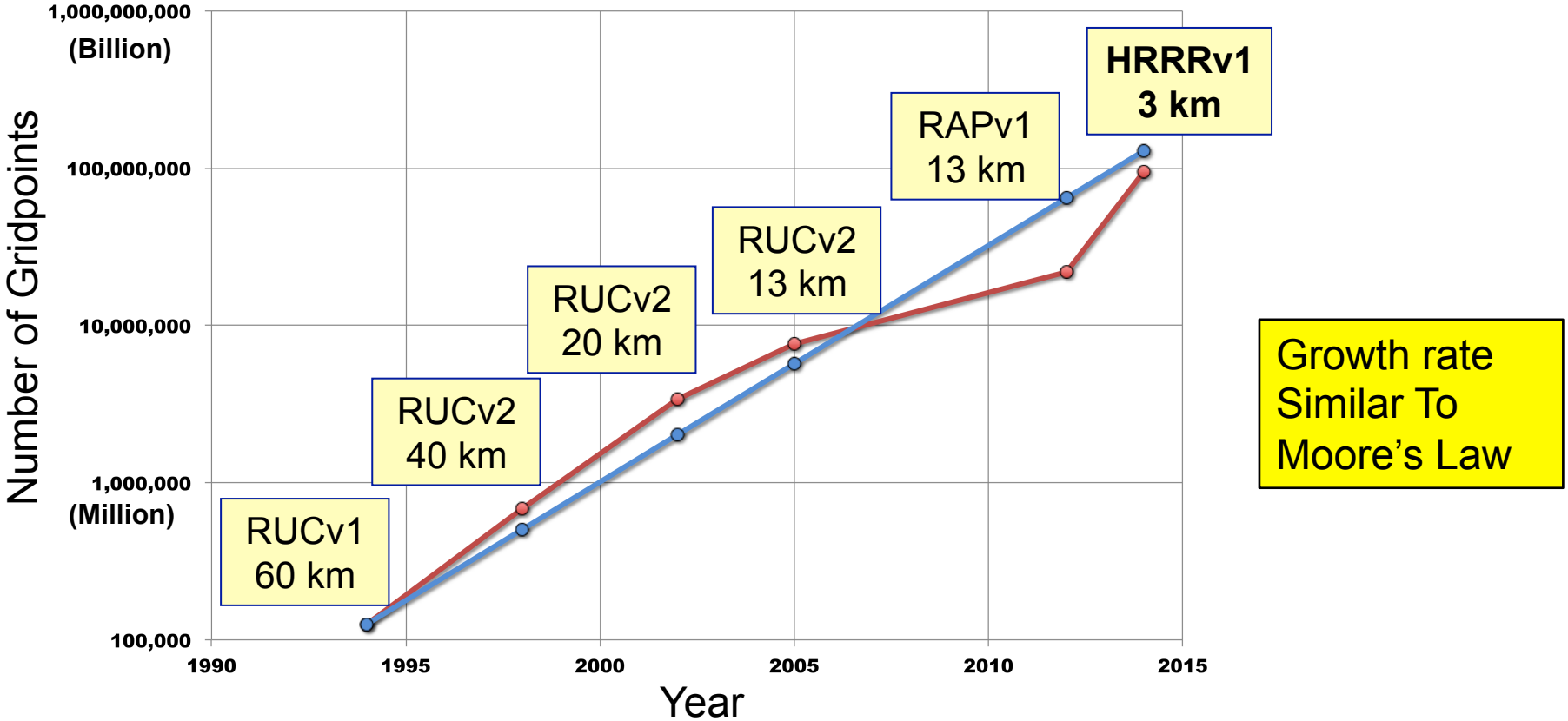
May – Oct 2010 HRRR run reliability

94.5% HRRR completion rate (including scheduled downtime)

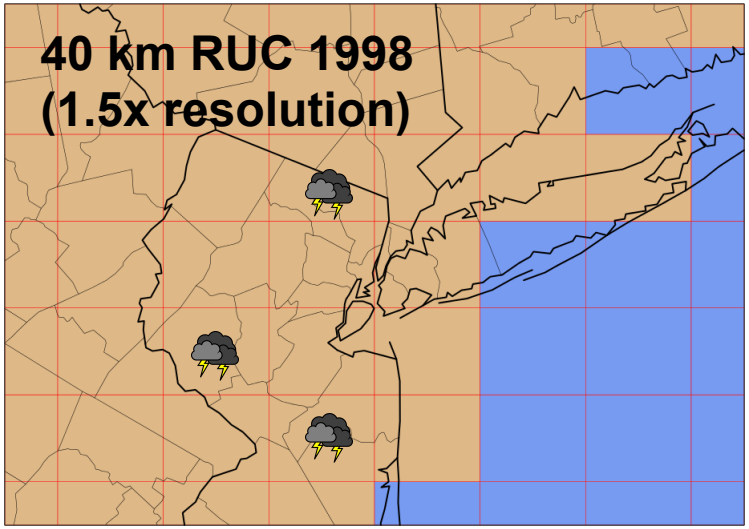
High Impact Prediction Needs: High Performance Computing

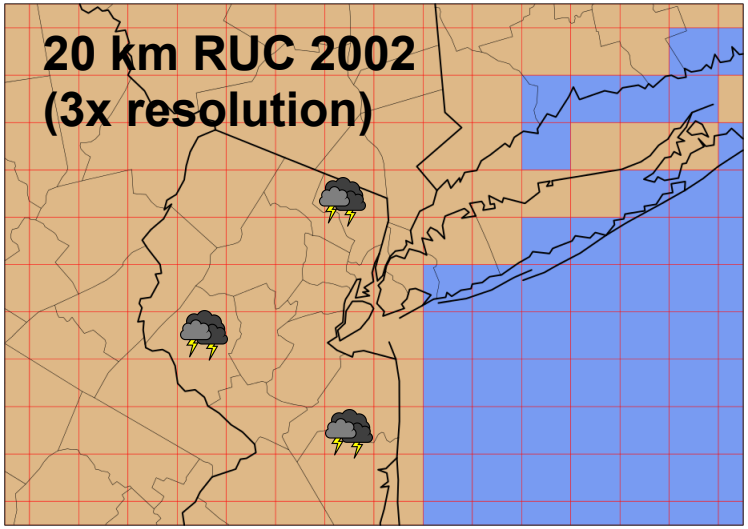
Growth of NOAA Frequently Updating Numerical Weather Guidance:
Rapid Update Cycle (RUC), Rapid Refresh (RAP) and
High-Resolution Rapid Refresh (HRRR)

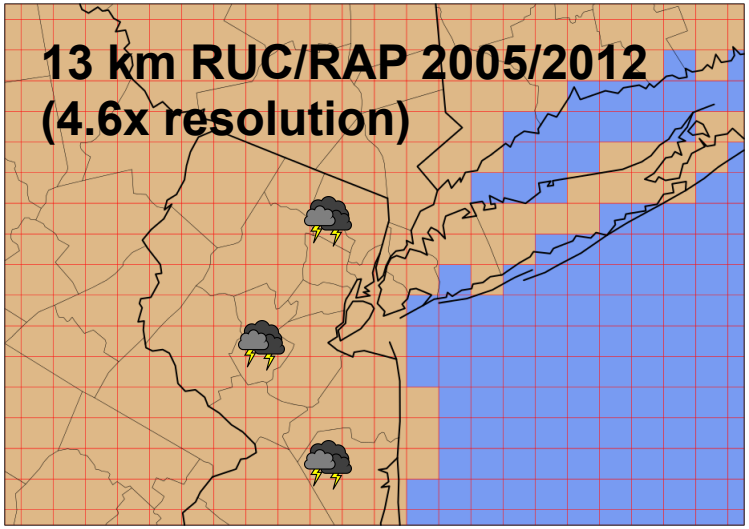
Moore's Law: Number of transistors or integrated circuits doubles every two years

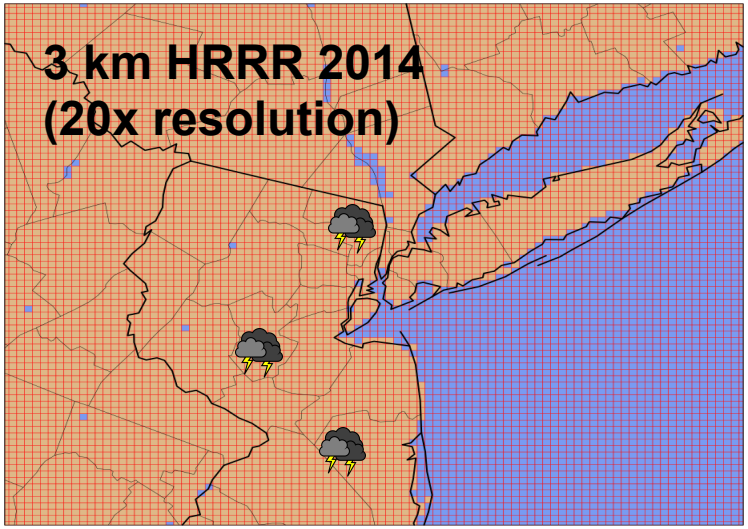


High Impact Prediction Needs: Higher Resolution Models



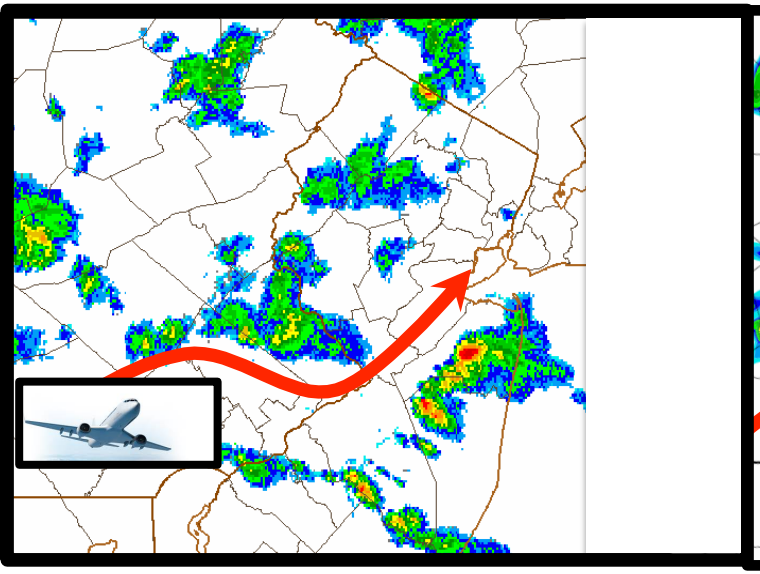






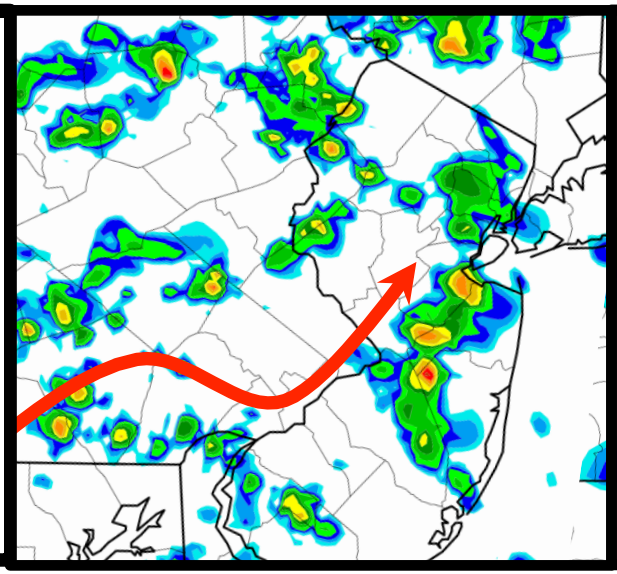
High-Impact Prediction Needs: Advanced NWP Model

07 June 2012 5 PM EDT
Reality



Aircraft must navigate around thunderstorms

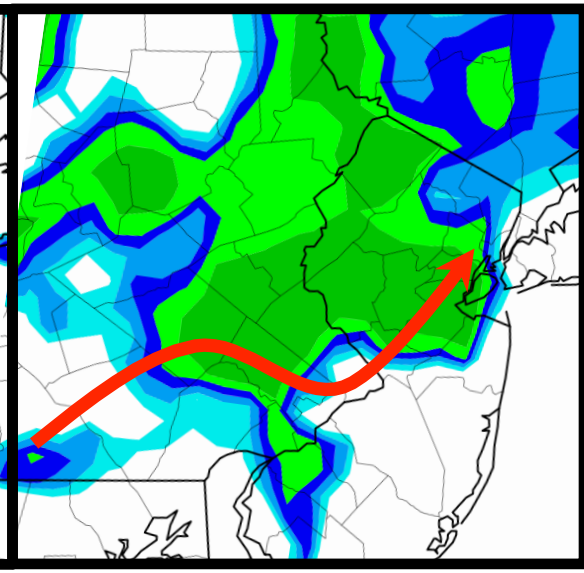
3-km HRRR
Explicit
Convection 6 hr forecast



Accurate Storm Structure

Accurate Estimate of Permeability

13-km RAP
Parameterized
Convection 6 hr forecast



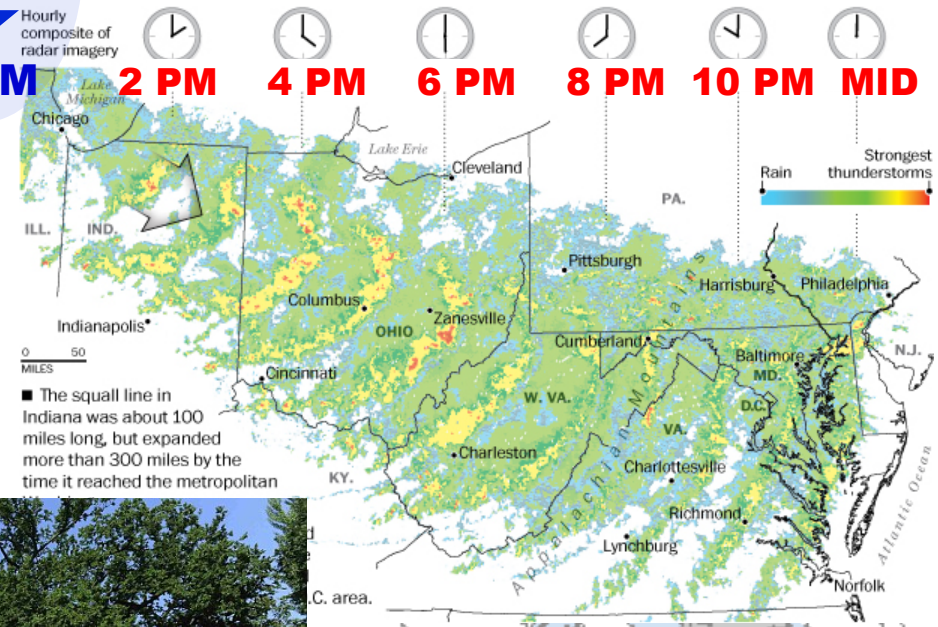
No Storm Structure

No Estimate of Permeability

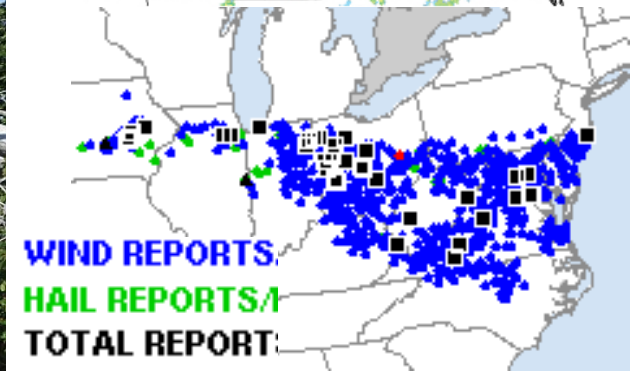
An Important Pinpoint Prediction Challenge: The 29 June 2012 Mid-Atlantic Derecho

Start HRRR run

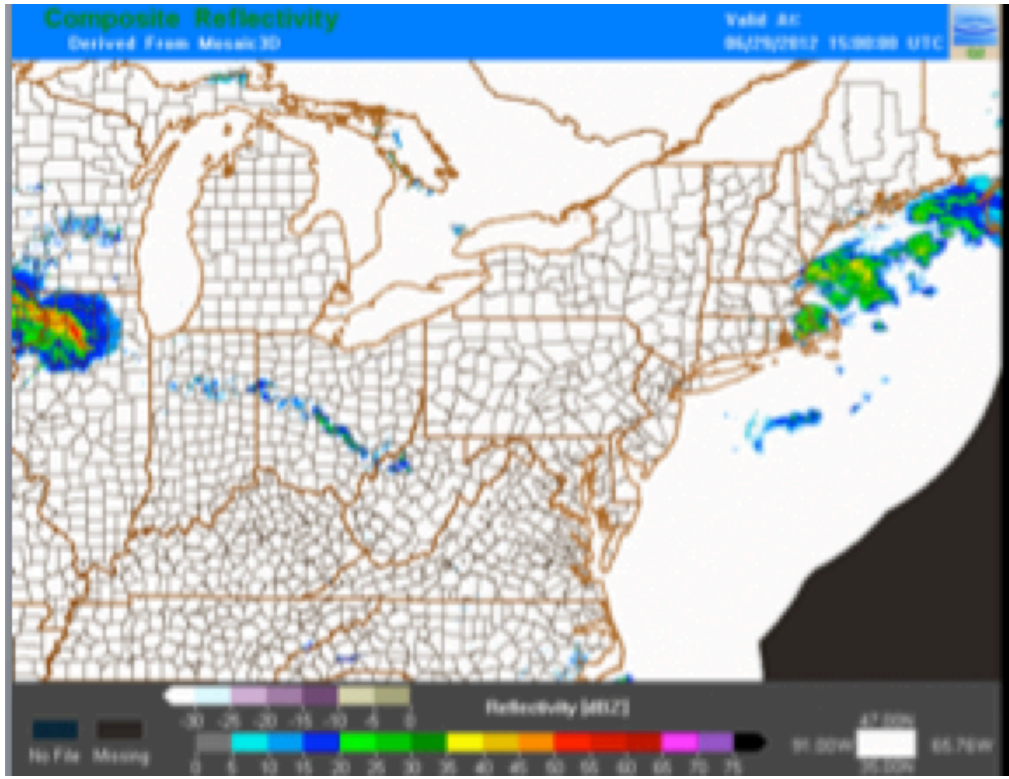
A fast-moving damaging wind event…

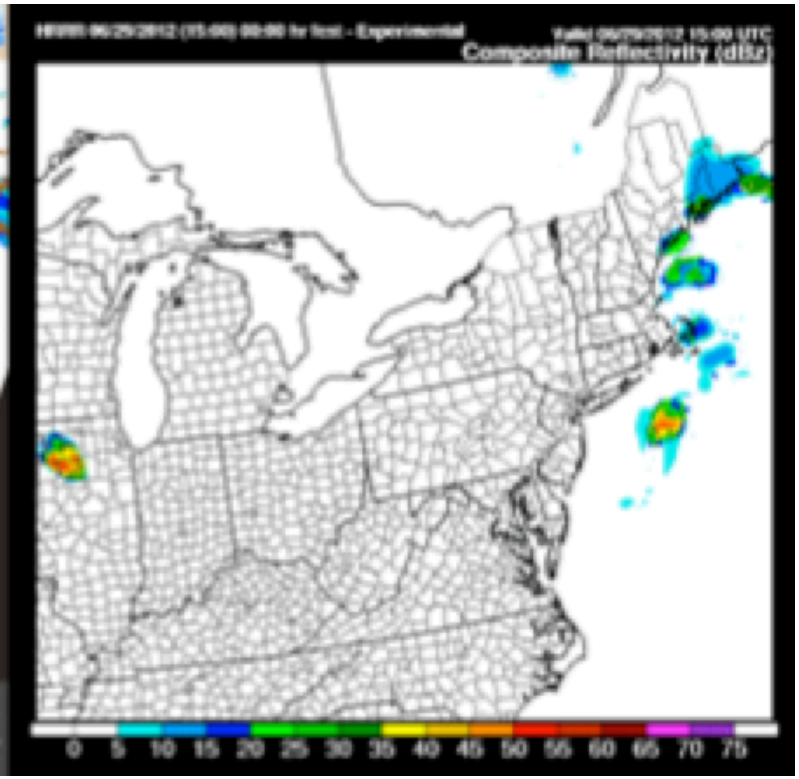


700 mile long swath of damage, 5 million without power, 22 fatalities



HRRR 15h forecast
15z 29 June – 06z 30 June 2012





Observed radar

HRRR forecast initialized 15z (11am Eastern Time)

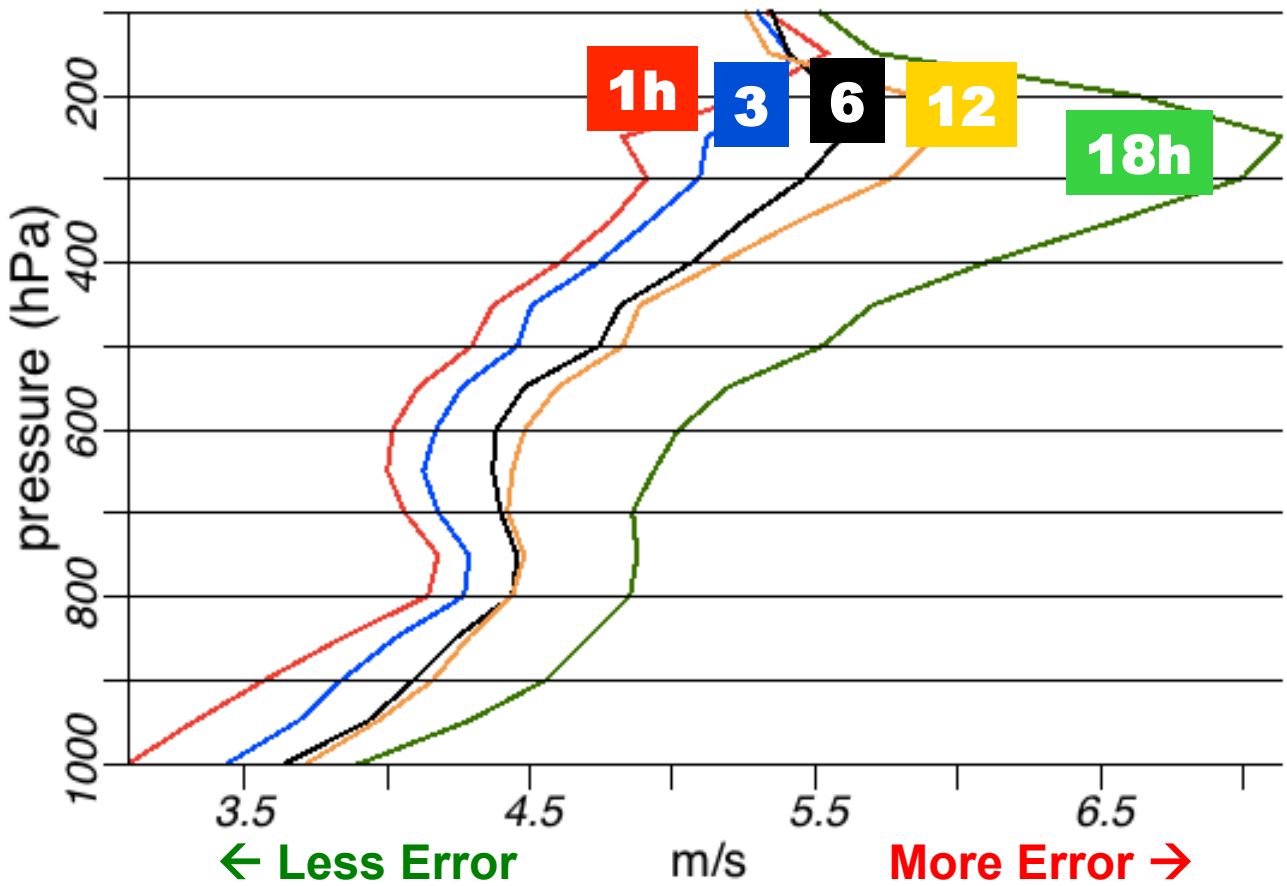
29 June 2012 – Mid-Atlantic/DC thunderstorm/derecho event

High Impact Prediction Needs: Advanced Obs Assimilation

Wind Forecast Accuracy vs Forecast Length

Like most numerical weather prediction the forecast errors increase with the forecast length

Motivation to use observations with very short term forecasts as first guess
→ **Hourly Cycling**

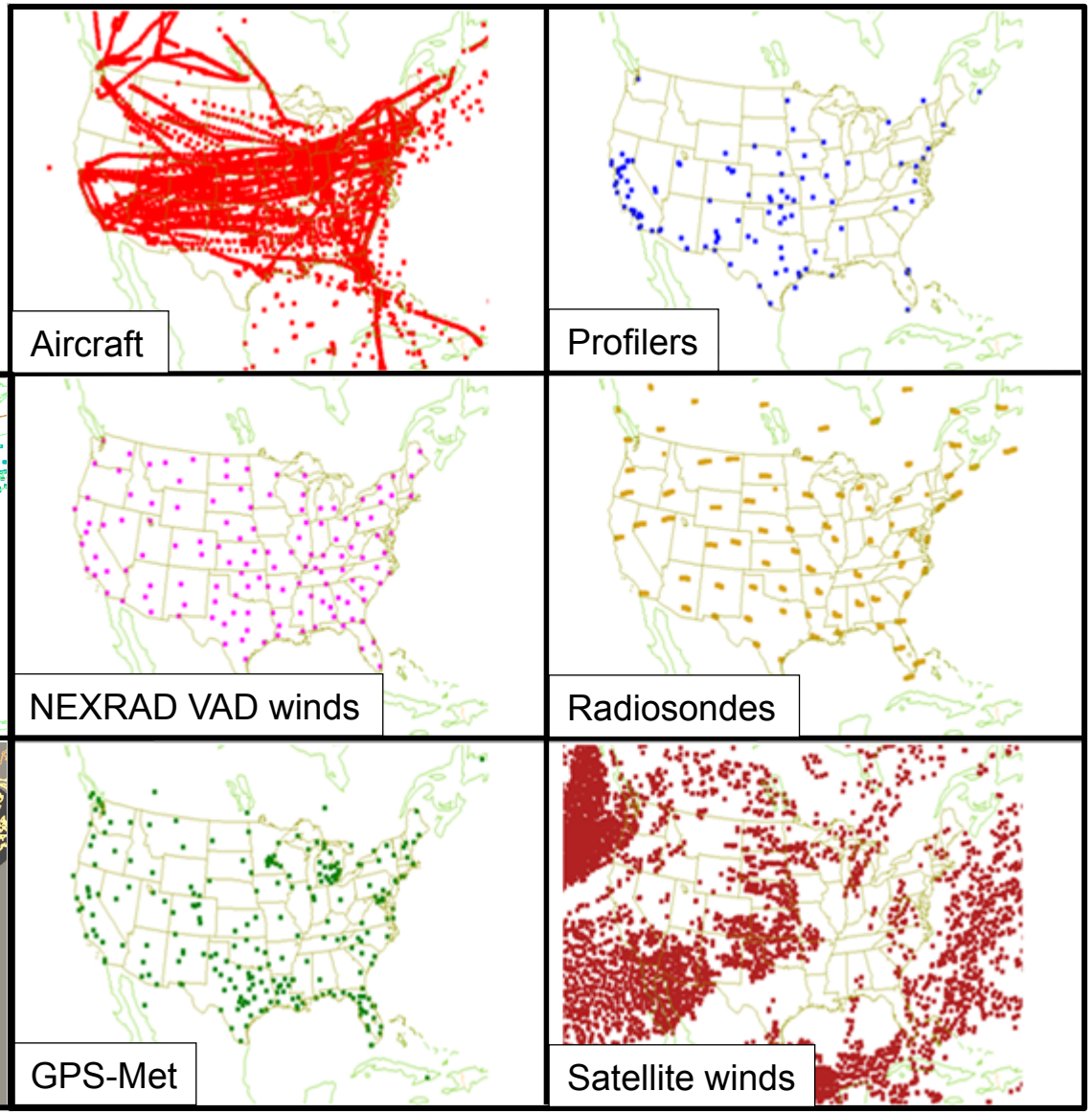


Wind Root Mean Square Error Verified Against RAOBS
Jan 1 – March 7, 2012

Why do the HRRR and the RAP use hourly updates?

Hourly cycling can also take advantage of high density (space and time) observations.

Examples of observation coverage



Radar assimilation is handled differently. (To be discussed)

High Impact Prediction Needs: High Density Observations

Observations Used in 2014 RAP/HRRR

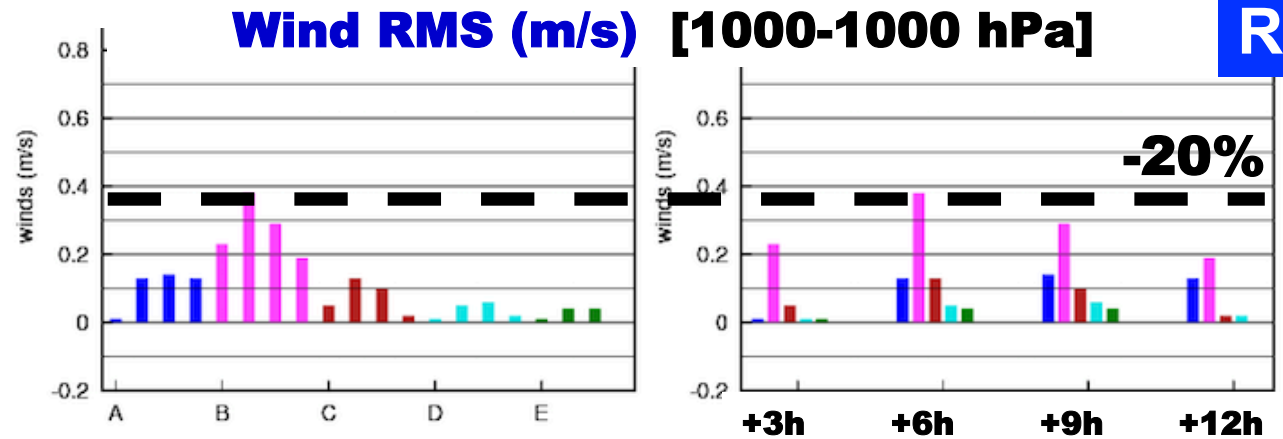
Hourly Observation Type	Variables Observed	Observation Count
Rawinsonde	Temperature, Humidity, Wind, Pressure	120
Profiler – NOAA Network	Wind	Down to 9 (!)
Profiler – 915 MHz	Wind, Virtual Temperature	20-30
Radar – VAD	Wind	125
Radar reflectivity – CONUS	Rain, Snow, Hail	1,500,000
Lightning – GLD360	(proxy reflectivity)	5,000
Aircraft	Wind, Temperature	2,000 -15,000
Aircraft - WVSS	Humidity	0 - 800
Surface/METAR	Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather	2200 - 2500
Buoys/ships	Wind, Pressure	200 - 400
GOES AMVs	Wind	2000 - 4000
AMSU/HIRS/MHS	Radiances	5,000
GOES cloud-top press/temp	Cloud Top Height	100,000
GPS – Precipitable water	Humidity	260
WindSat Scatterometer	Winds	2,000 – 10,000

RAPv3: Observations used (new 2015)

HRRRv2 – all except radiances into 3km GSI assimilation

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

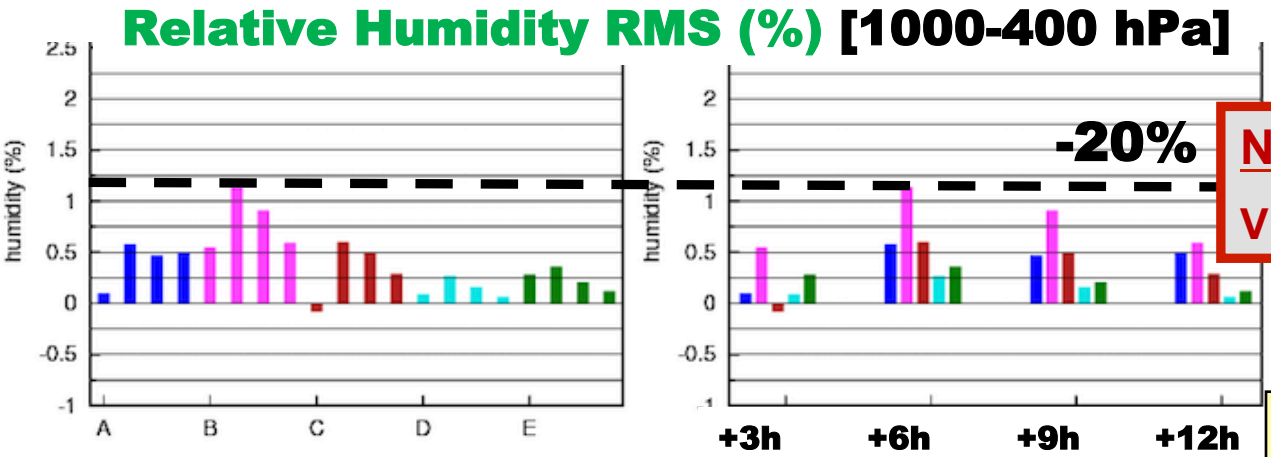
RAP 2013 obs impact



A - withhold rawinsonde
B - withhold all aircraft ob
C - withhold surface obs
D - withhold AMVs - Exp.
E - withhold GPS-Met PW

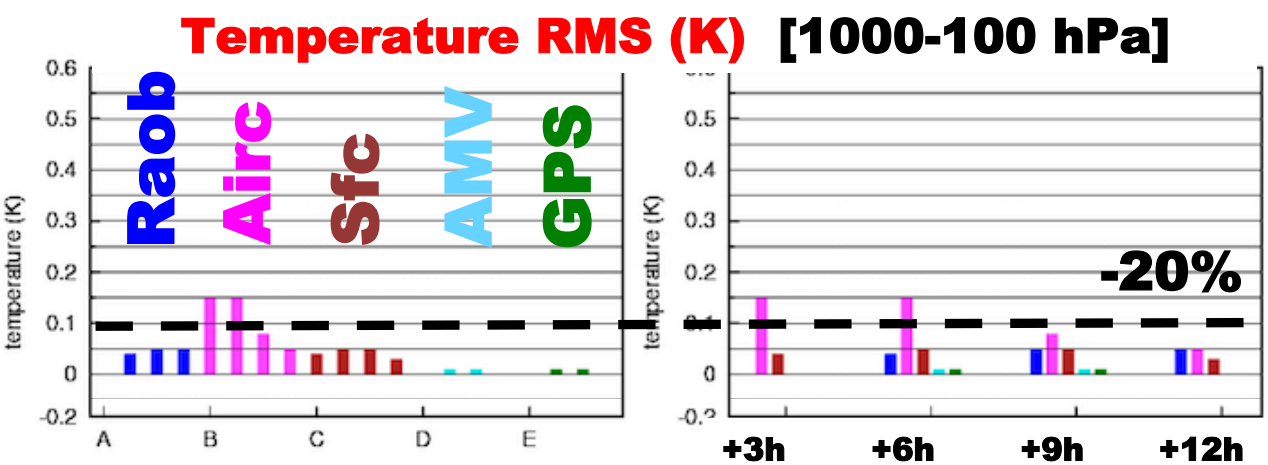
RAP data impact

-- North America
-- May 2013 experiments
-- 12z and 00z combined



Normalize: 6h Fcst – 0h Anx

V – 1.8 m/s, RH – 6%, T – 0.5K



Aircraft – largest impact

wind/RH/temp – all have up to 20% reduction forecast error, especially 6h-9h fcsts

Following in importance:

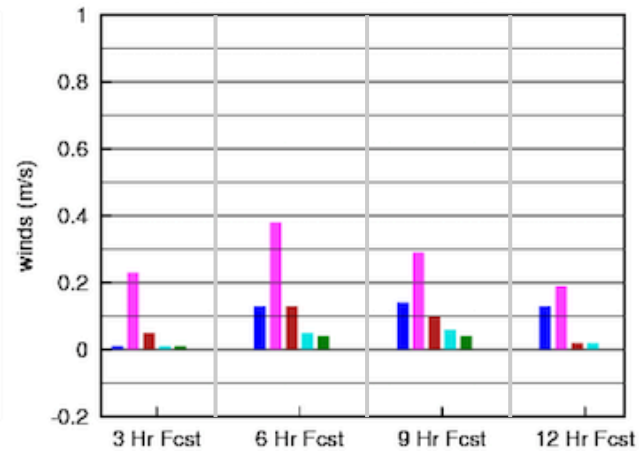
Raob, Surface, GPS-Met, AMVs

What impact do the observations have?

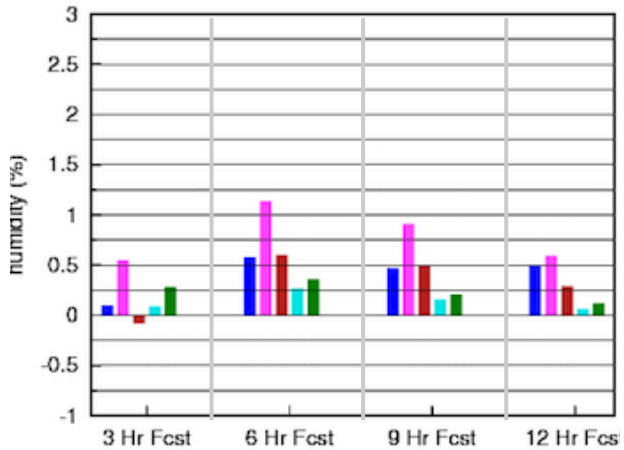
Impact for raob, aircraft, METAR, GOES AMV, GPS observations

The study was done for the RAP during a one week period of May in 2013.

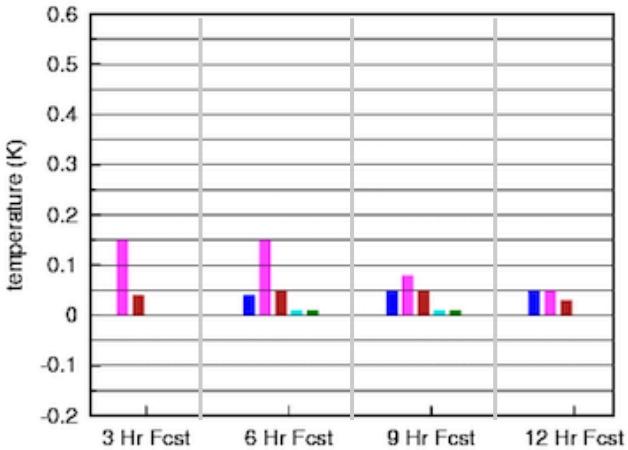
Wind
1000-100 hPa



RH
1000-400 hPa



Temperature
1000-100 hPa



Total error increase when the following obs were removed:

- A - withhold rawinsonde obs
- B - withhold all aircraft obs
- C - withhold surface obs
- D - withhold AMVs
- E - withhold GPS-Met PW obs

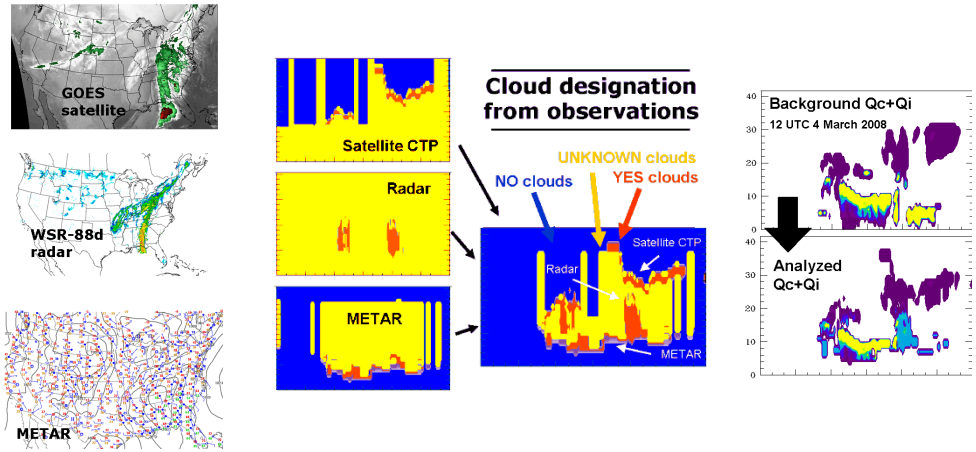
Most observation types have positive impact for all forecast hours.

Aircraft observations have largest positive impact, i.e. 20% more error at 6 hour when those obs are withheld.

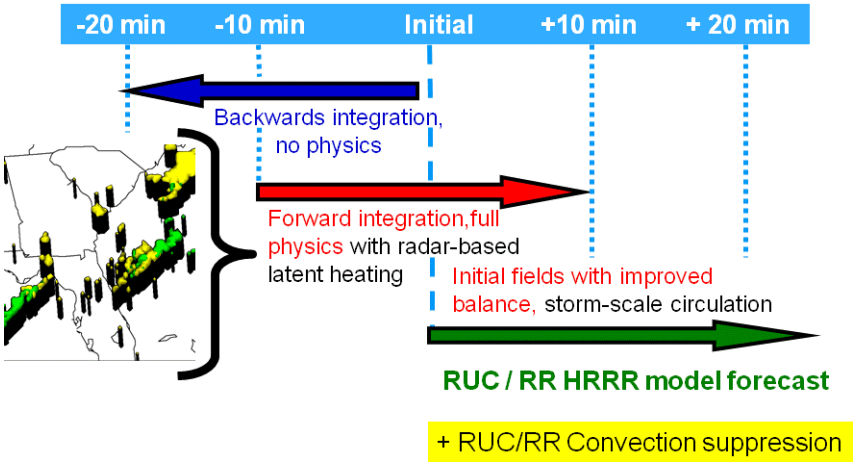
These observations provide information on the mesoscale (and larger). (Radar critical for precip/storms.)

Rapid Refresh Specific Analysis Features

Cloud and hydrometeor analysis



Digital filter-based reflectivity assimilation (DDFI)



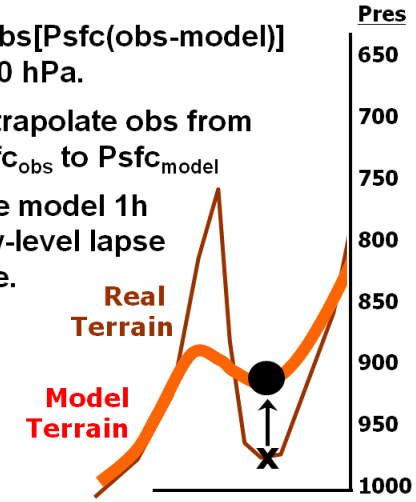
Special treatments for surface observations

Elevation correction

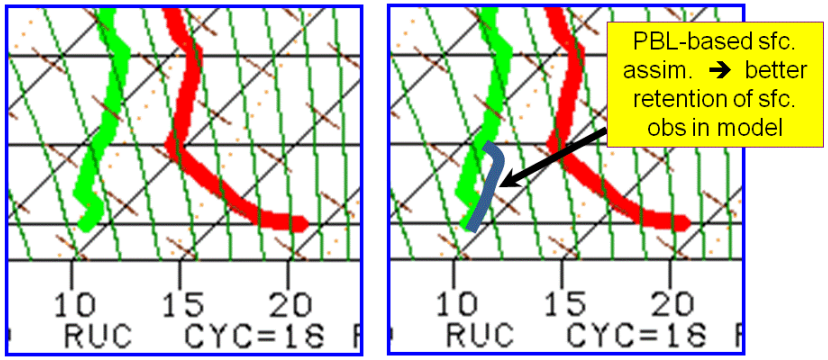
If abs[Psfc(obs-model)] < 70 hPa.

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

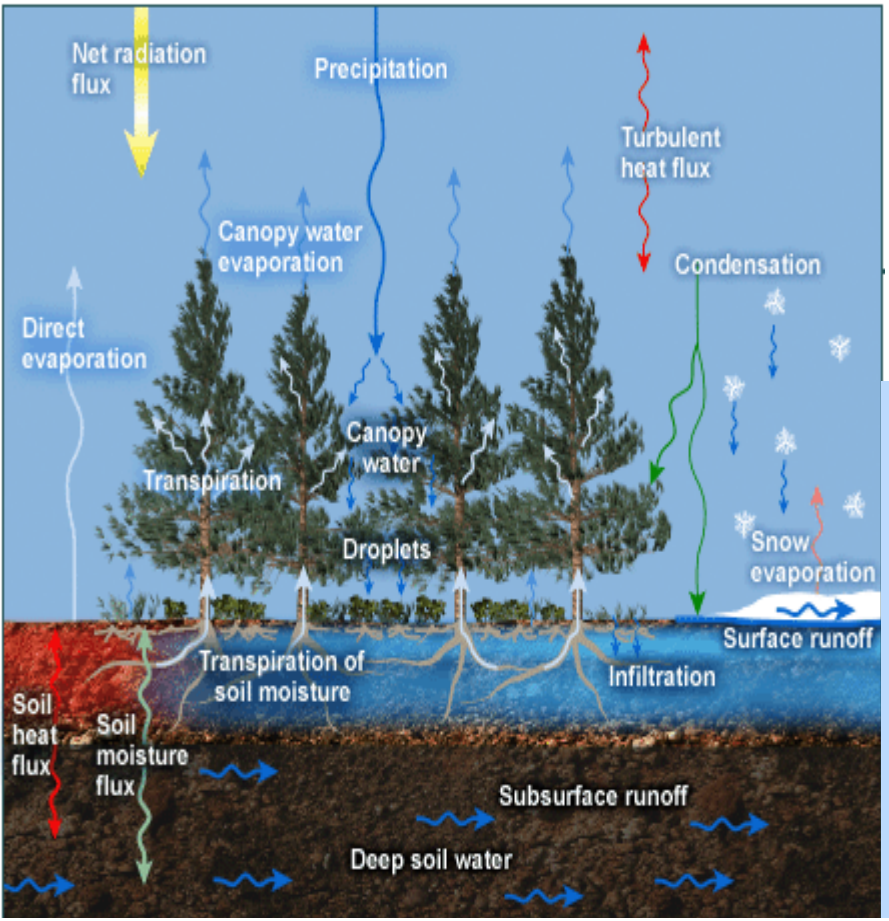
Use model 1h low-level lapse rate.



PBL-based pseudo-observations



Updates to RUC Land Surface Model



OLD	NEW
~ 8 m	~ 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?

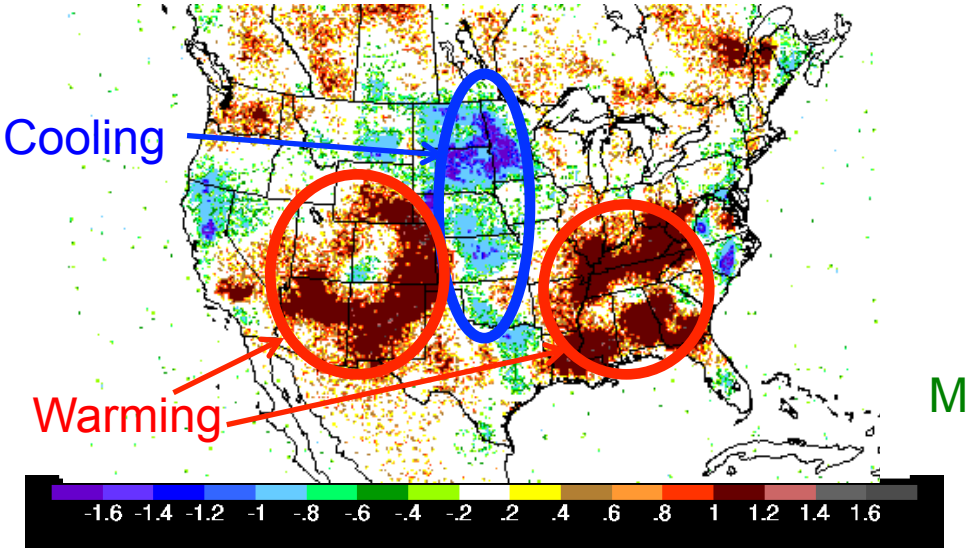
- 9 soil layers, 2 snow layers
- Surface observations are used to update the LSM through the data assimilation step. For example, the soil temperature is decreased and soil moisture is increased where the model is too warm and too dry compared to the surface observations.

Example Soil Adjustments

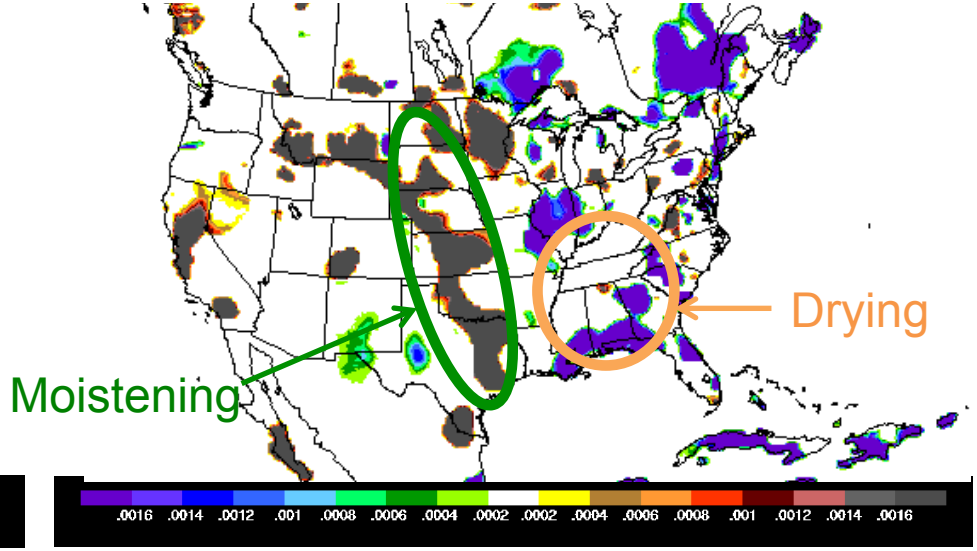
20 UTC

03 June 2013

Soil Temperature



Soil Moisture



NCEP RAPv2 and HRRR 2014

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	CONUS	1799 x 1059	3 km	50	20 mb	RAP	Hourly - RAP (no-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 9-lev
HRRR	WRF-ARW v3.4.1+	GSI 3D-VAR	3-km 15-min LH	RRTM/ Goddard	Thompson v3.4.1	None	MYNN	RUC 9-lev

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	10 min	MODIS Fractional	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	No	5 min	MODIS Fractional	0.07 K/s	20 s

NCEP RAPv3 and HRRRv2 2015

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)
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Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.6.1+	GSI Hybrid 3D-VAR/Ensemble	13-km DFI	RRTMG/ RRTMG	Thompson – aerosol-aware v3.6.1	GF – v3.6.1	MYNN v3.6.1+	RUC 9-lev v3.6.1+
HRRR	WRF-ARW V3.6.1+	GSI 3D-VAR/ Ensemble	3-km 15-min LH	RRTMG/ RRTMG	Thompson – Aerosol-aware v3.6.1	None	MYNN	RUC 9-lev v3.6.1+

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

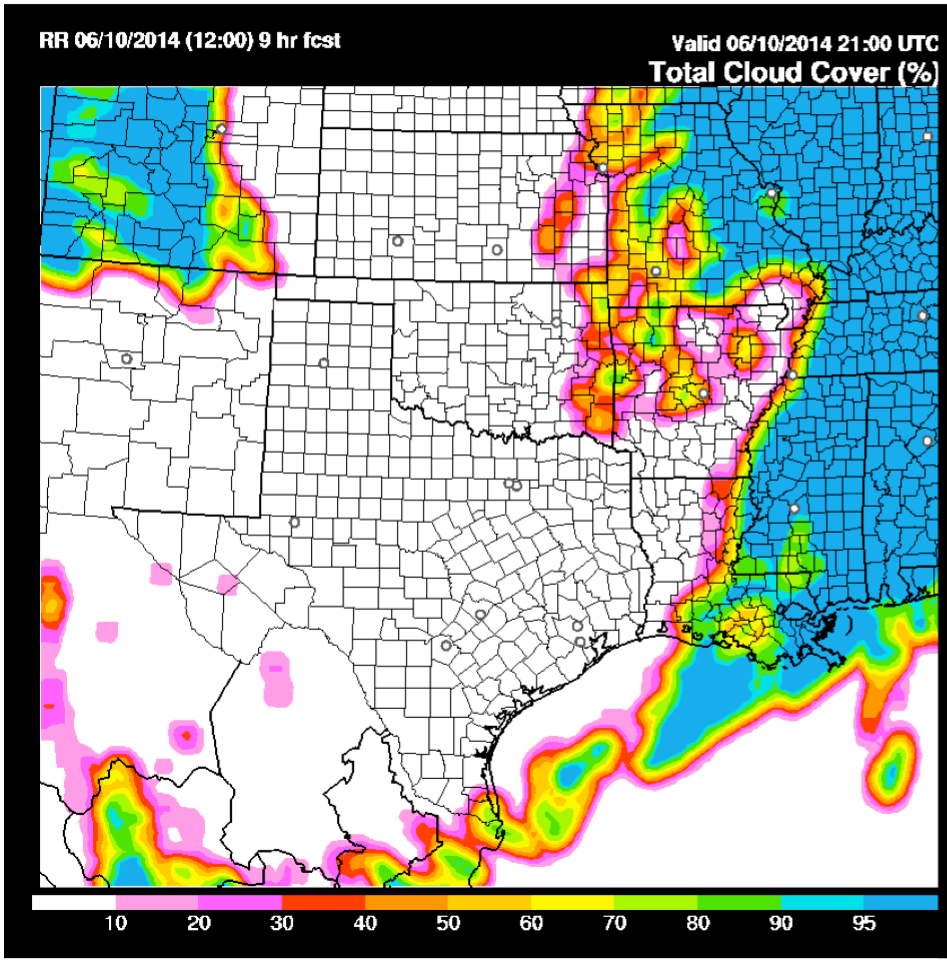
NCEP RAPv3/HRRRv2-2015 Changes

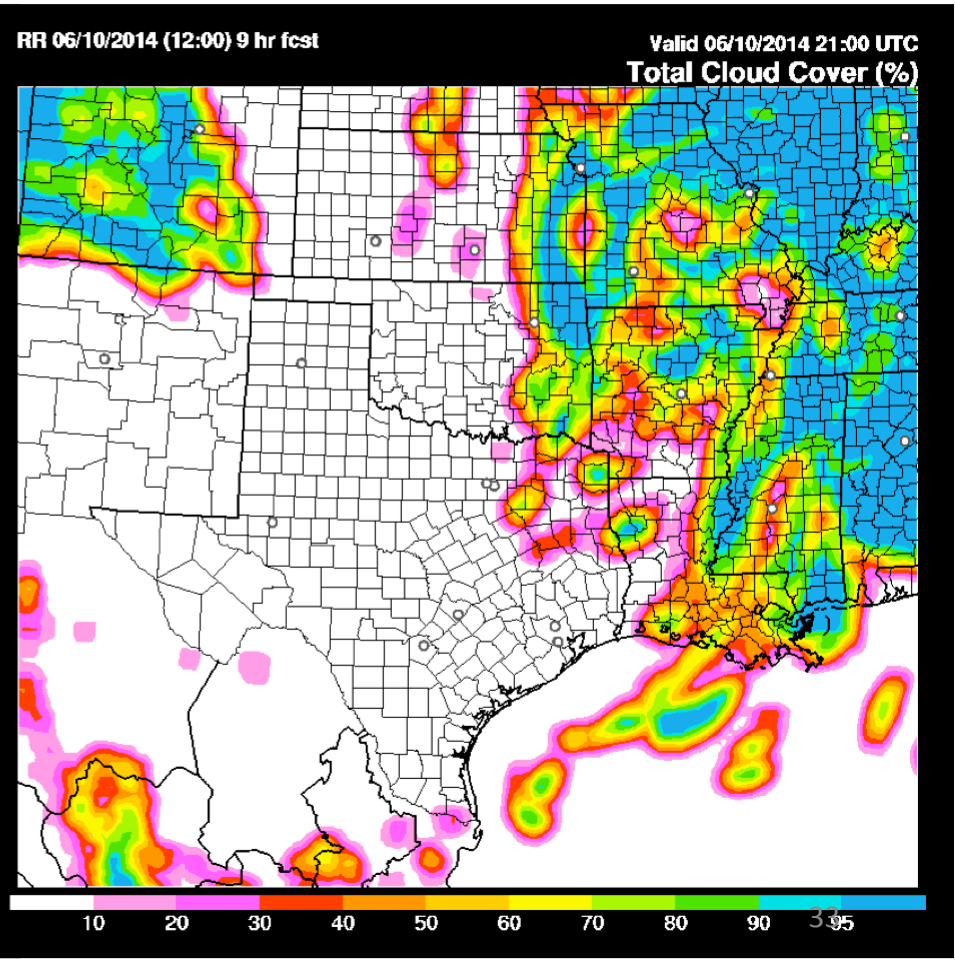
Use of forecast aerosol fields to have prognostic cloud-condensation nuclei (CCN).

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

WRFv3.5.1 aerosol unaware

WRFv3.6 Aerosol-aware



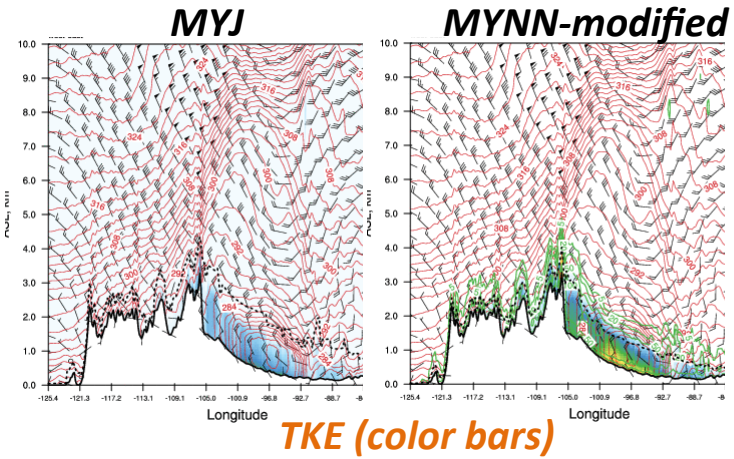


RAP / HRRR use of MYNN PBL scheme

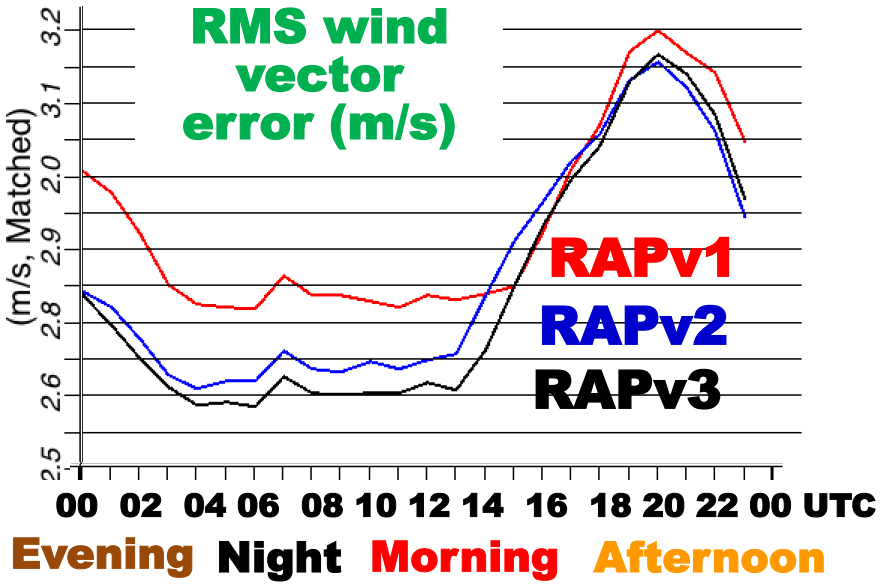
First implemented with RAPv2 / HRRR 2013 – better convection, wind forecasts

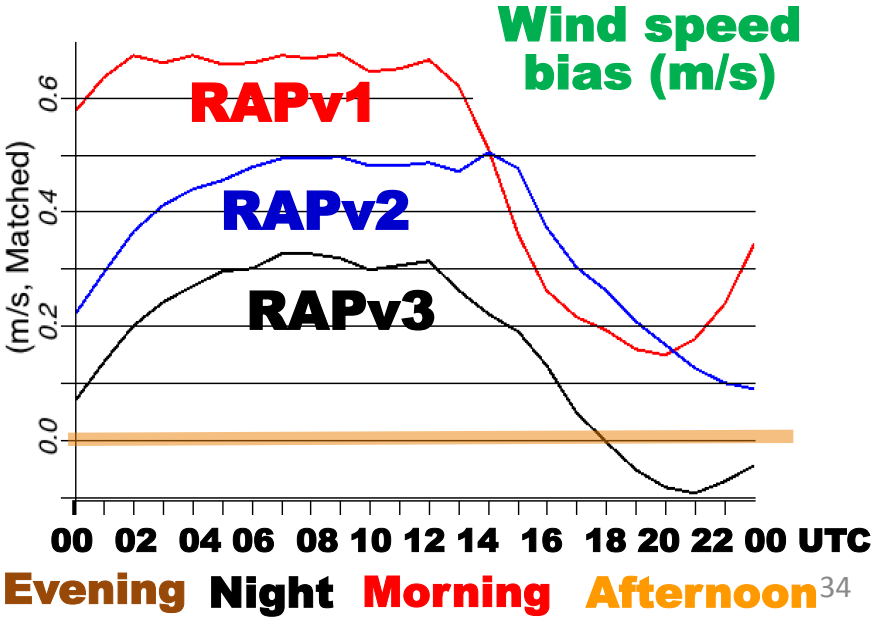
Improved mixing length formulations to flexibly change behavior across the stability spectrum

Improved surface layer scheme (customization to PBL)



Further enhancements for RAP v3 / HRRR v2 -- cloud mixing, refined closure constants, coupling to different shallow cu schemes





CIRES

Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

Use of Solar Irradiance Measurements to Improve the Physical Parameterizations in the Rapid Refresh and High-Resolution Rapid Refresh Models

Jaymes Kenyon

Joseph Olson, John Brown, William Moninger,
Eric James, Allison McComiskey, and Kathy Lantz

NOAA / Earth System Research Laboratory
Boulder, Colorado

2015 Global Monitoring Annual Conference
19 May 2015

ESRL RAP and HRRR Configurations

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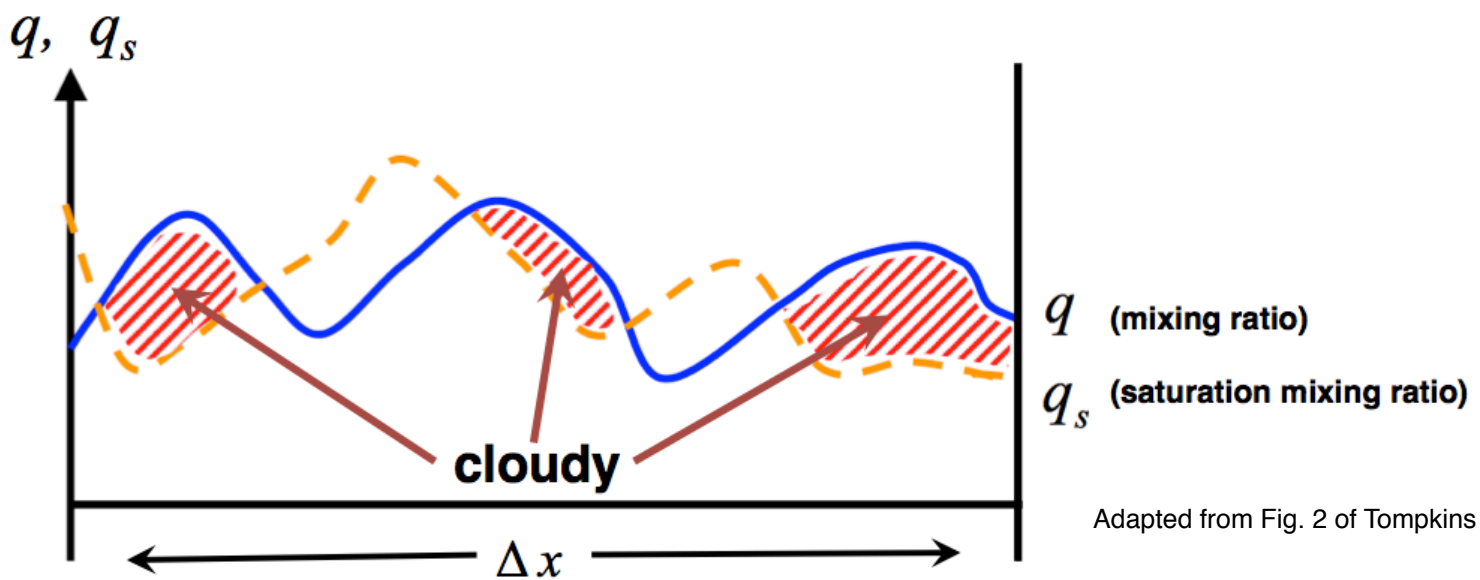
Cloud Representation in a Model

- If model grid cells represented homogeneous volumes (in water vapor & temperature), only binary cloud fractions (*0 or 1*) would be needed

- **Reality:** grid cells represent ensemble averages, subgrid-scale variability exists, and fractional (non-binary) cloud coverage may exist

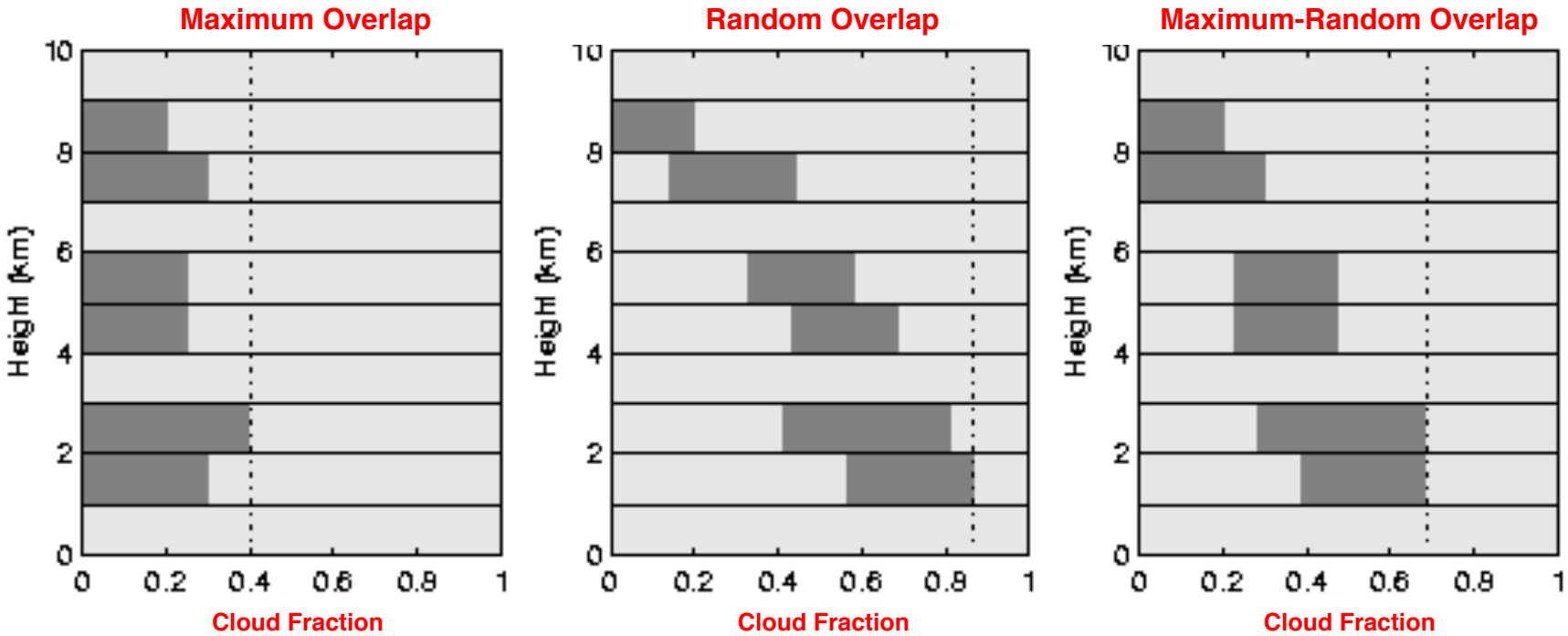


Adapted from Fig. 2 of Tompkins (2005)

- **Scientific Challenge #1**: modeling fractional cloud coverage requires that we make assumptions regarding subgrid-scale variability

Cloud–Radiation Coupling

Some Historically Common Cloud "Overlap" Approximations:

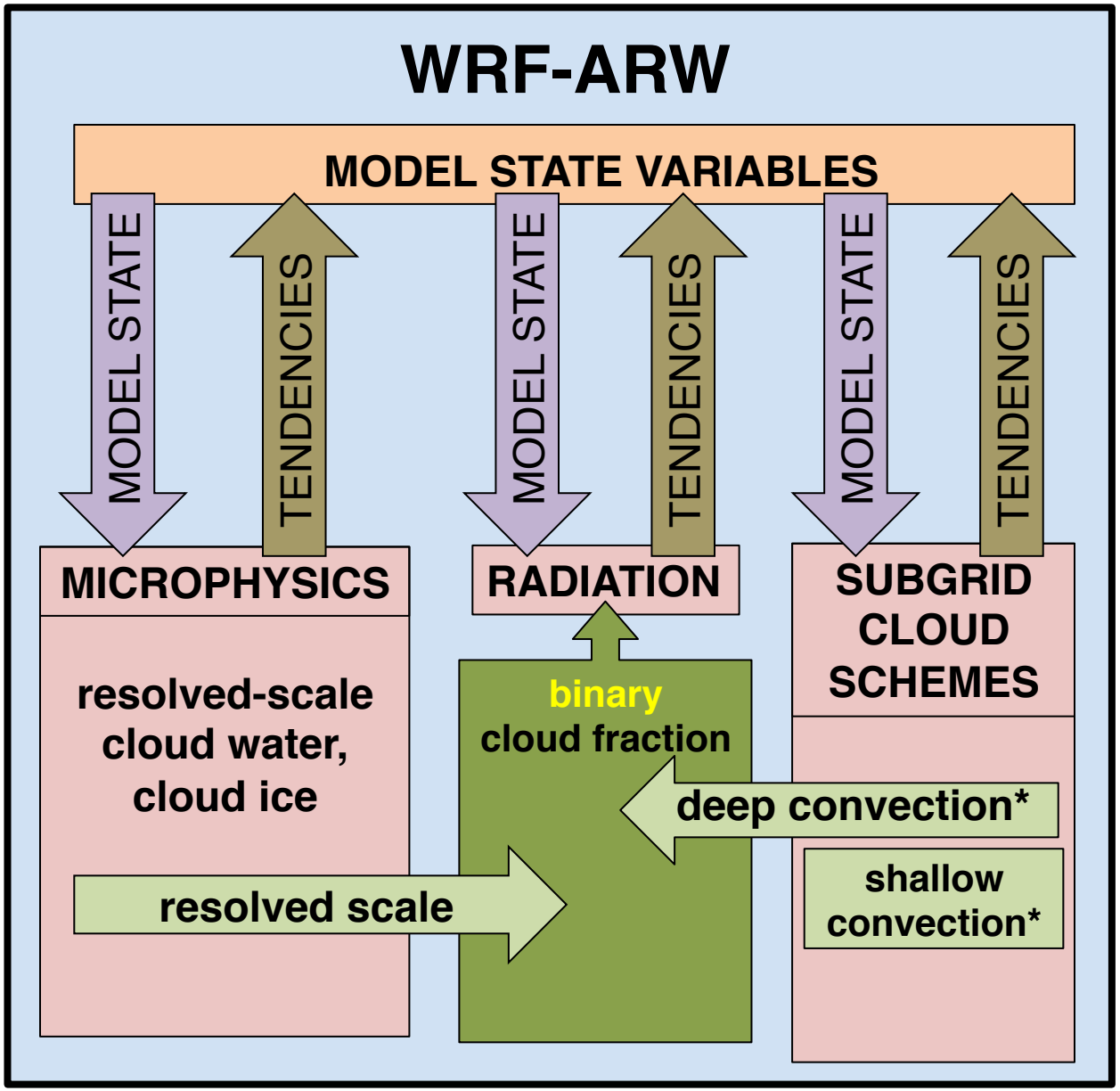


(Figure adapted from met.rdg.ac.uk/radar/research/cloudoverlap)

- RRTMG scheme assumes a cloud overlap according to the Monte-Carlo Independent Column Approximation (McICA) (Pincus et al. 2003)

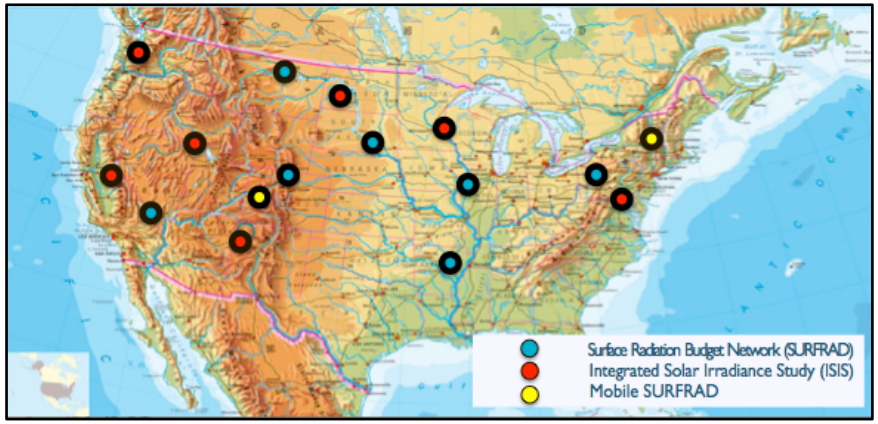
- **Scientific Challenge #2**: modeling cloud–radiation interaction requires additional assumptions

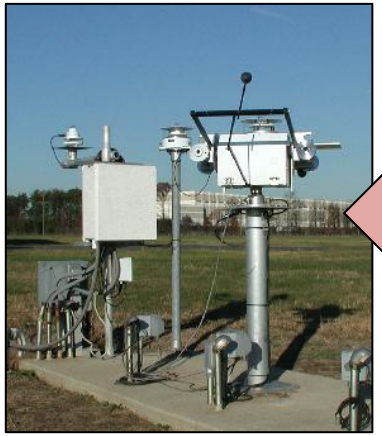
RAP / HRRR Cloud Representation: Recent Past



*RAP only

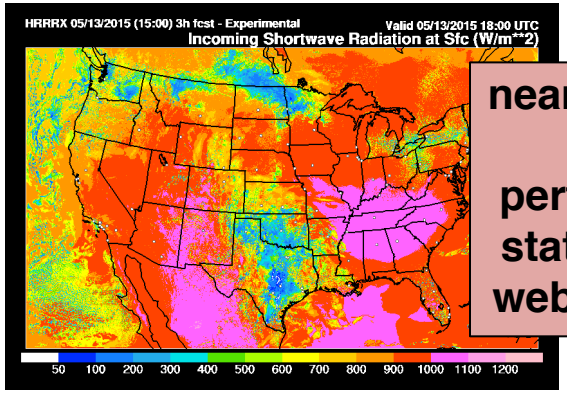
RAP / HRRR Irradiance Verification from GMD's SURFRAD / ISIS



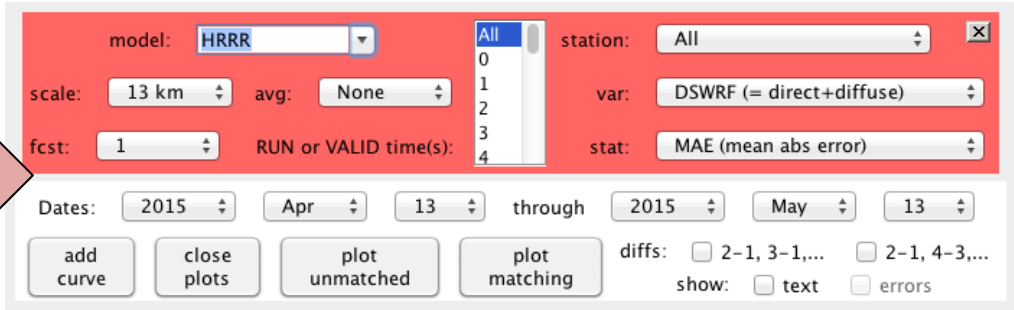


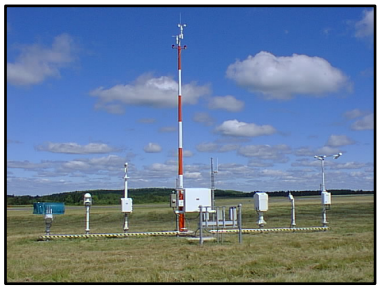
14 SURFRAD / ISIS sites

near-real-time data processing



near-real-time model performance statistics via web interface





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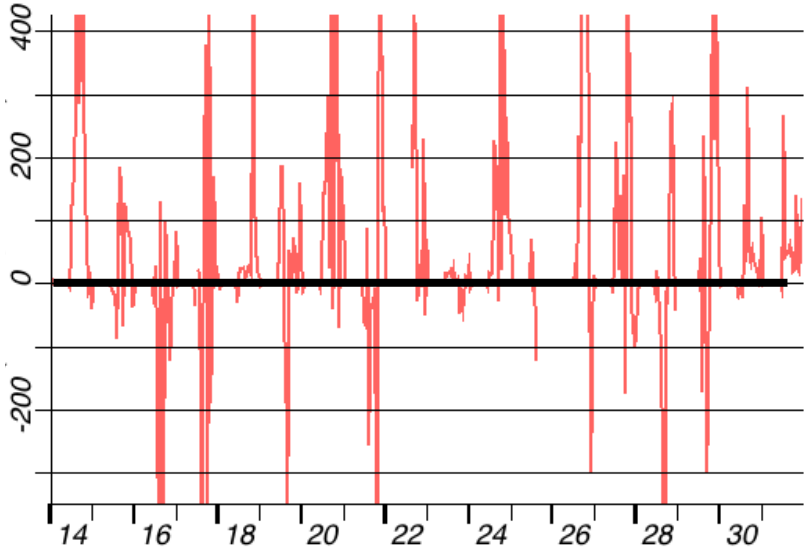
Summer 2014: Excessive Surface Irradiance in RAP and HRRR

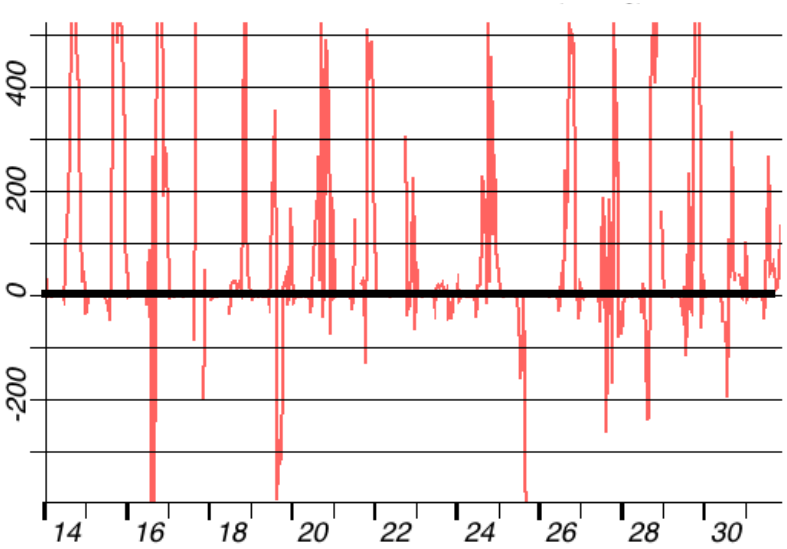
12-h GHI Forecast Bias at Bondville, Illinois (W m $^{-2}$)

RAP



May 2014

HRRR



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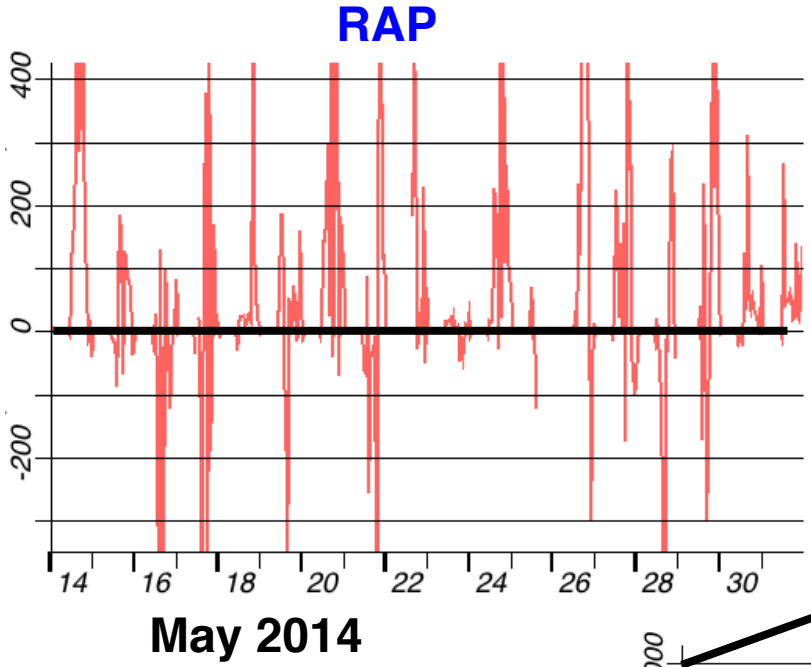
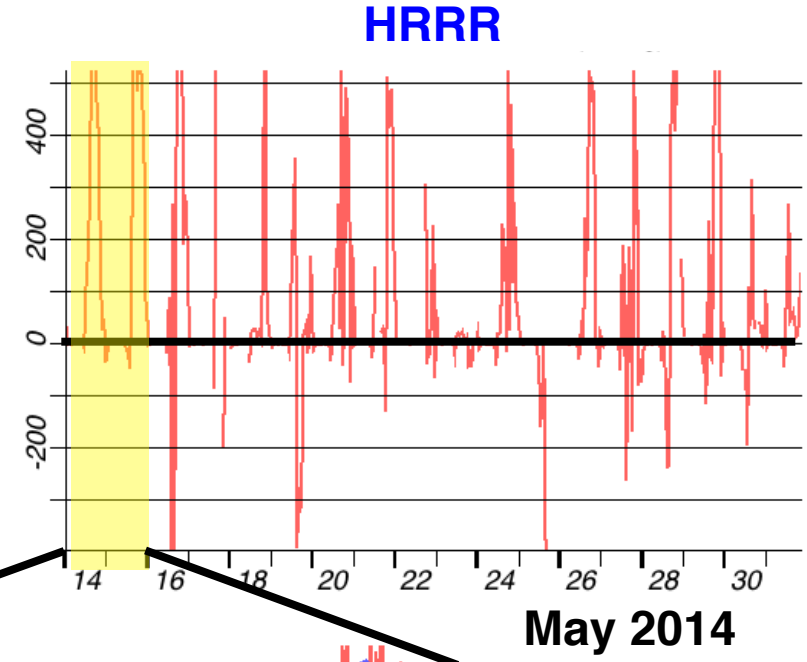
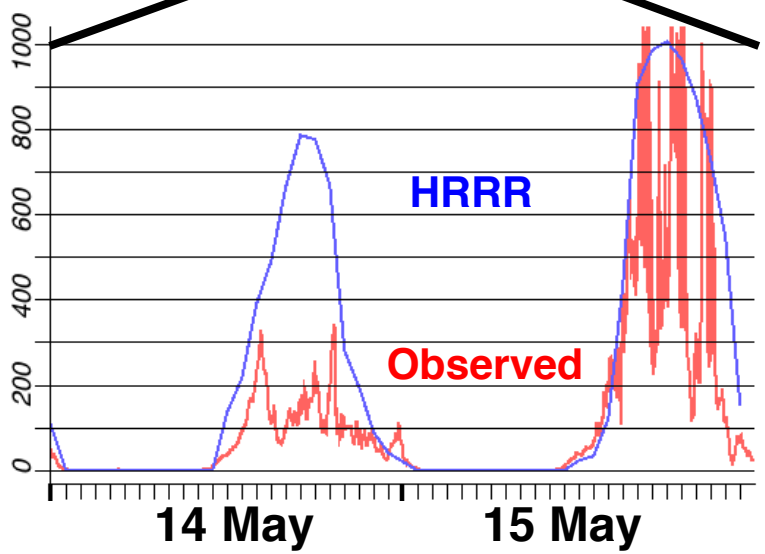
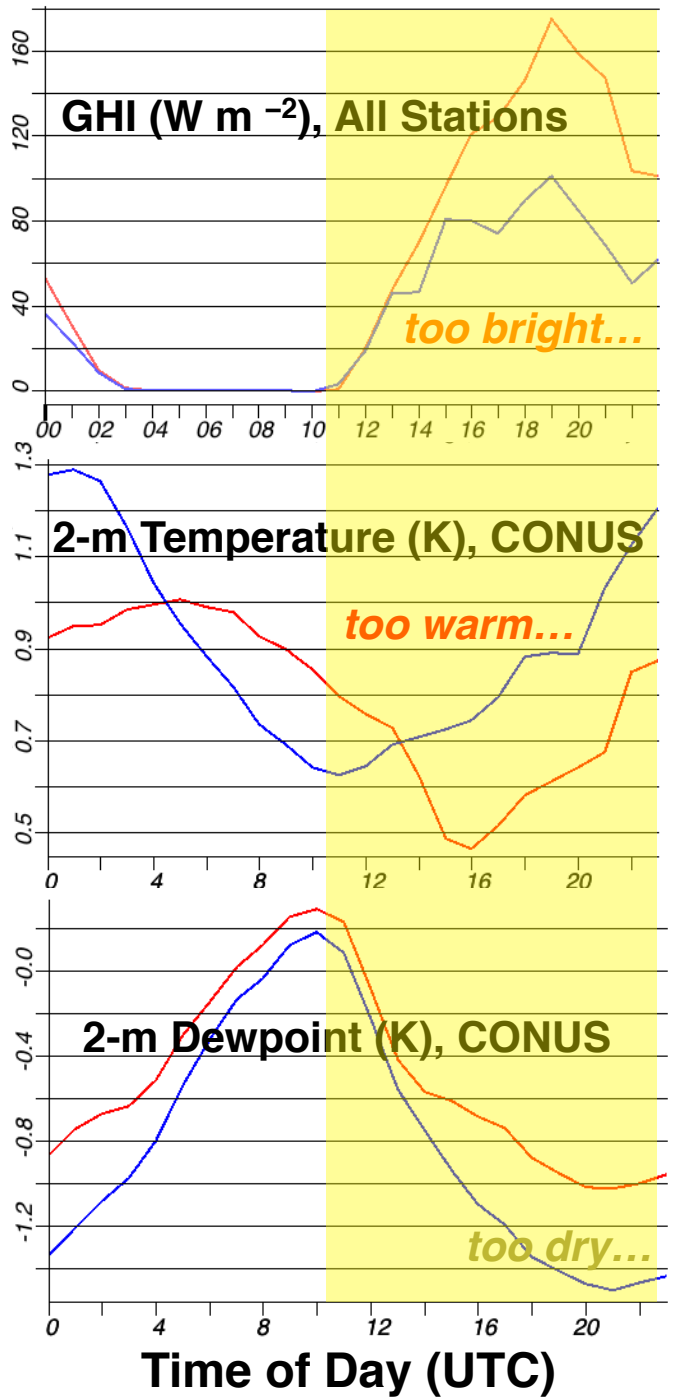






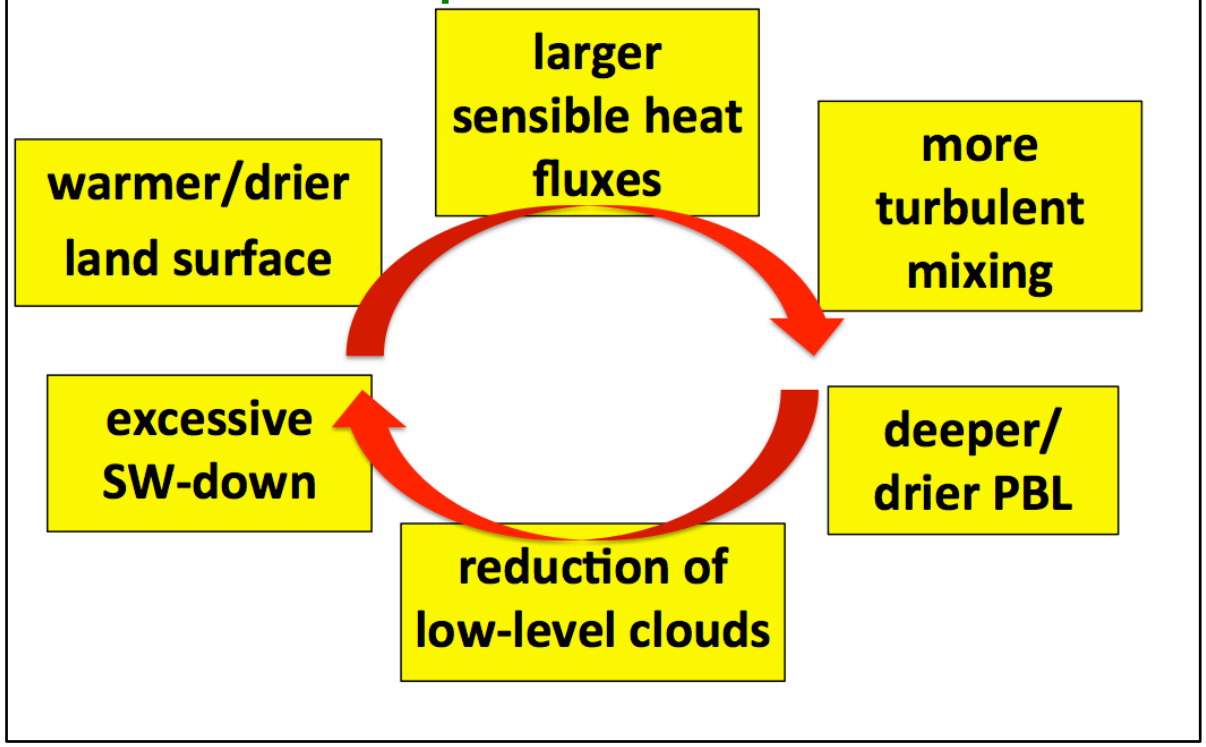
Low-Level Warm–Dry Bias



12-h Forecast Biases, 14–31 May 2014

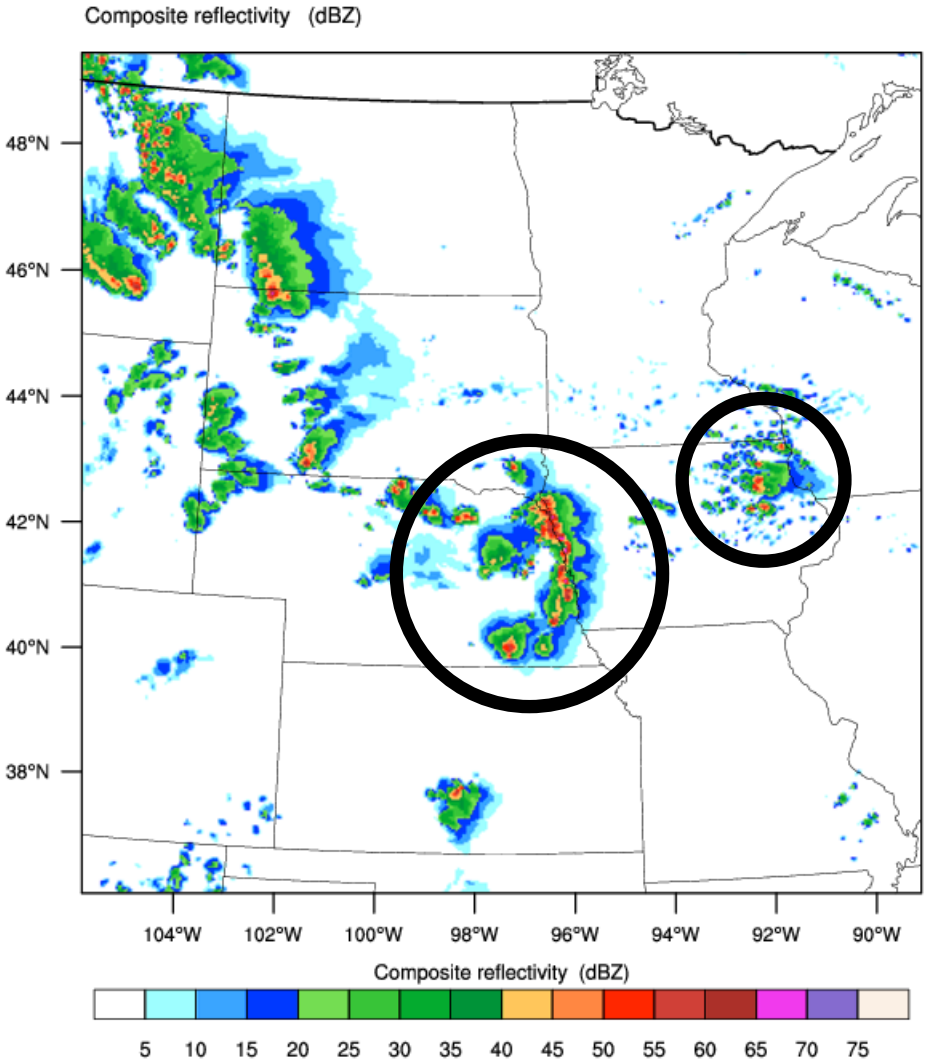
HRRR
RAP

Conceptual Bias Feedback

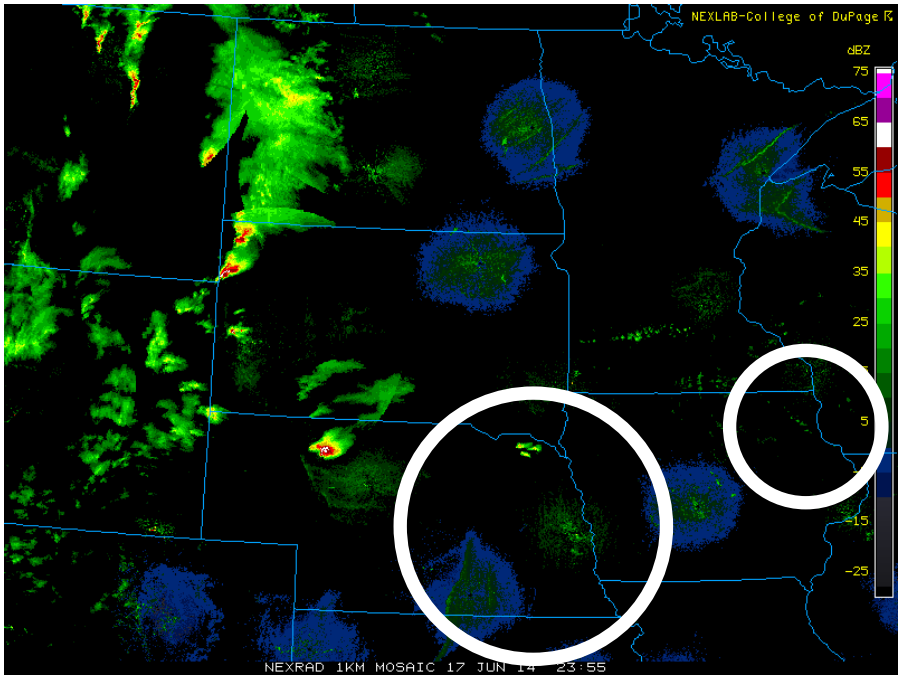


Related Effect: Excessive Deep Convection in HRRR

4-h forecast of composite reflectivity (valid 0000 UTC 18 Jun 2014)



Observed



Source: UCAR

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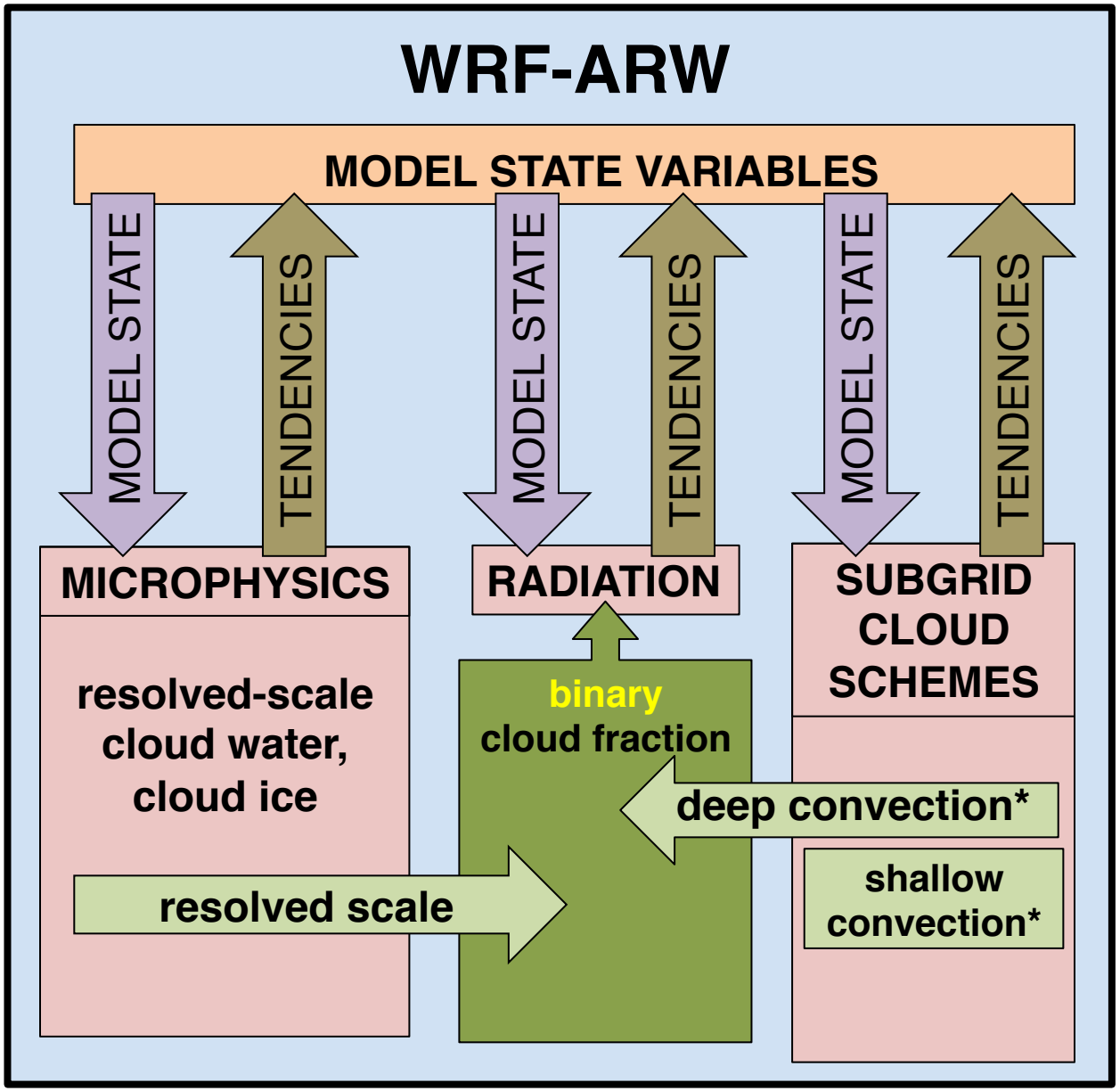

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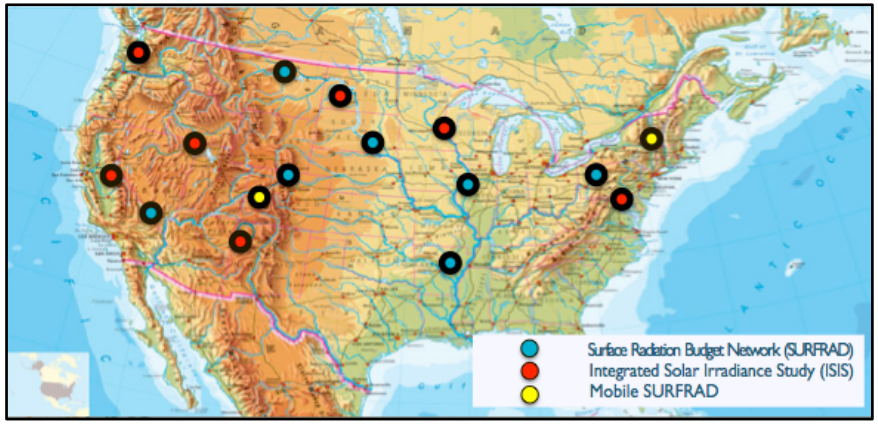

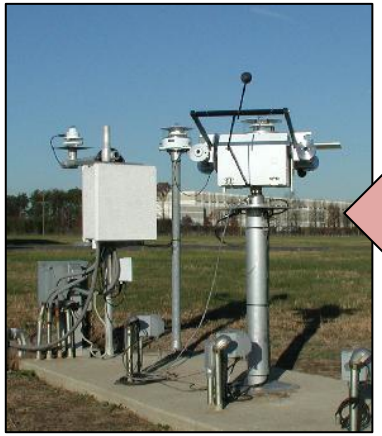

14 SURFRAD / ISIS sites

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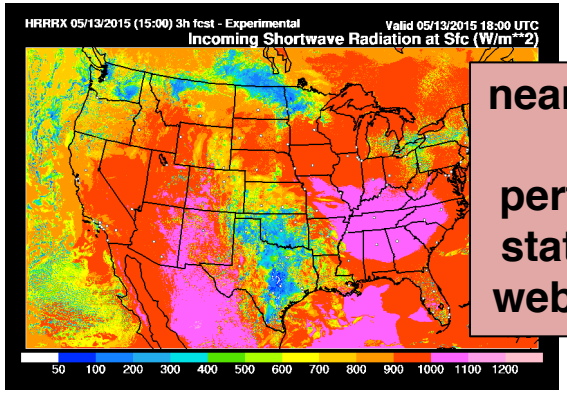

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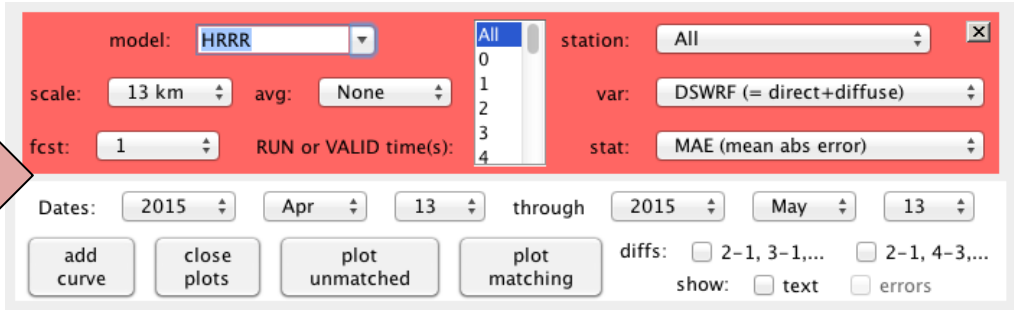

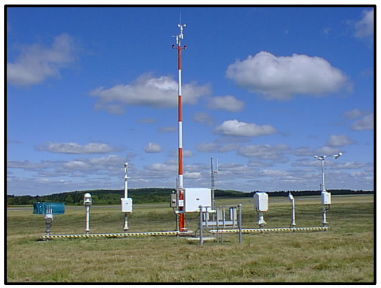

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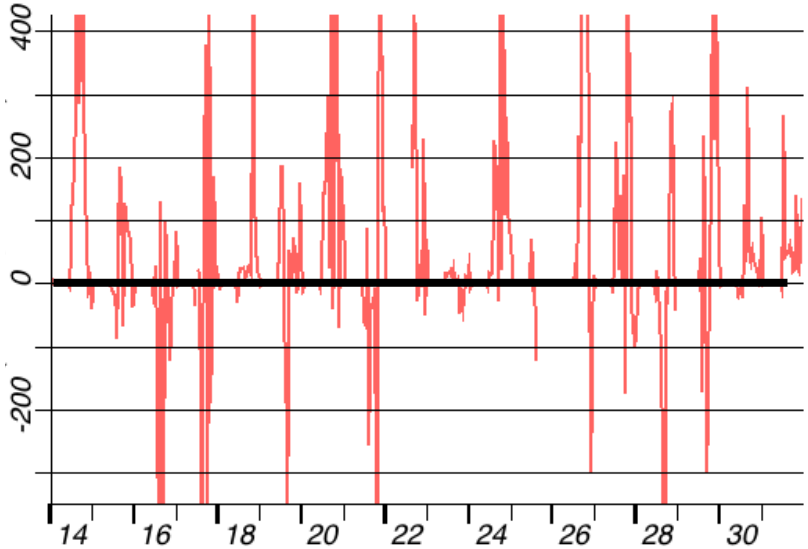
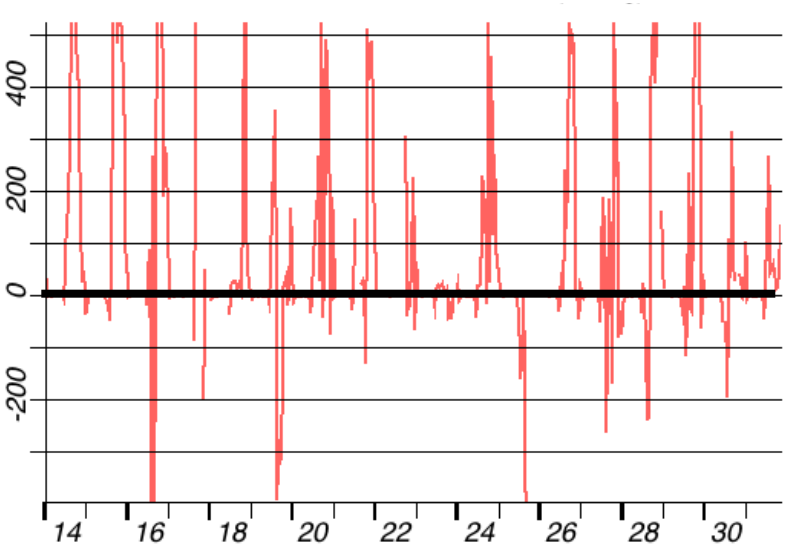


May 2014

HRRR



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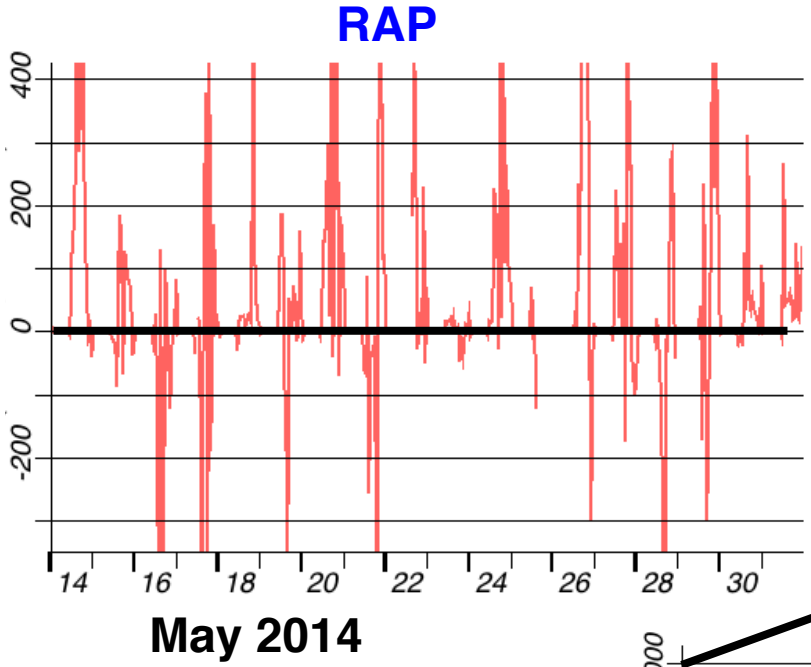

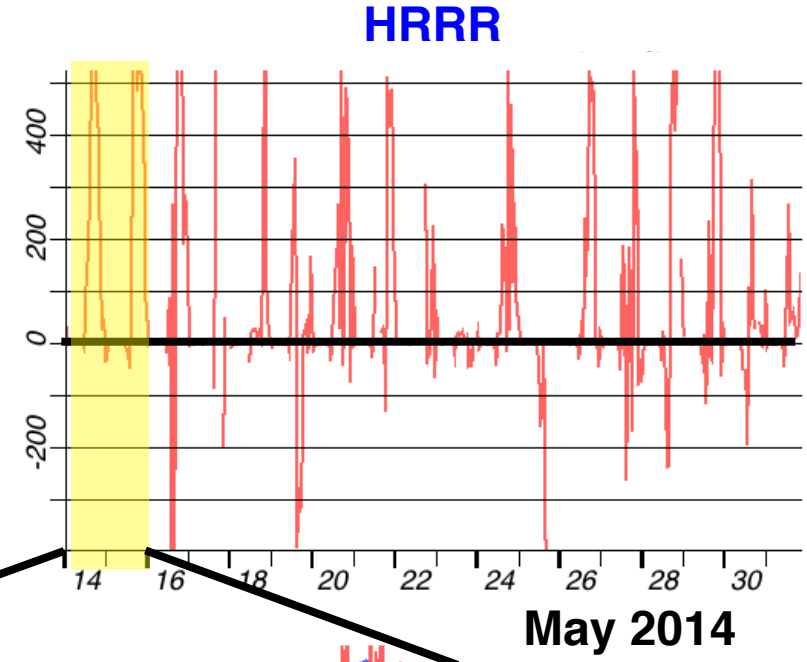

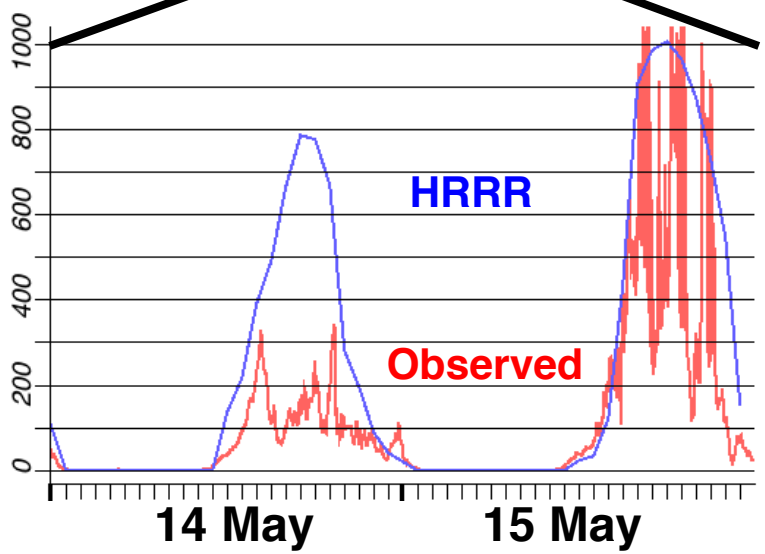

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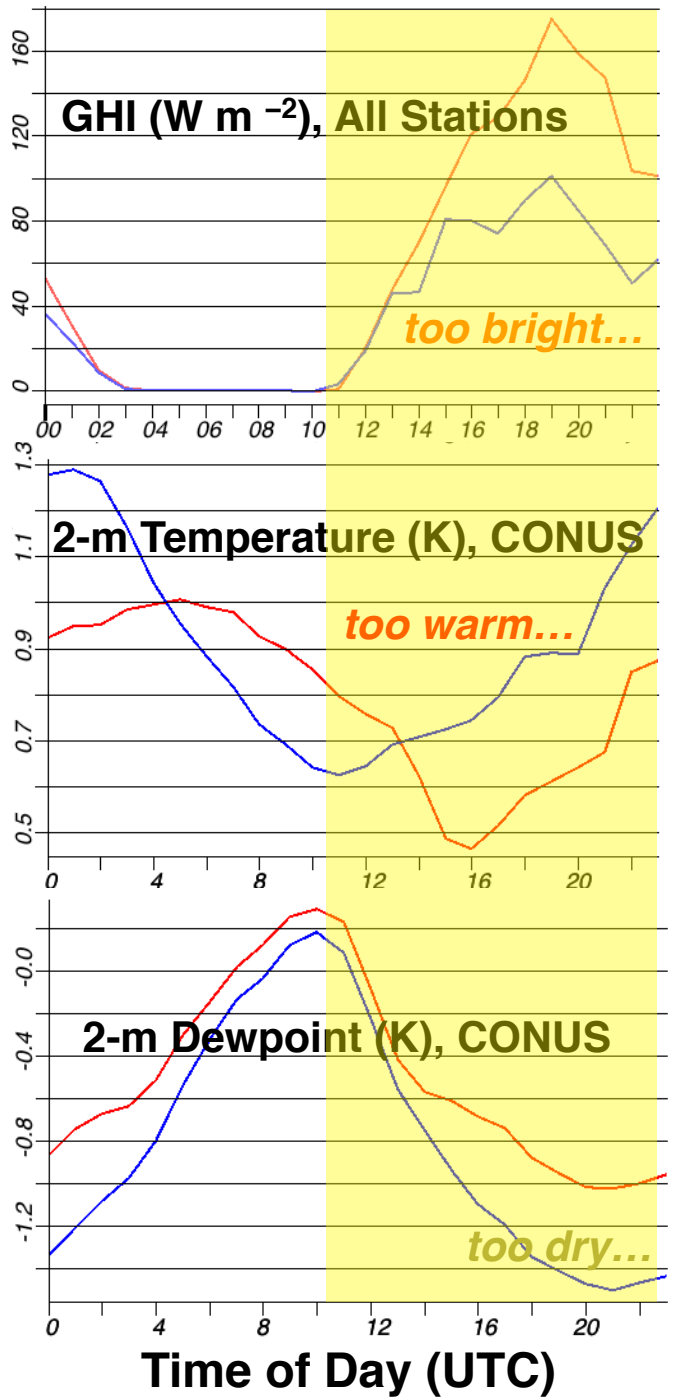
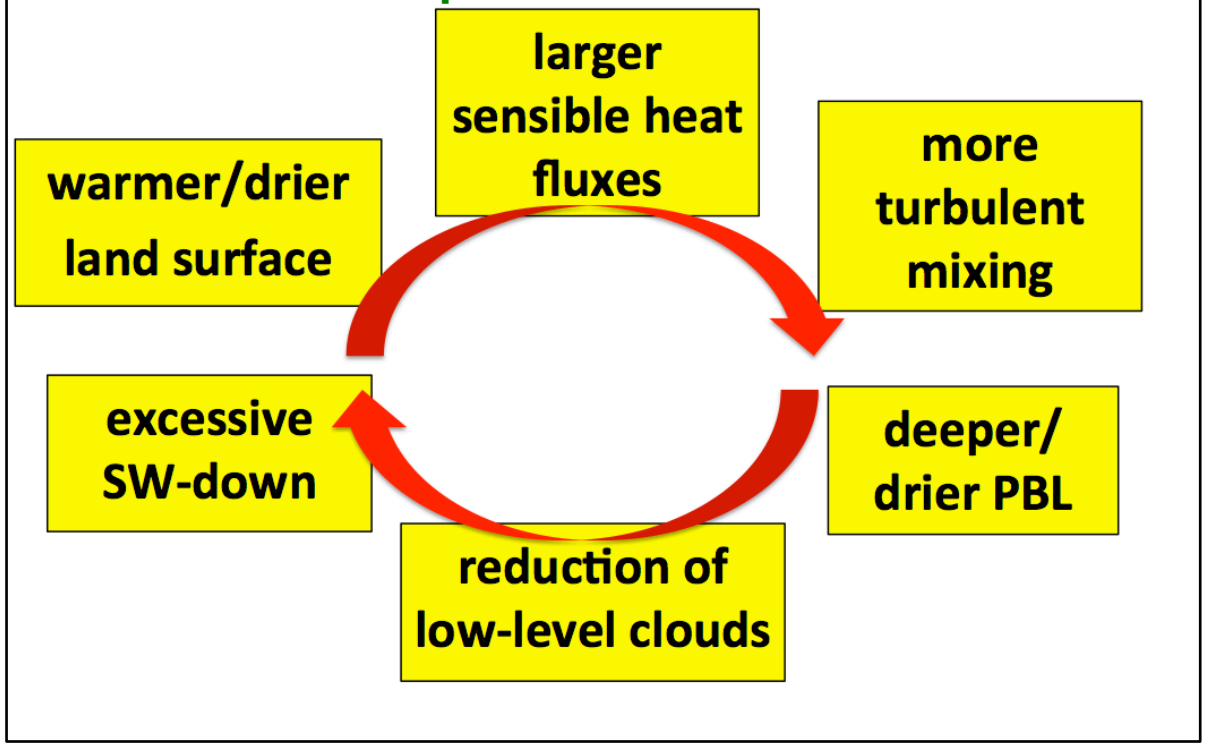


12-h Forecast Biases, 14–31 May 2014

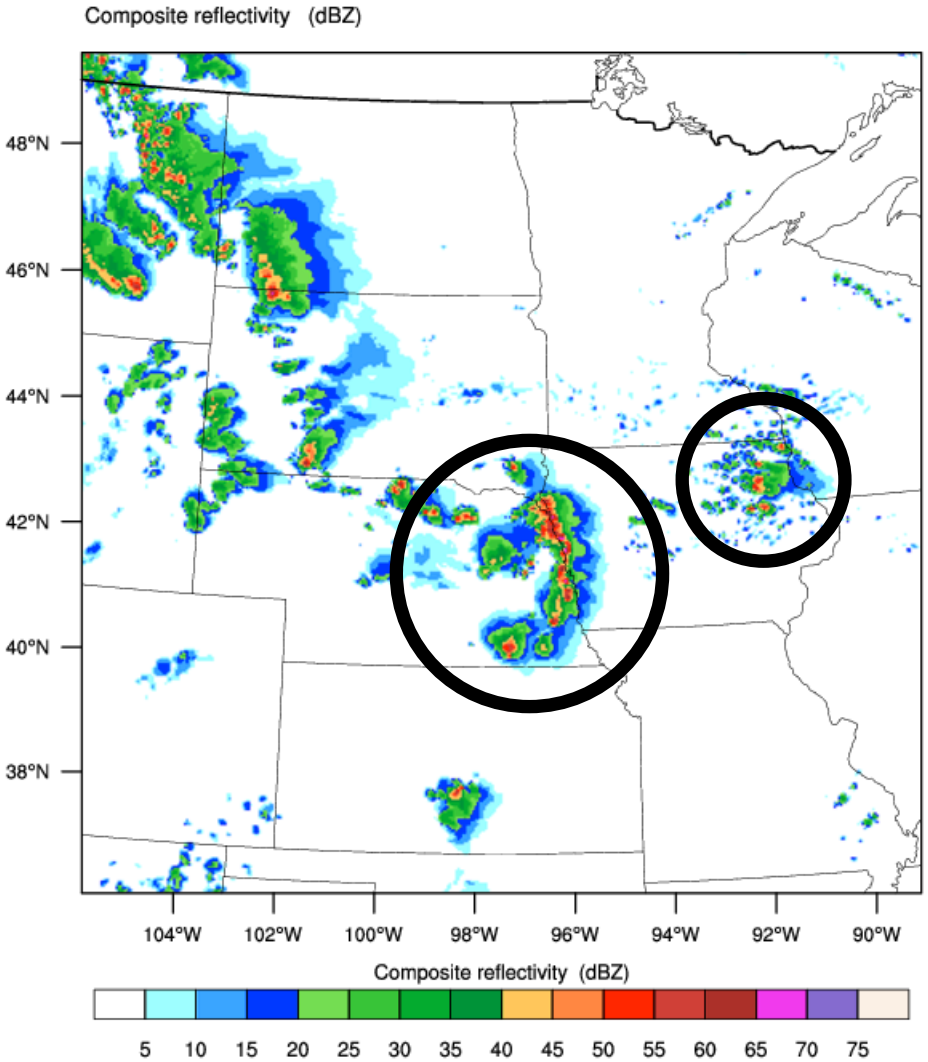
HRRR
RAP

Conceptual Bias Feedback

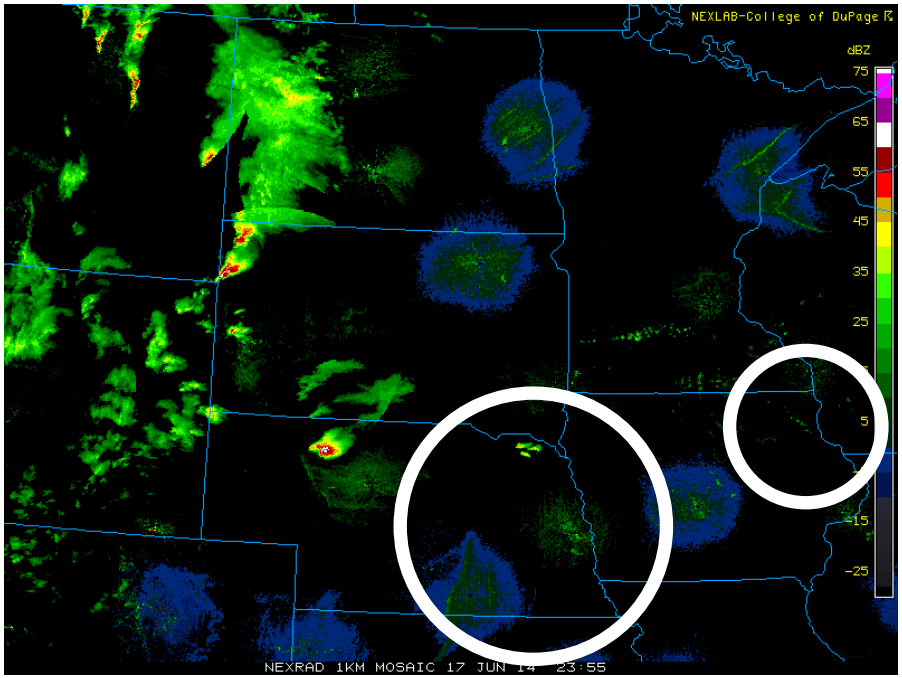


Related Effect: Excessive Deep Convection in HRRR

4-h forecast of composite reflectivity (valid 0000 UTC 18 Jun 2014)



Observed



Source: UCAR

Successful RAP / HRRR Bias Mitigation Strategies

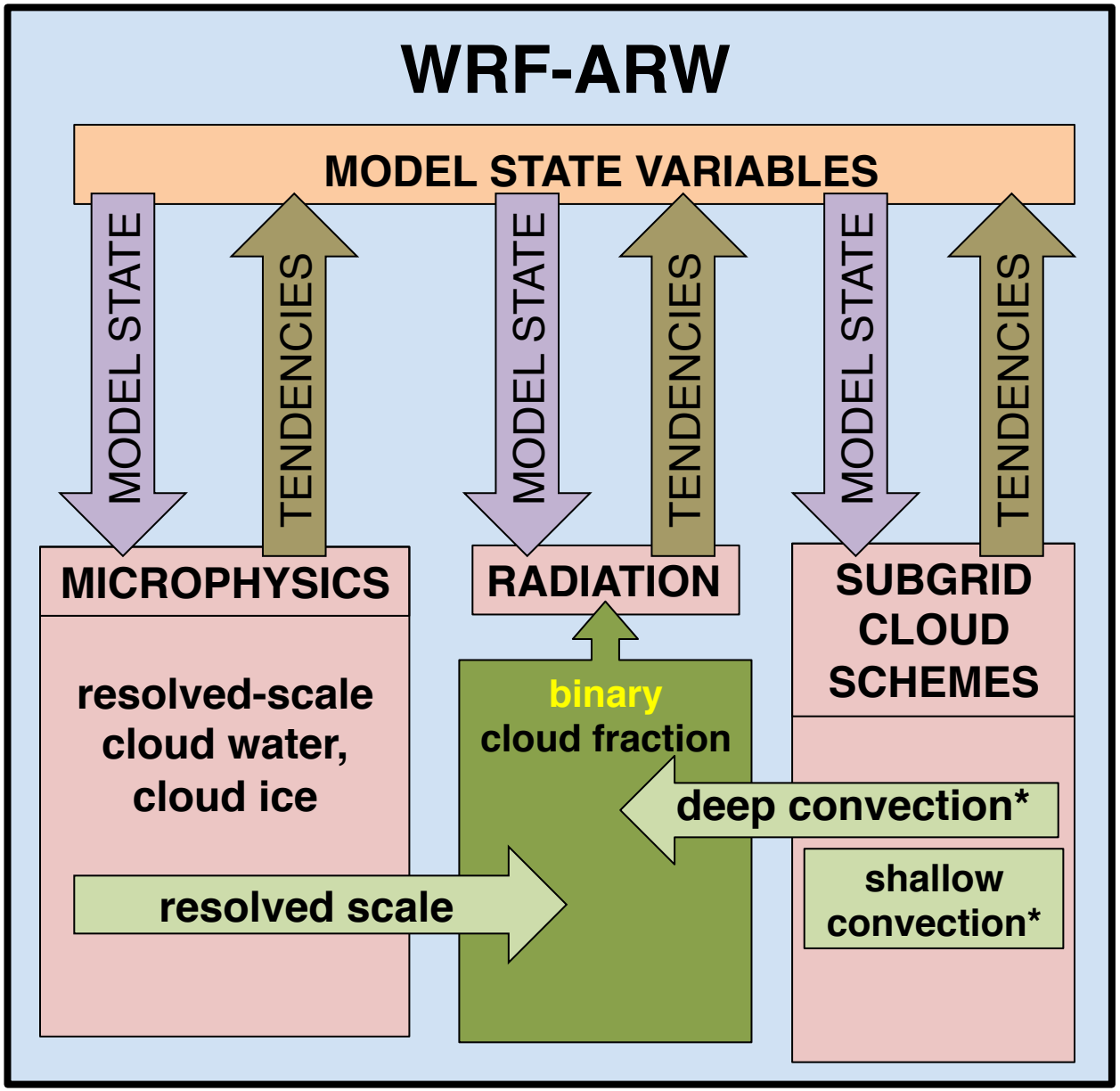
- **(1) Modify the RUC land-surface model (RUC-LSM)**
  - Reduce vegetation wilting points
  - Prevent wilting of cropland areas (i.e., “parameterize” irrigation)

- **(2) Improve the parameterization of subgrid-scale shallow cumulus**

  ➔ and fully couple to radiation

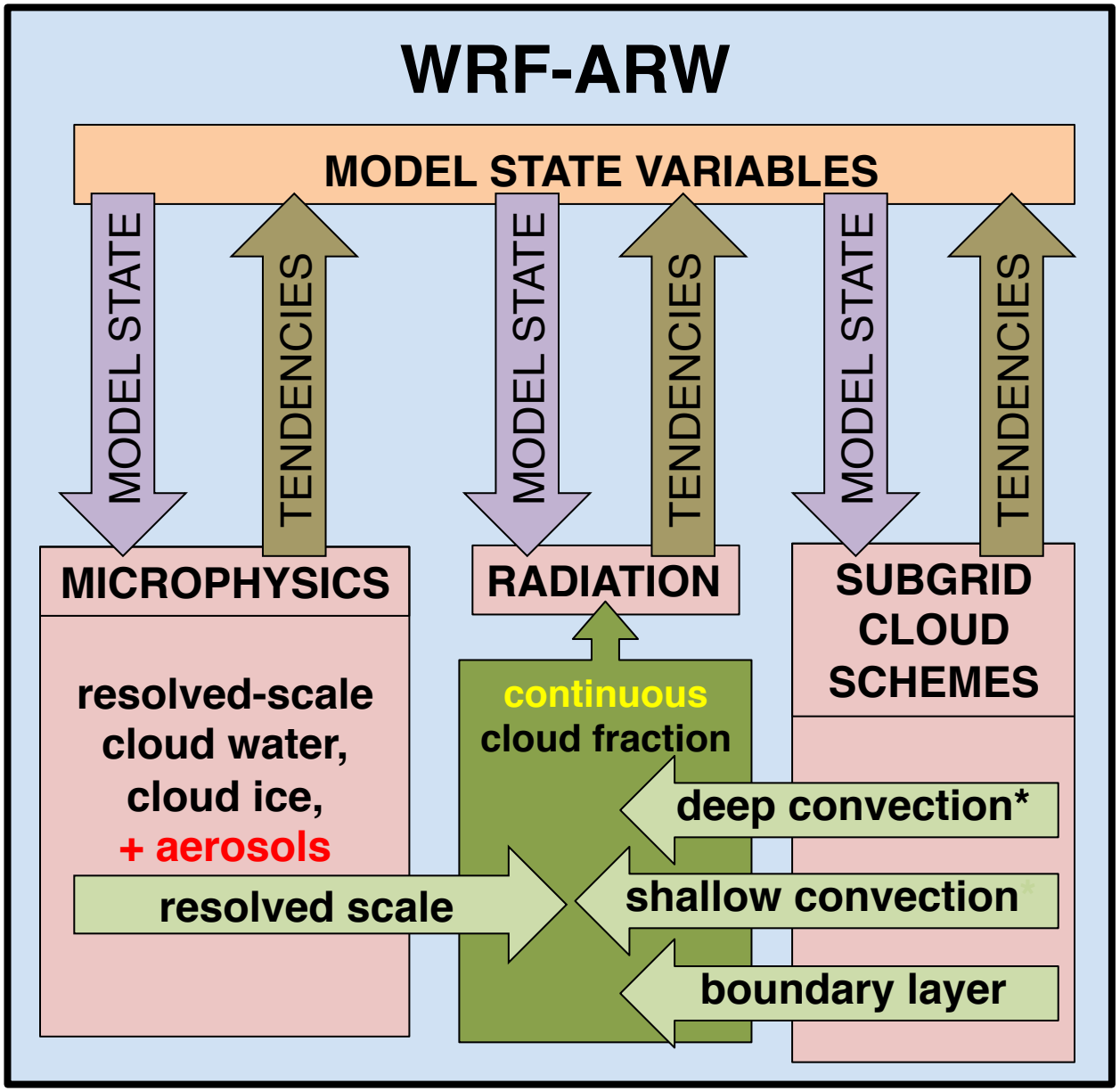
  - Develop Grell–Freitas–Olson shallow cumulus scheme
  - Develop a supplemental cloud fraction (in PBL scheme) for passive-phase (“forced”) shallow cumulus and stratus clouds

RAP / HRRR Cloud Representation: Recent Past



*RAP only

RAP / HRRR Cloud Representation: New Approach



"Deep" Convection

"Shallow" Convection

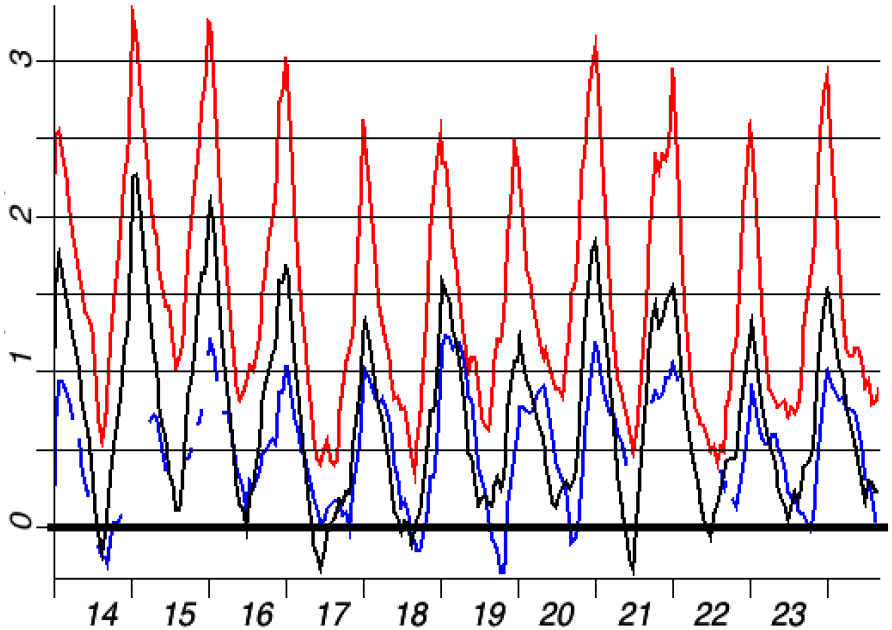
*RAP only

Stratus

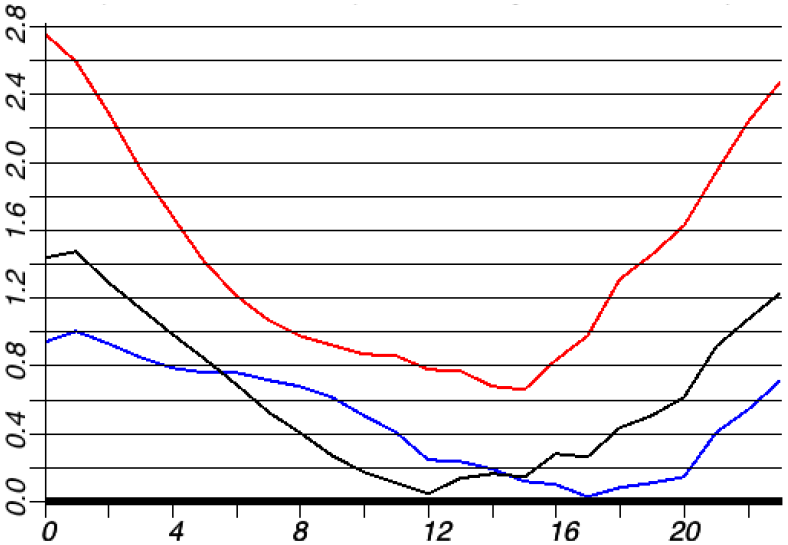
Results: Improved Low-Level Temperature Forecasts

2-m Temperature Bias (K), 12-h Forecasts, CONUS

Control (Unmodified)
w/ Improved Subgrid Clouds
w/ Improved Subgrid Clouds and Land Surface



August 2014

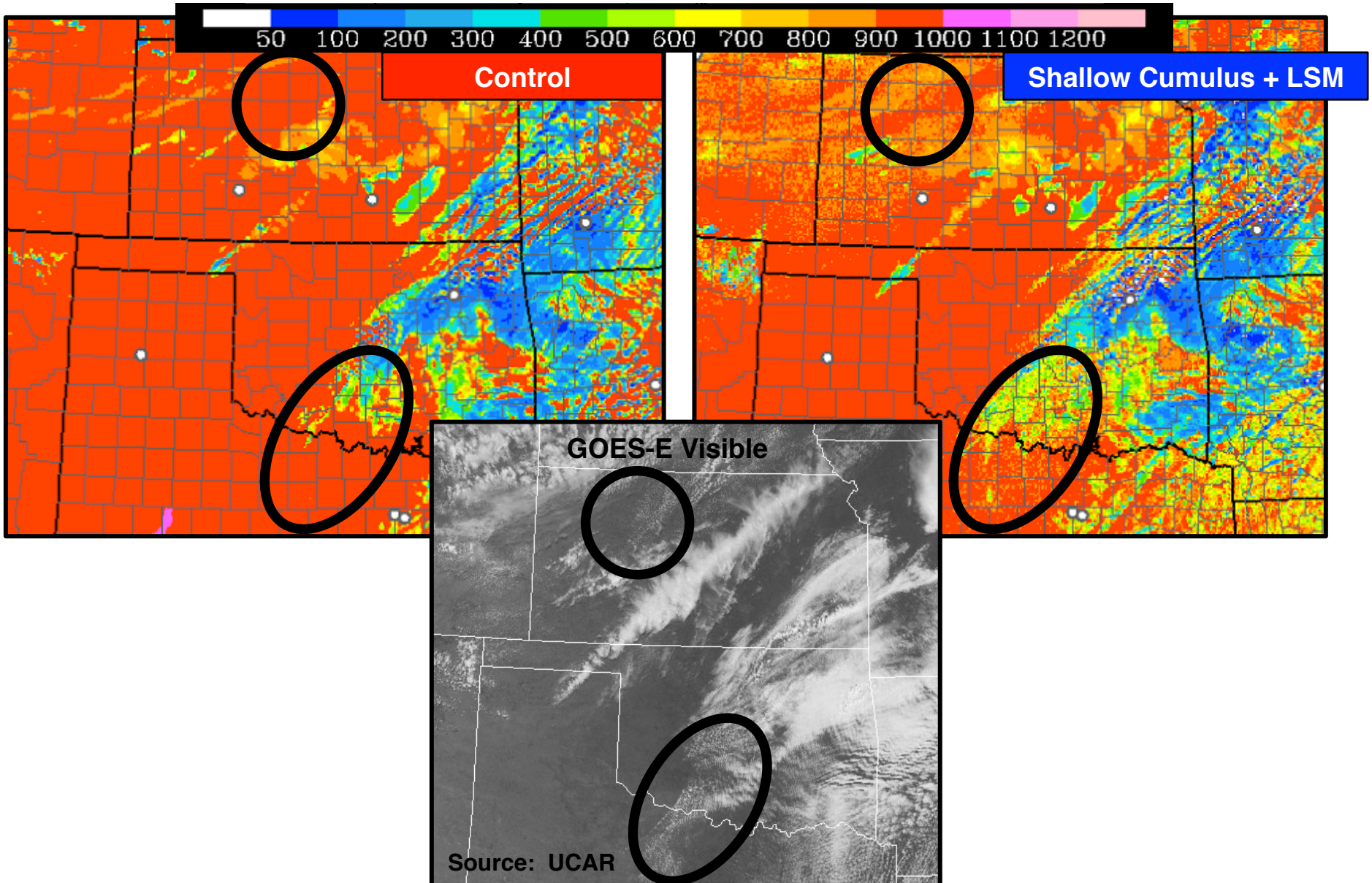


Time of Day (UTC)

~2-K reduction in late-afternoon warm bias; smaller diurnal bias variation

Results: Improved Cloud Representation

8-h forecasts of surface GHI (W m^{-2}) valid 1700 UTC 20 May 2013



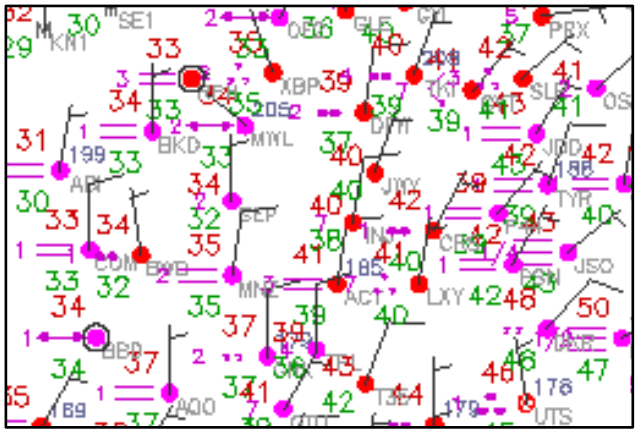
Conclusions

- SURFRAD / ISIS measurements from GMD have facilitated RAP / HRRR model improvements

- New physical parameterizations will provide
  (1) **better RAP / HRRR solar irradiance and cloud ceiling forecasts**

  (2) **better RAP / HRRR forecasts overall**

  (3) **improved internal model physics**
  Applicable to regional /short-range but also Global NWP to seasonal prediction



- Ongoing & future work will:
  - Consolidate disparate cloud schemes
  - Develop prognostic cloud representations
  - Improve “scale-aware” aspects for finer model grid spacing

Summary: RAPv3 vs. RAPv2

Winds -- Consistent RAPv3 improvement for both upper-air and surface, for all seasons

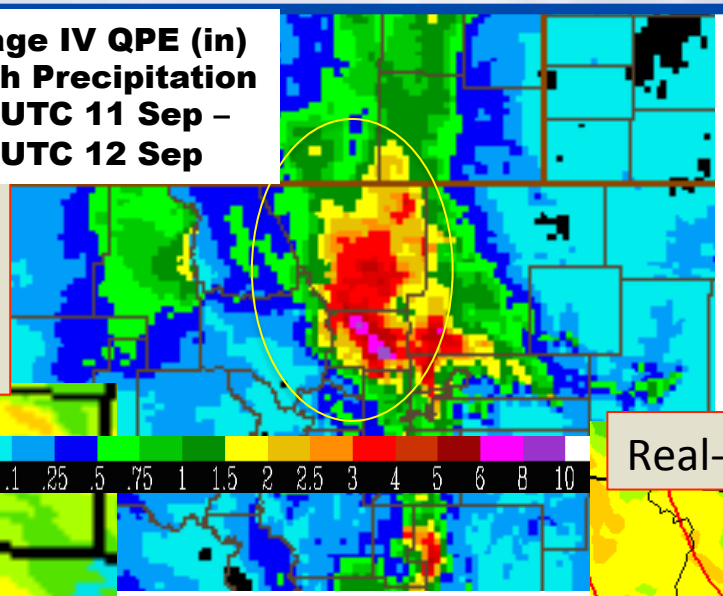
Temperature – Reduced low-level warm bias for warm season afternoon / evening. Improved upper-level temperature forecasts

Moisture – Reduced low-level dry bias for warm season afternoon / evening. Improved upper-level relative humidity forecast

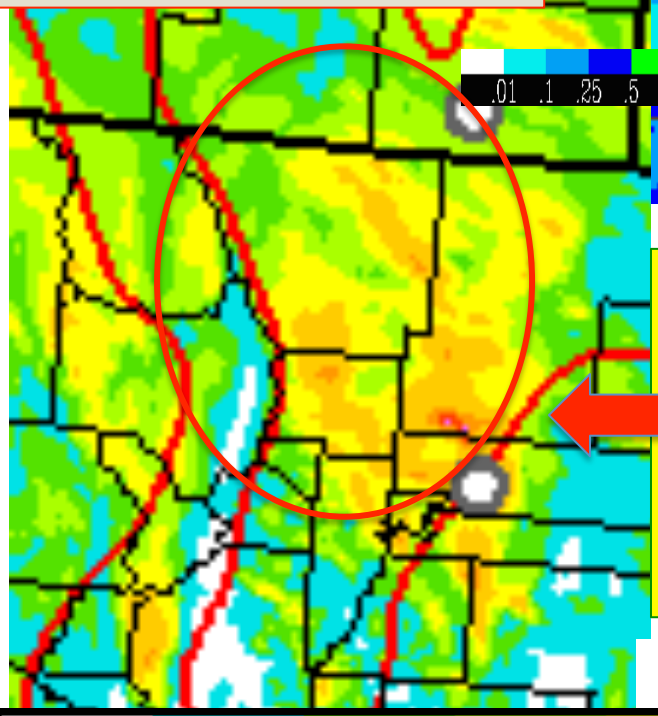
Precipitation – Slight improvement, reduced low thresh high bias / increased high thresh low bias

HRRR – Colorado Sept 2013 Flood Case

Stage IV QPE (in)
24-h Precipitation
12 UTC 11 Sep –
12 UTC 12 Sep

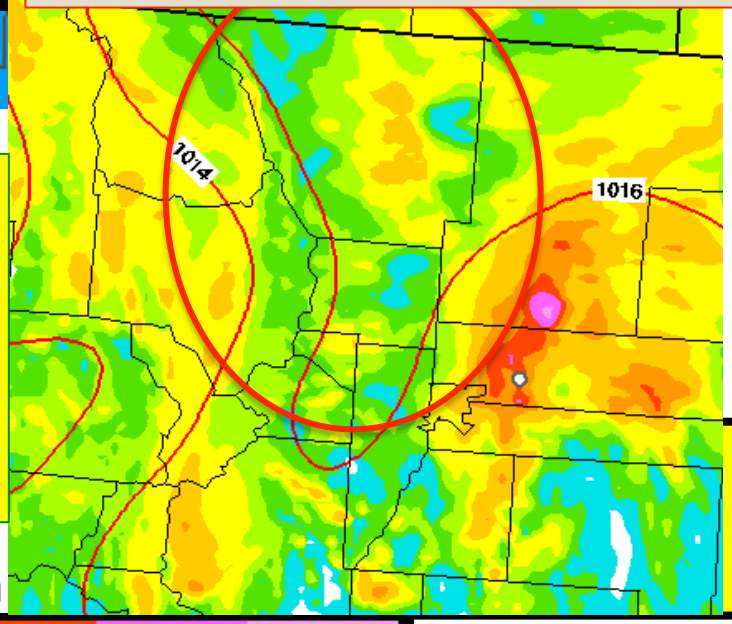


Control
Rerun – 2014 version
Init 18z 11 Sep
Valid 09z 12 Sep



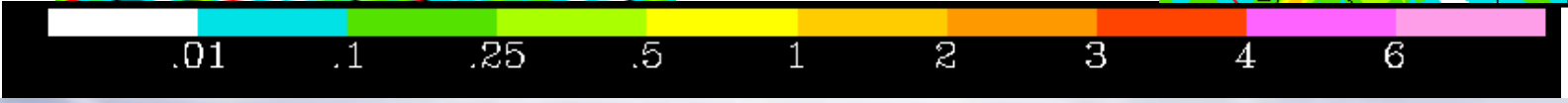
Real-time HRRR
Init 18z 11 Sep
Valid 09z 12 Sep

Real-time – not HRRR's finest hour



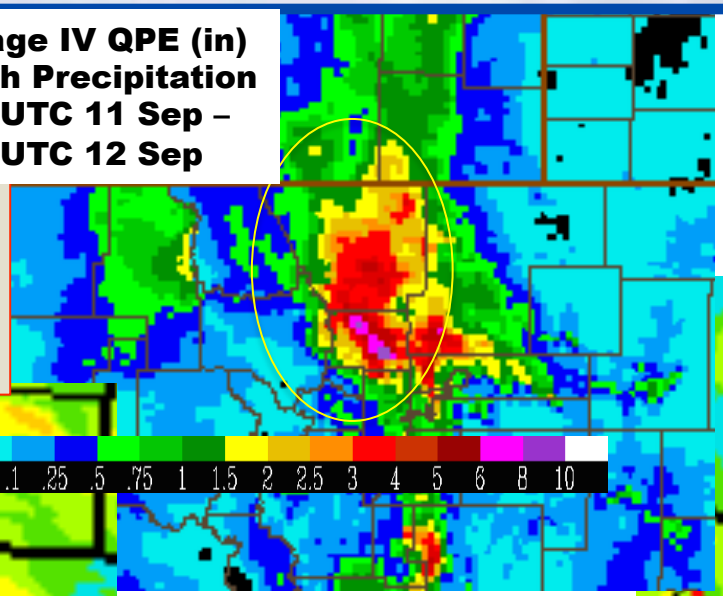
Major improvement for Colorado flood case with 2014 improvements to RAP-scale ensemble and radar assimilation

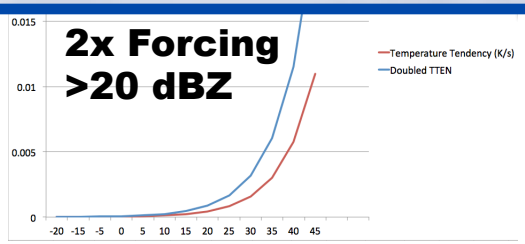
15-h precipitation



HRRR – Colorado Sept 2013 Flood Case

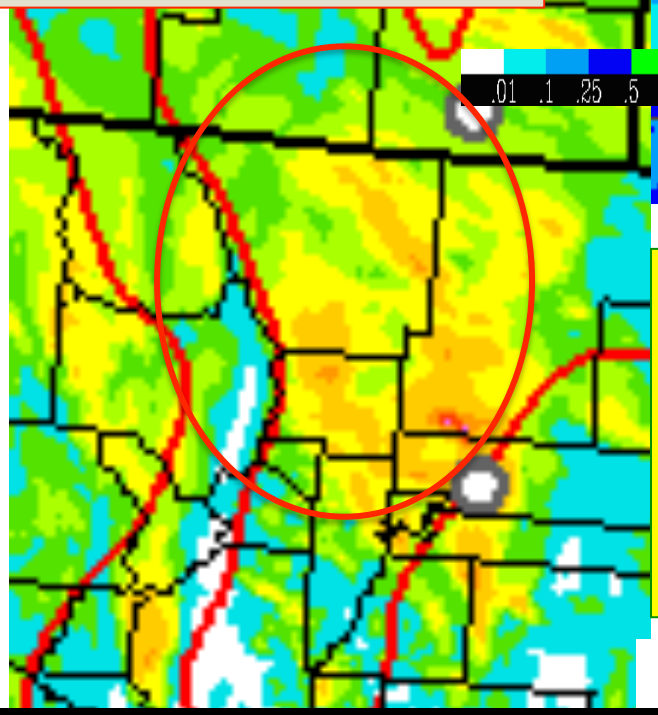
Stage IV QPE (in)
24-h Precipitation
12 UTC 11 Sep –
12 UTC 12 Sep

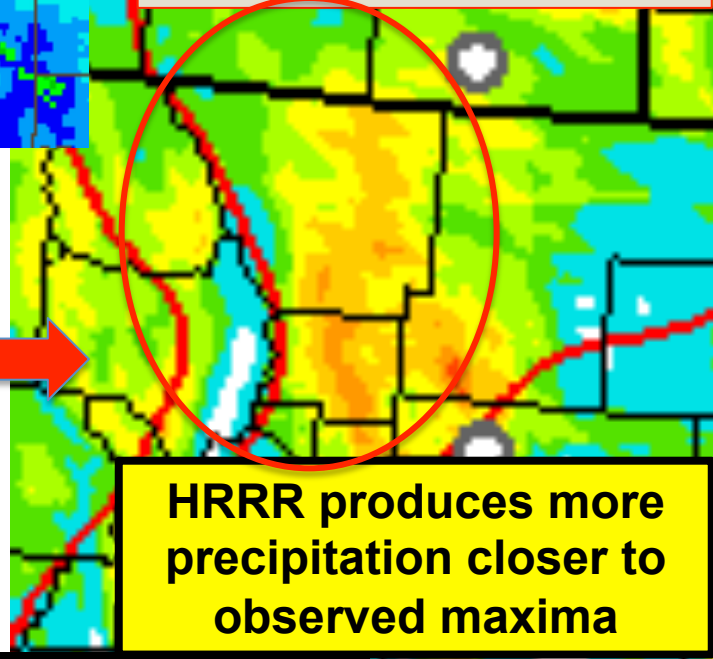




Control
Rerun – 2014 version
Init 18z 11 Sep
Valid 09z 12 Sep

"Warm Rain" HRRR
Init 18z 11 Sep
Valid 09z 12 Sep





Further improvement
Use warm-rain ZR - change to 2x heating – stronger accurate focus on Boulder and Larimer Counties.

15-h precipitation

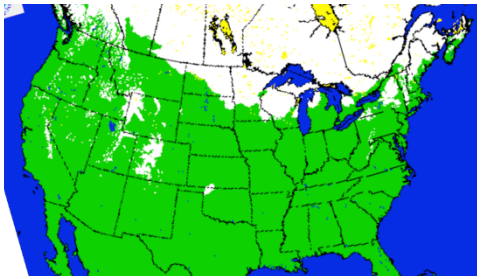
HRRR produces more precipitation closer to observed maxima

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).

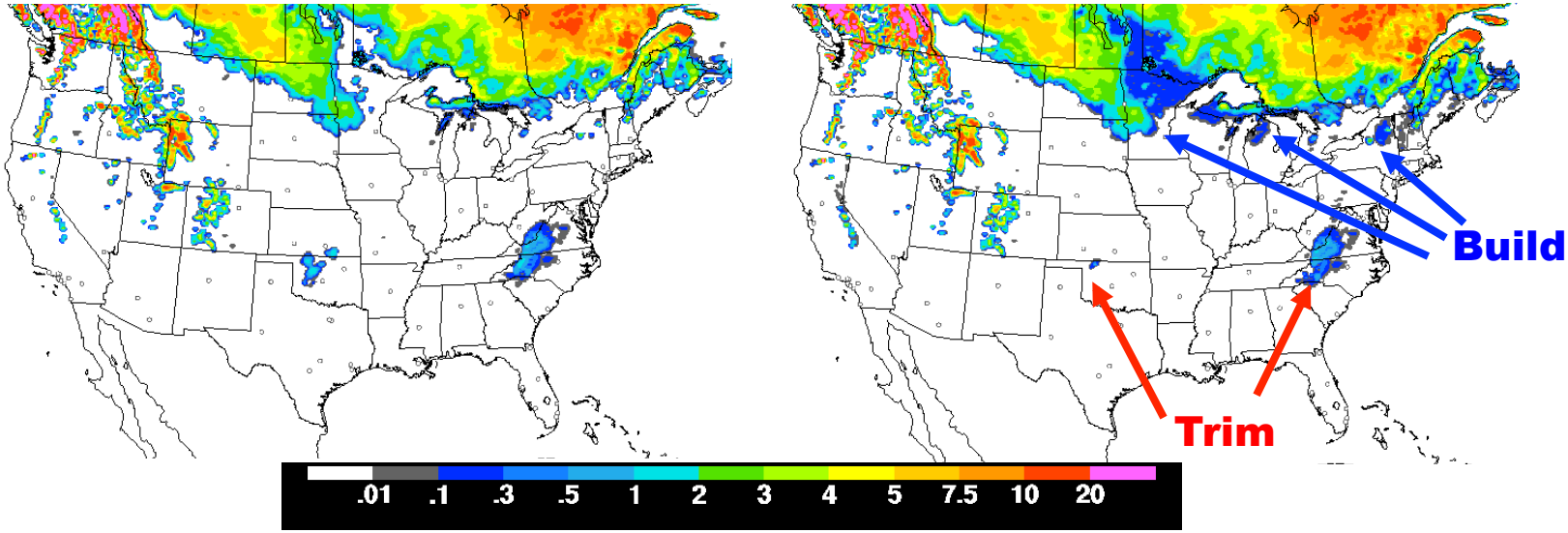
IMS Surface Snow Water Equivalent
Valid 0000 UTC



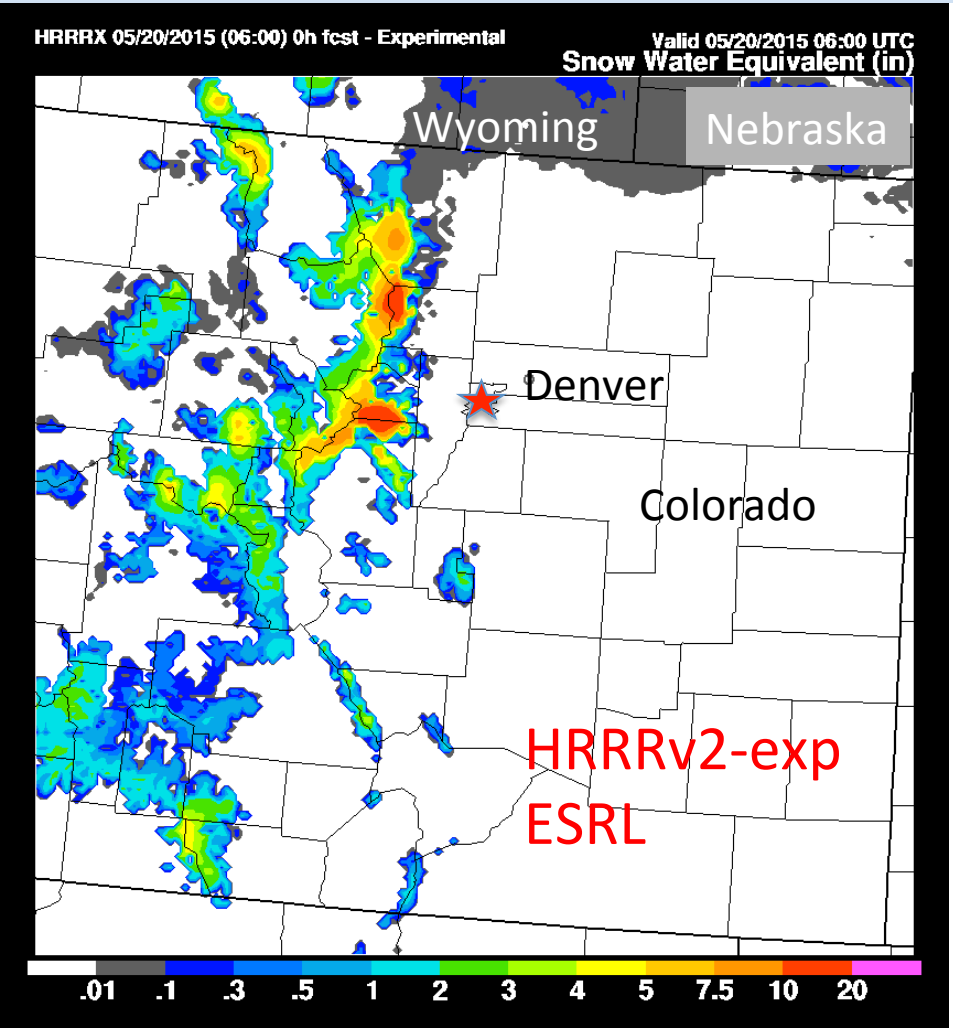
Model Surface Snow Water Equivalent
Valid 0000 UTC

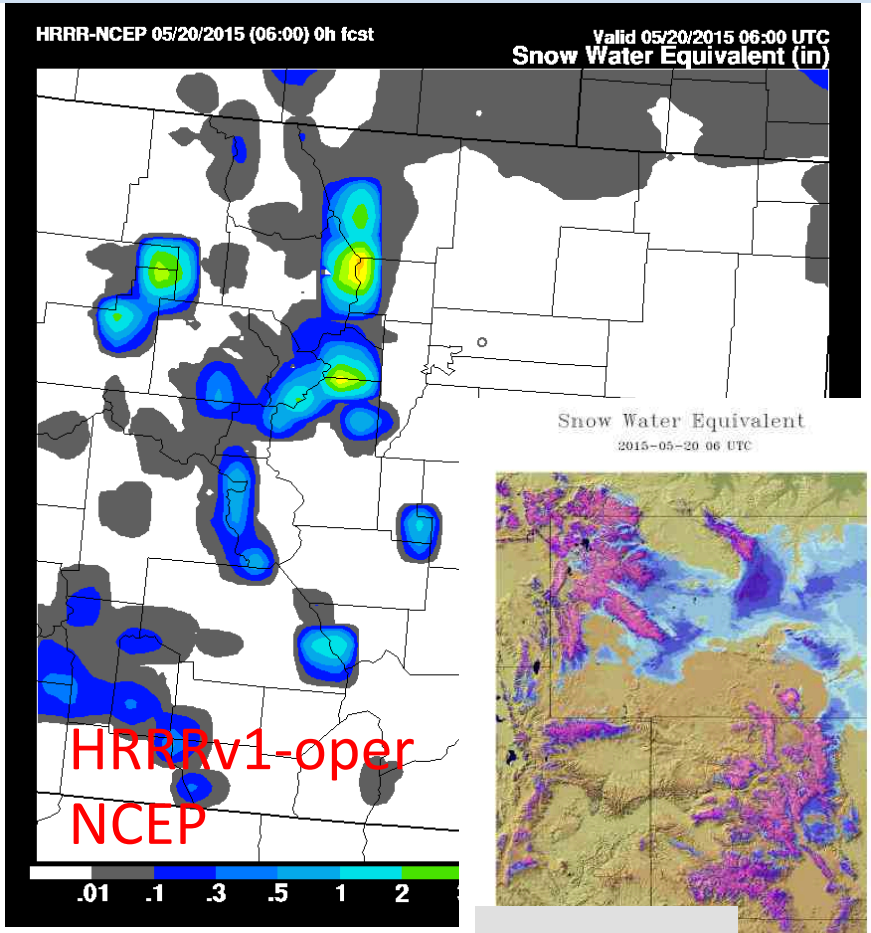
Before NOAA IMS snowcover update

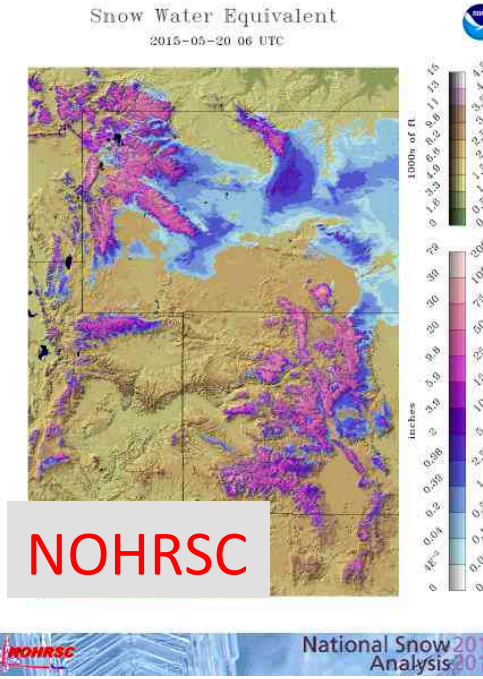
After NOAA IMS snowcover update



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







Snow water equivalent – 06z 20 May 2015 – inches

ESRL RAPv2 and HRRR 2013

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	CONUS	1799 x 1059	3 km	50	20 mb	RAP	Hourly - RAP (no-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 9-lev
HRRR	WRF-ARW v3.4.1+	GSI 3D-VAR	3-km 15-min LH	RRTM/ Goddard	Thompson v3.4.1	None	MYNN	RUC 9-lev

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	10 min	MODIS Fractional	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	No	5 min	MODIS Fractional	0.07 K/s	20 s

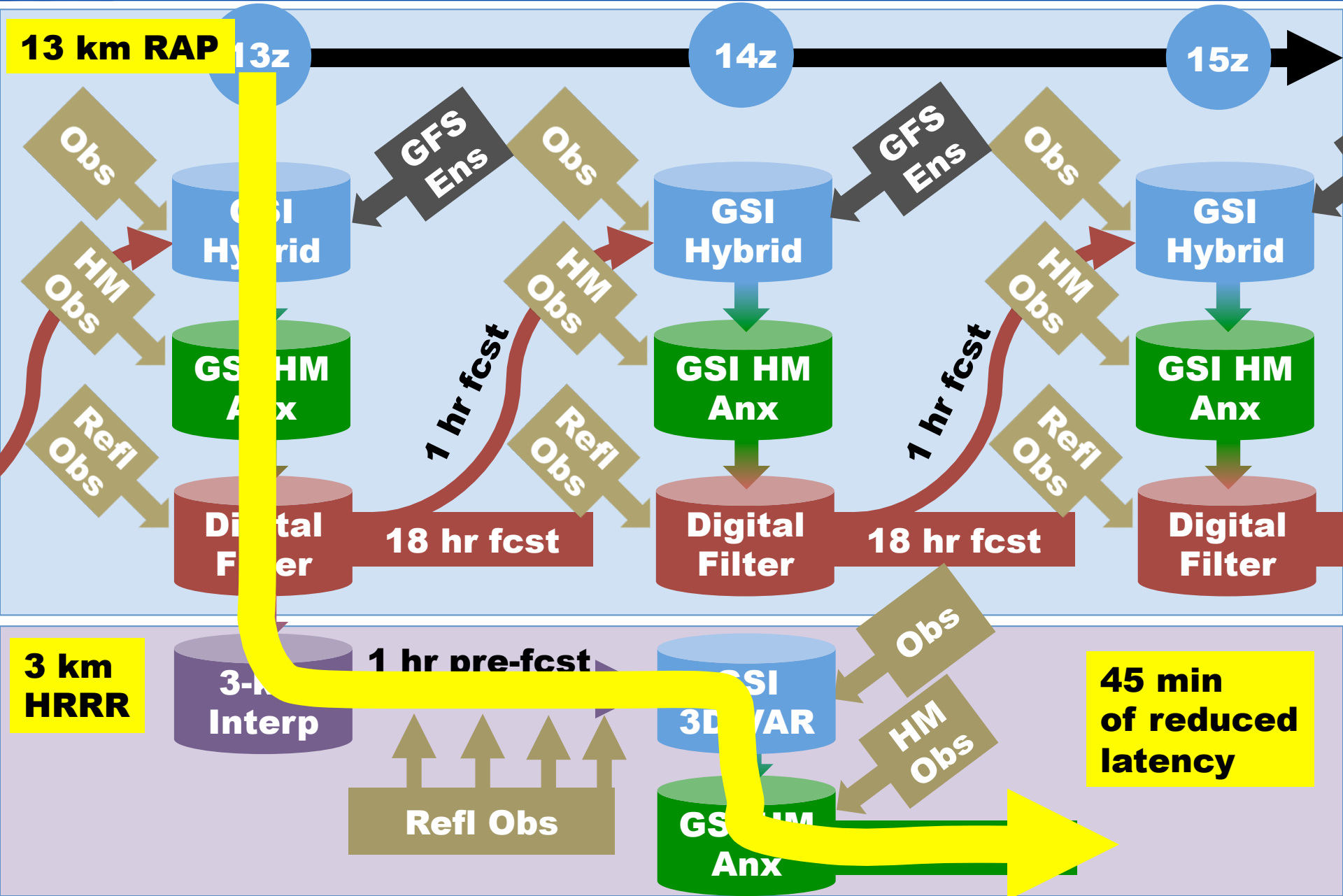
NCEP RAPv3 and HRRRv2 2015

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	CONUS	1799 x 1059	3 km	50	20 mb	RAP	Hourly - RAP (no-cycle)

Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.6.1+	GSI Hybrid 3D-VAR/Ensemble	13-km DFI	RRTMG/ RRTMG	Thompson – aerosol-aware v3.6.1	GF – v3.6.1	MYNN v3.6.1	RUC 9-lev v3.6.1
HRRR	WRF-ARW V3.6.1+	GSI 3D-VAR/ Ensemble	3-km 15-min LH	RRTMG/ RRTMG	Thompson – Aerosol-aware v3.6.1	None	MYNN	RUC 9-lev v3.6.1

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 Fractional	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 (Ruiz-Arias)	MODIS Fractional	0.07 K/s	20 s

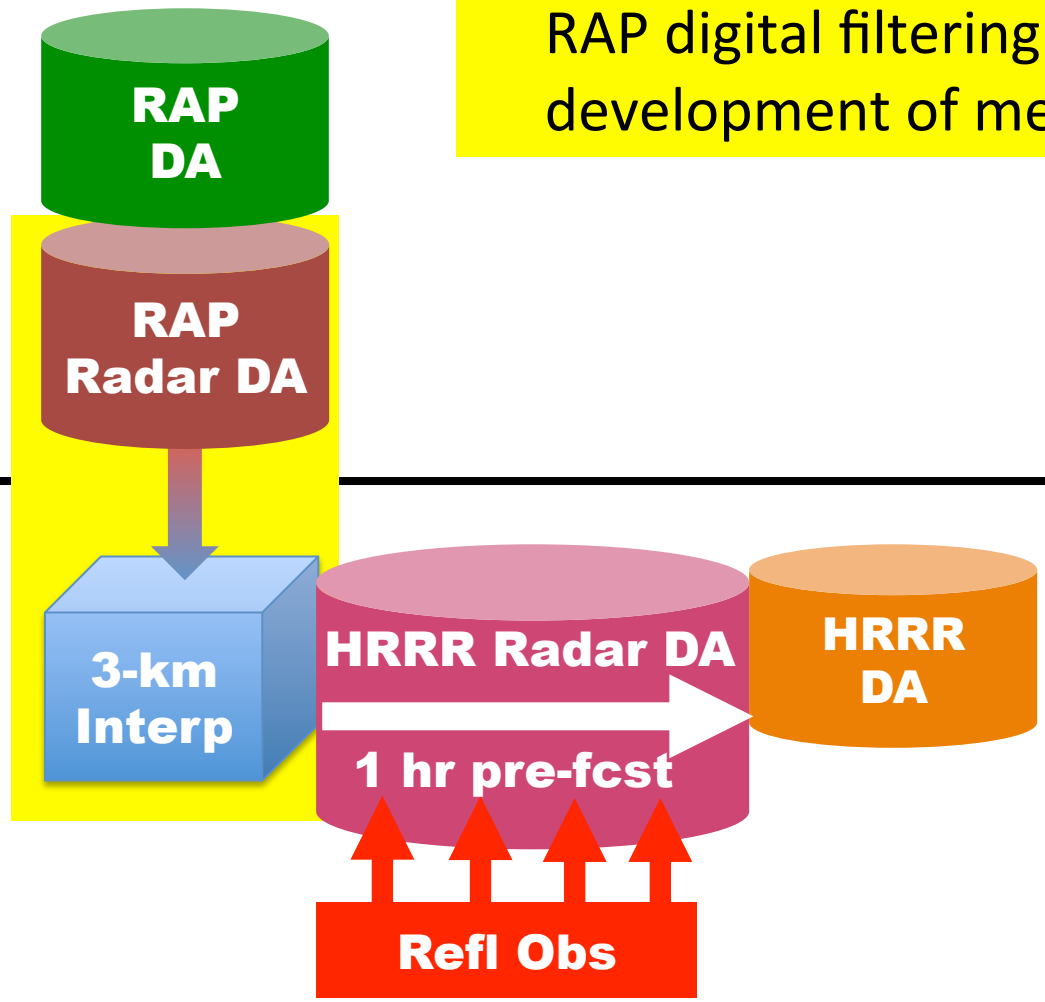
2013 HRRR Initialization from RAPv2



Breakdown of the Analysis Components

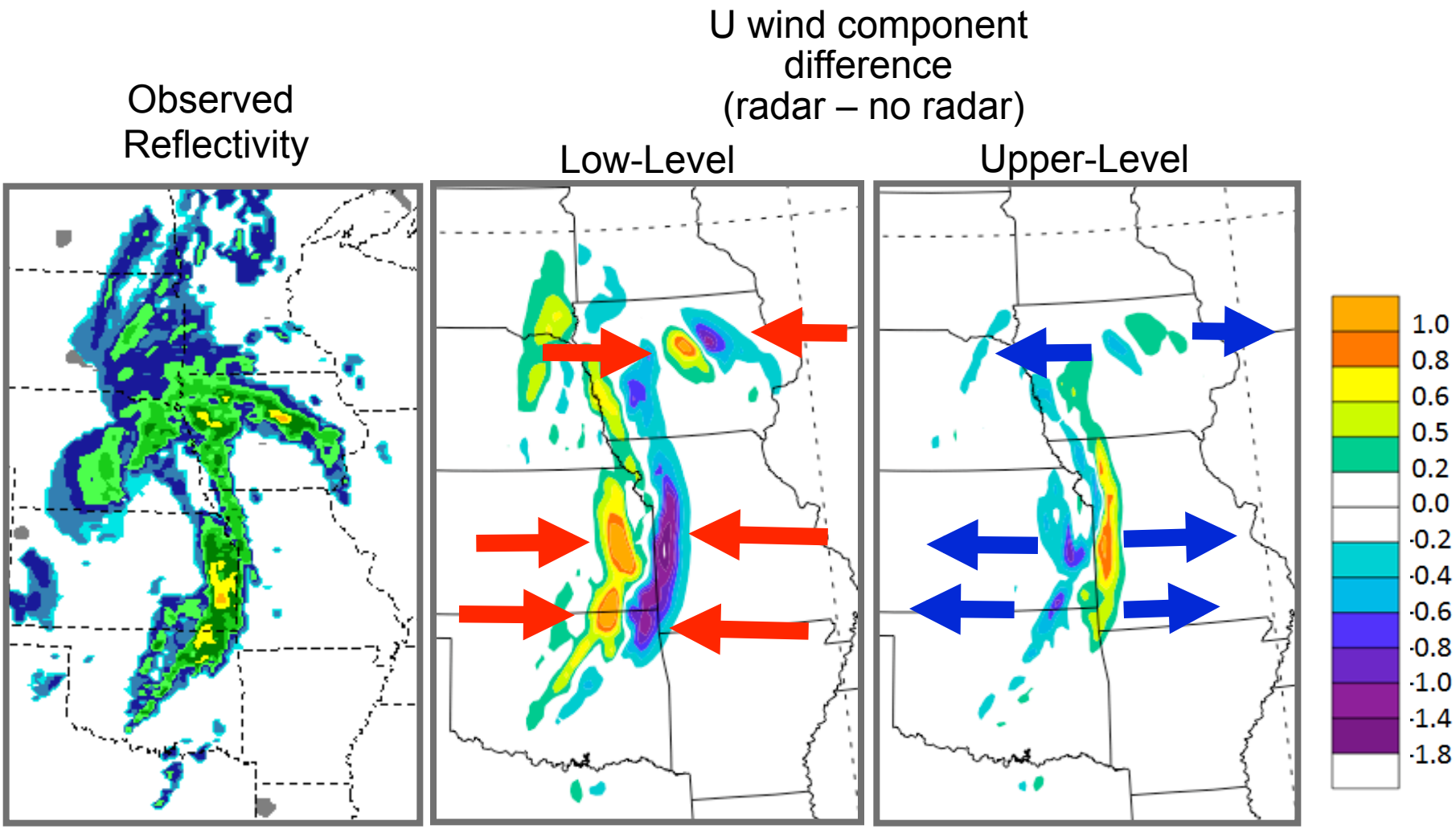
13 km RAP

1. Radar data assimilation at 13 km in the RAP digital filtering promotes the development of mesoscale circulations.



3 km HRRR

What is the impact of the radar DA in the RAP?



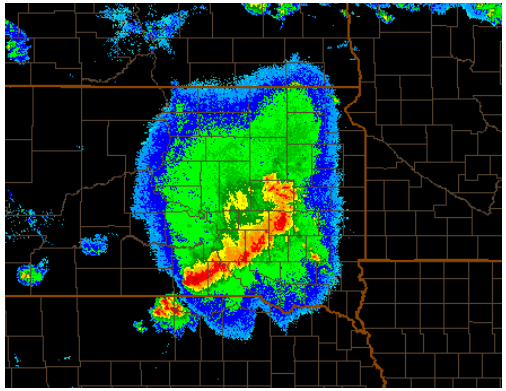
1400 UTC
22 Oct 2008
Z = 3 km

Enhanced Convergence

Enhanced Divergence

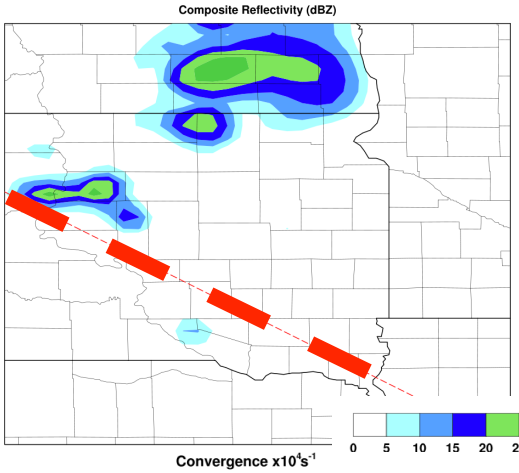
What is the impact of the RAP radar DA in the HRRR?

Observed Reflectivity

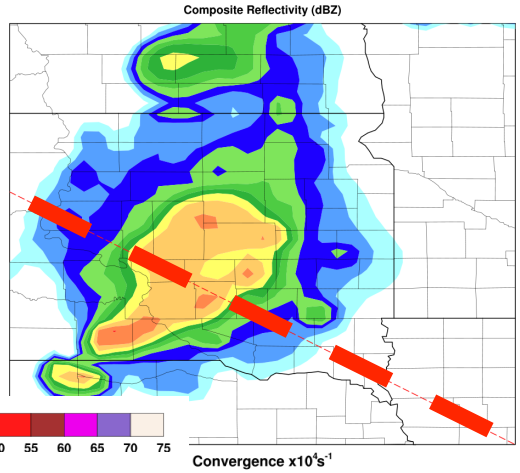


Analyses

No Radar DA

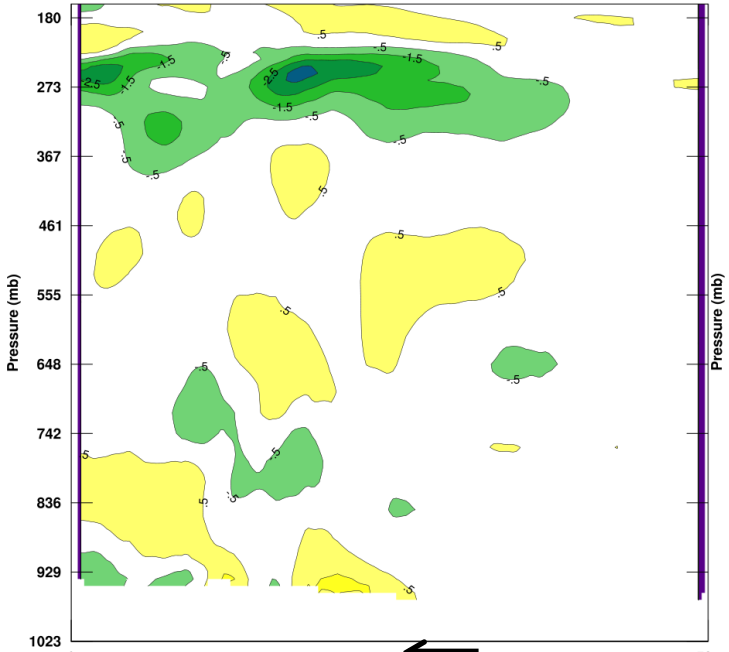


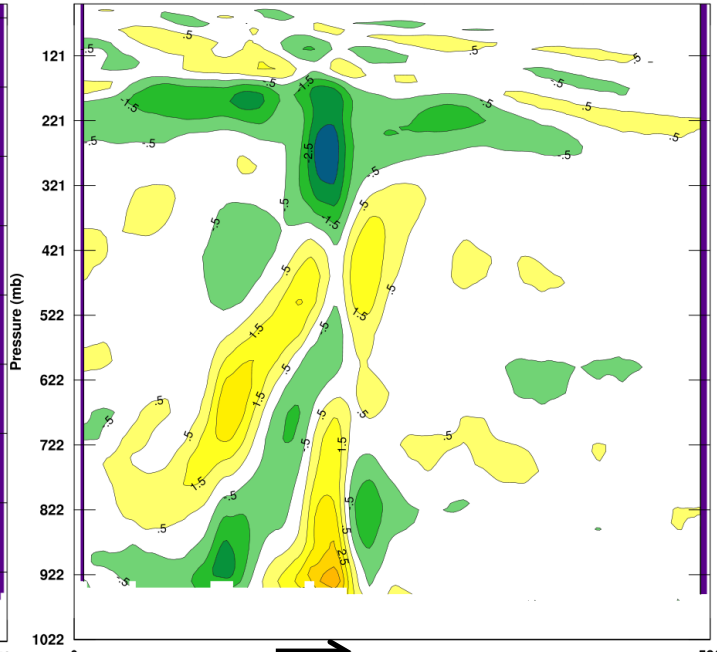
Radar DA



0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

The reflectivity and vertical cross-sections of horizontal convergence show a storm-scale response in the HRRR from the radar assimilation in the RAP digital filtering.





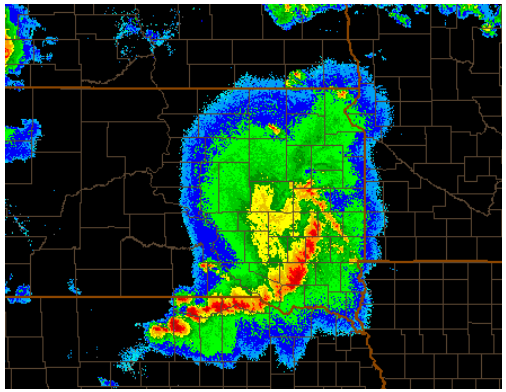
Divergence ← → Convergence

-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9

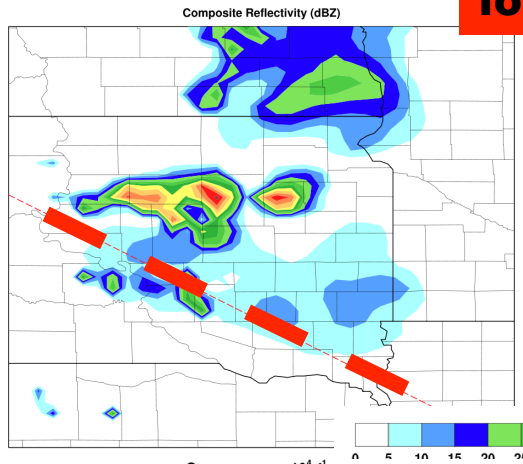
What is the impact of the RAP radar DA in the HRRR?

1-hour forecasts

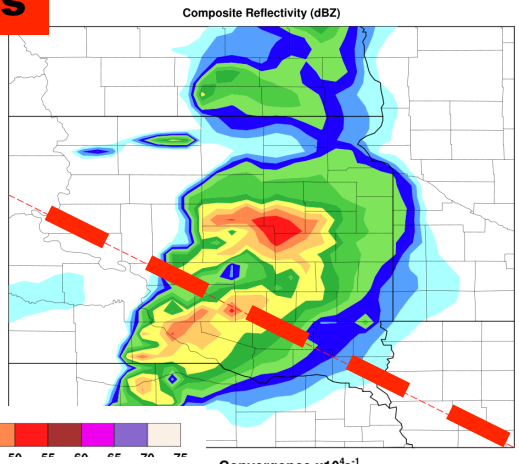
Observed Reflectivity



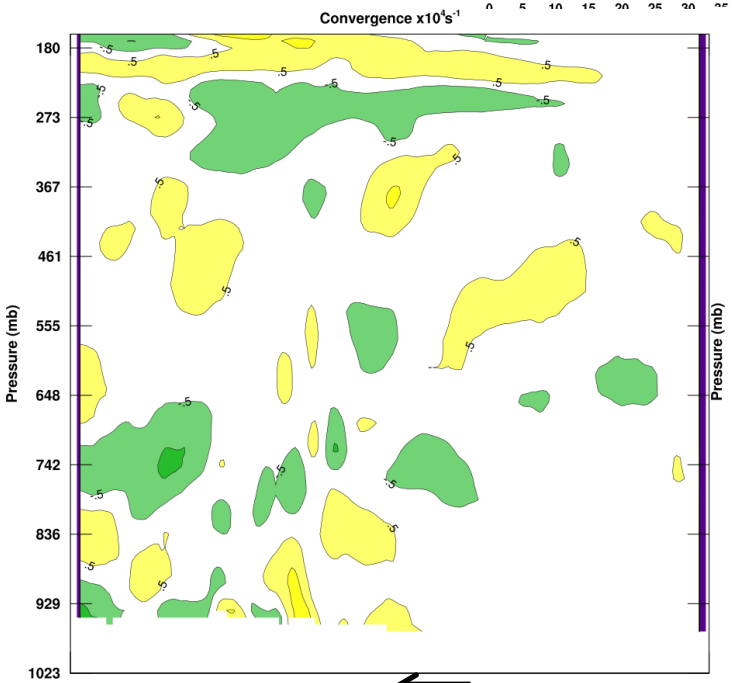
No Radar DA

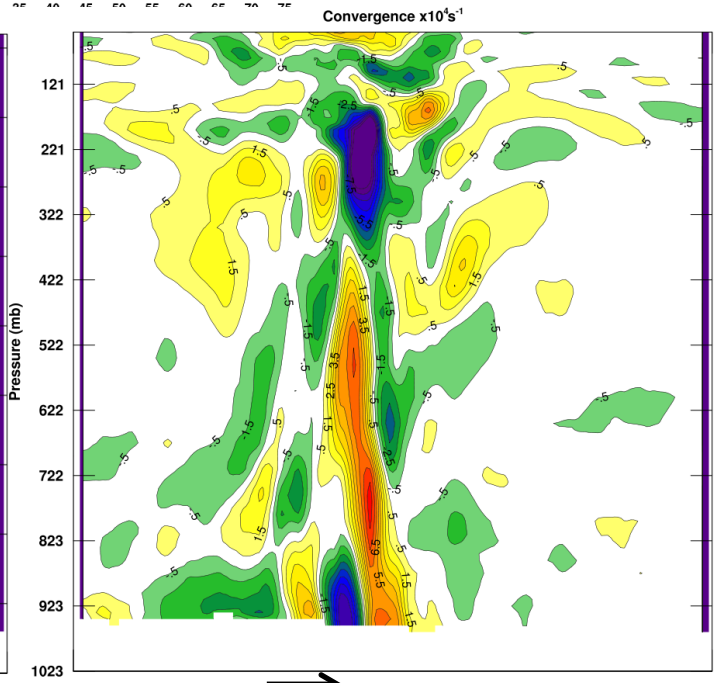


Radar DA

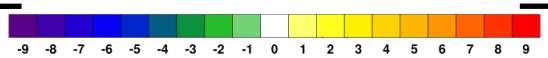


The storm-scale response to the radar data assimilation persists in a 1-hour forecast.



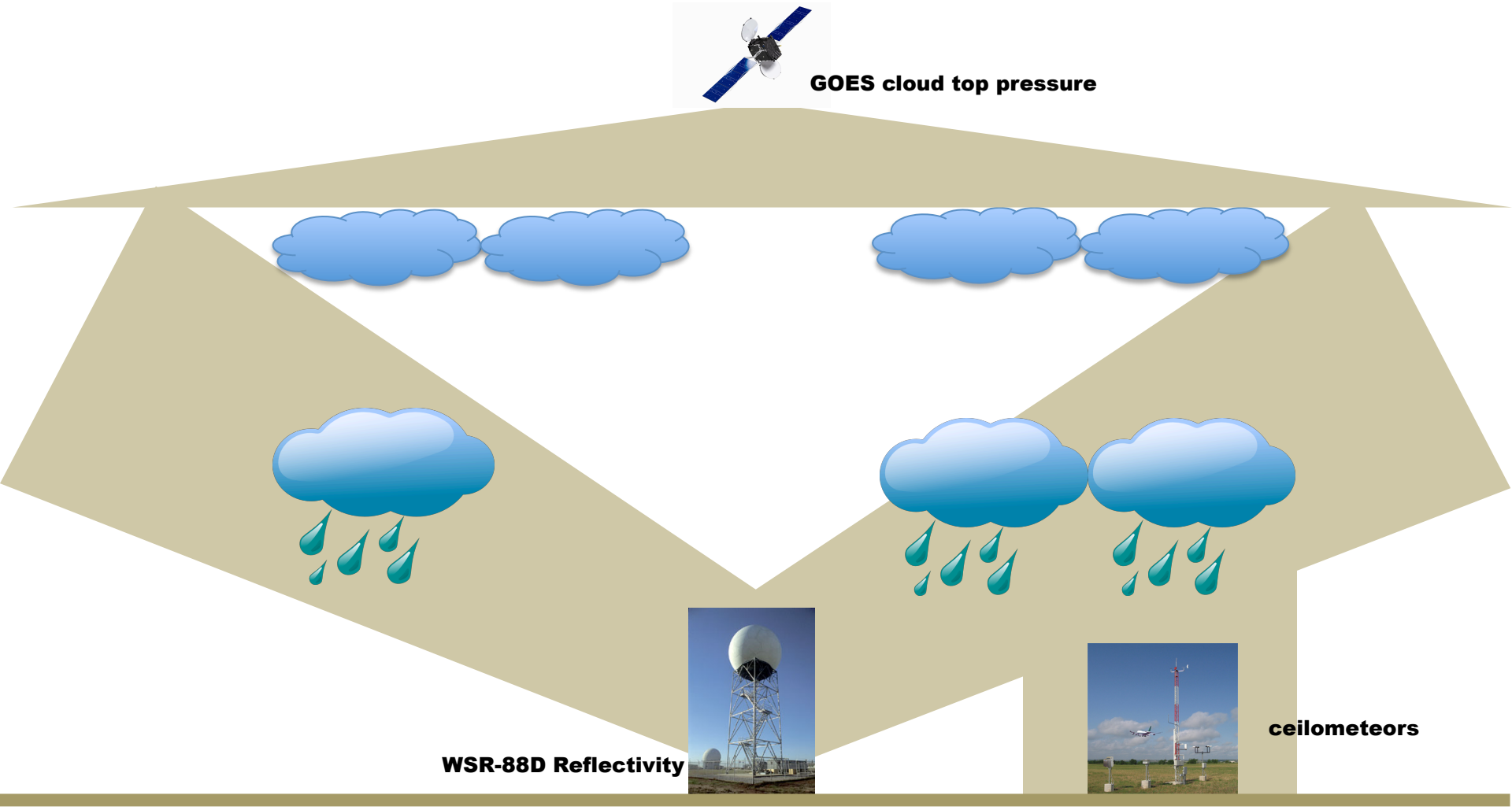


Divergence ← → Convergence



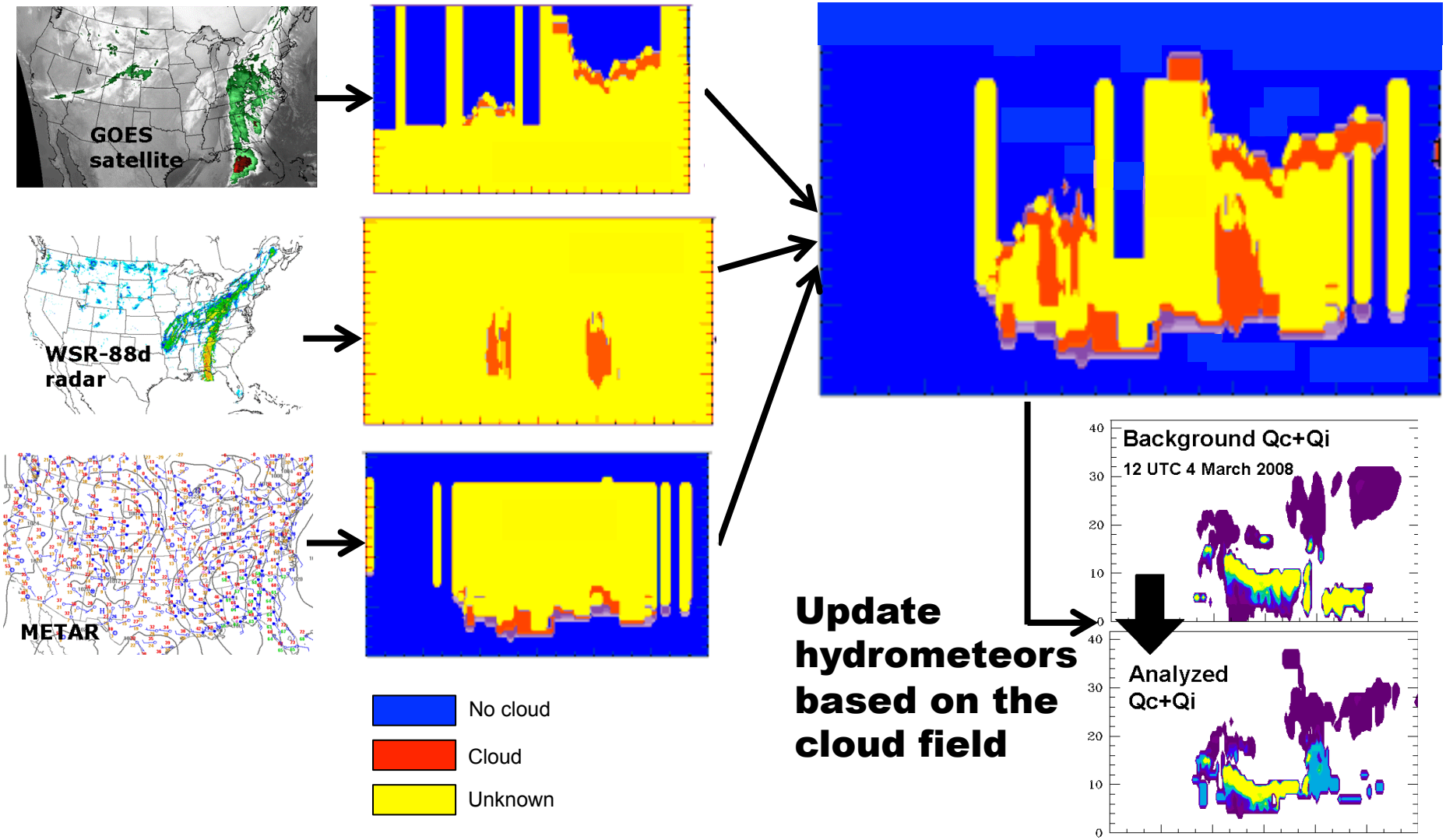
What is the cloud and precipitation hydrometeor (HM) analysis?

The 3 km model hydrometeors are updated based on cloud and precipitation observations to provide a high resolution analysis.

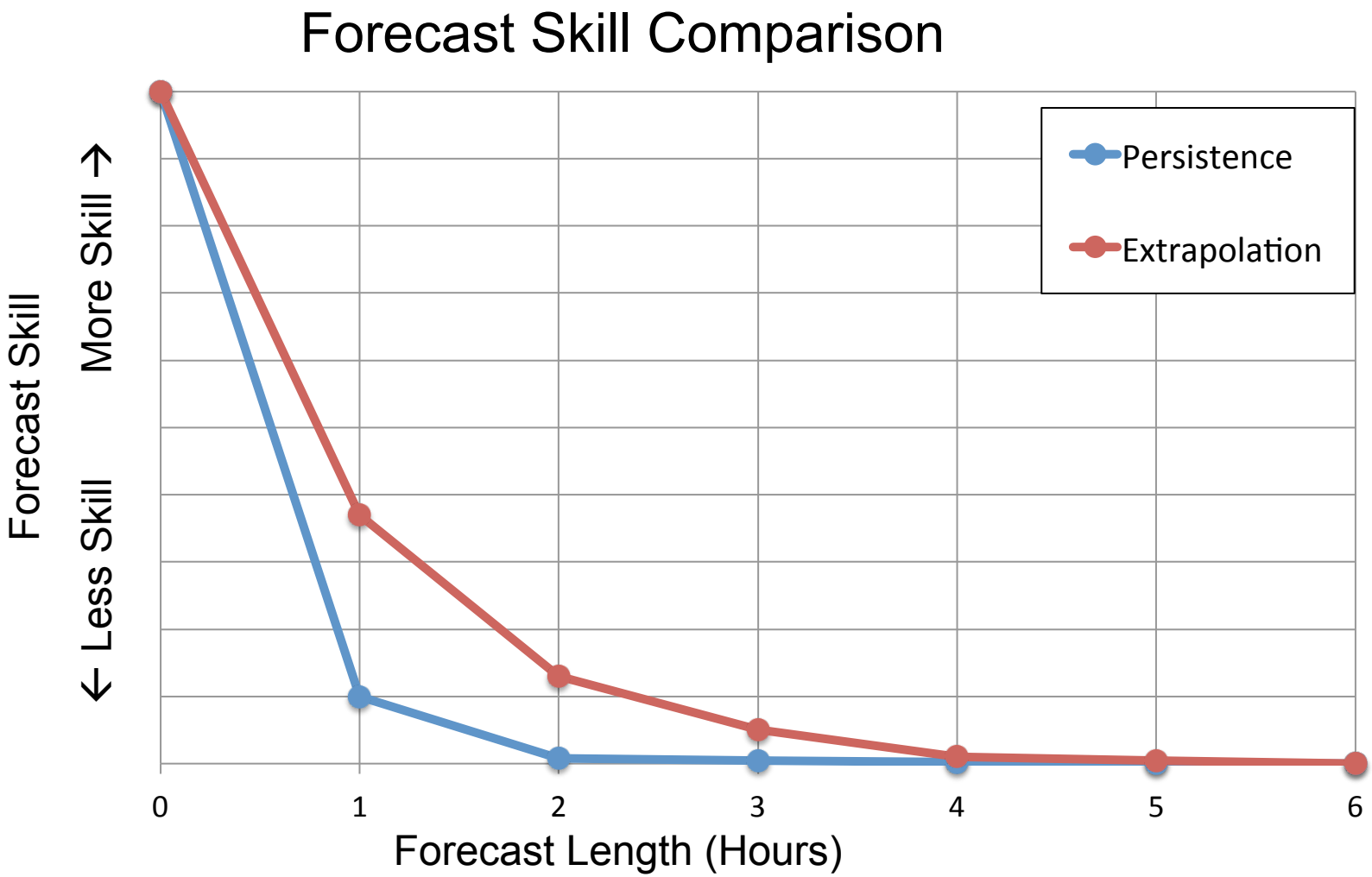


What is the cloud and precipitation hydrometeor analysis?

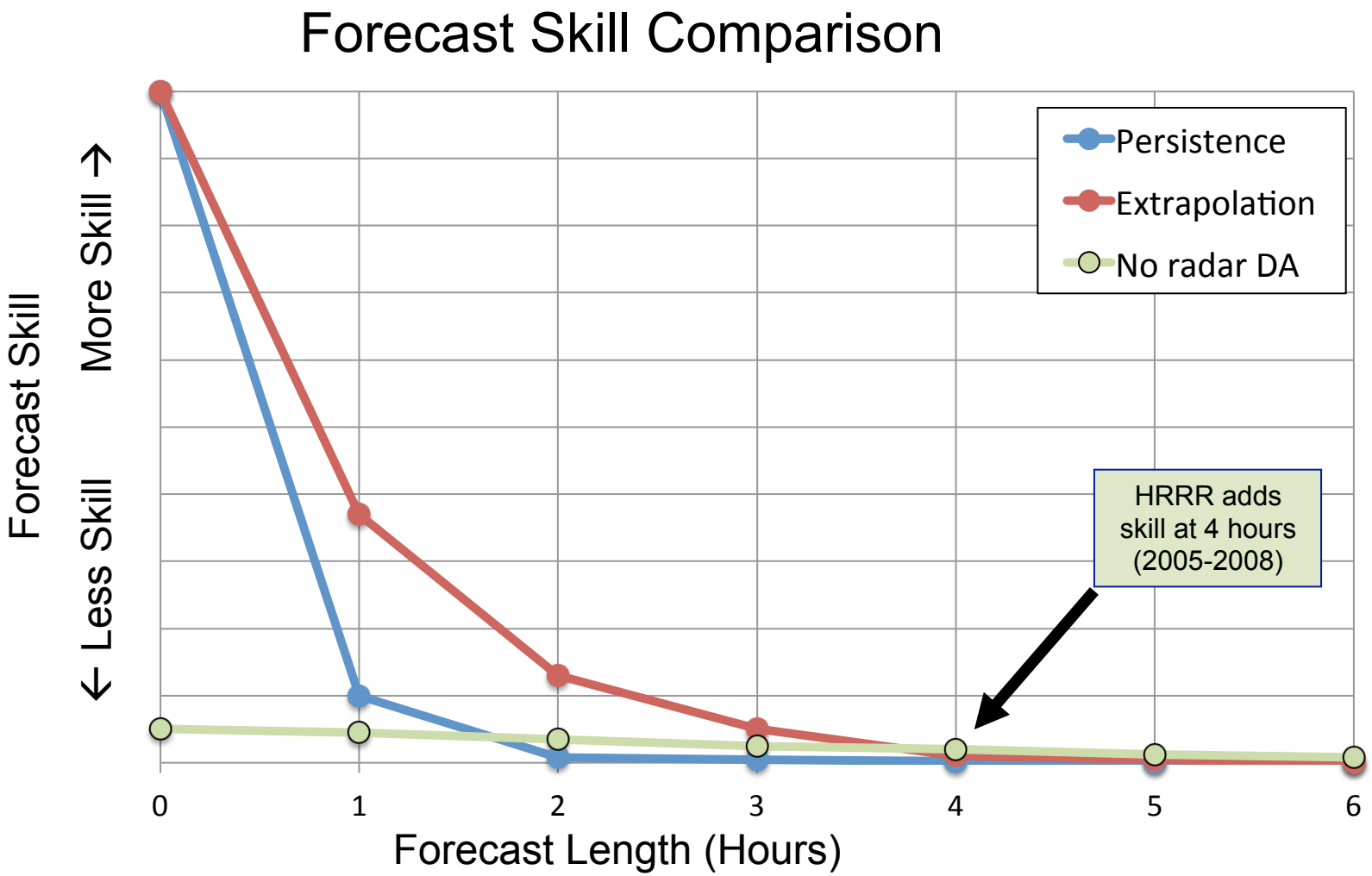
Observations **Map to cloud field** **Merge cloud field**



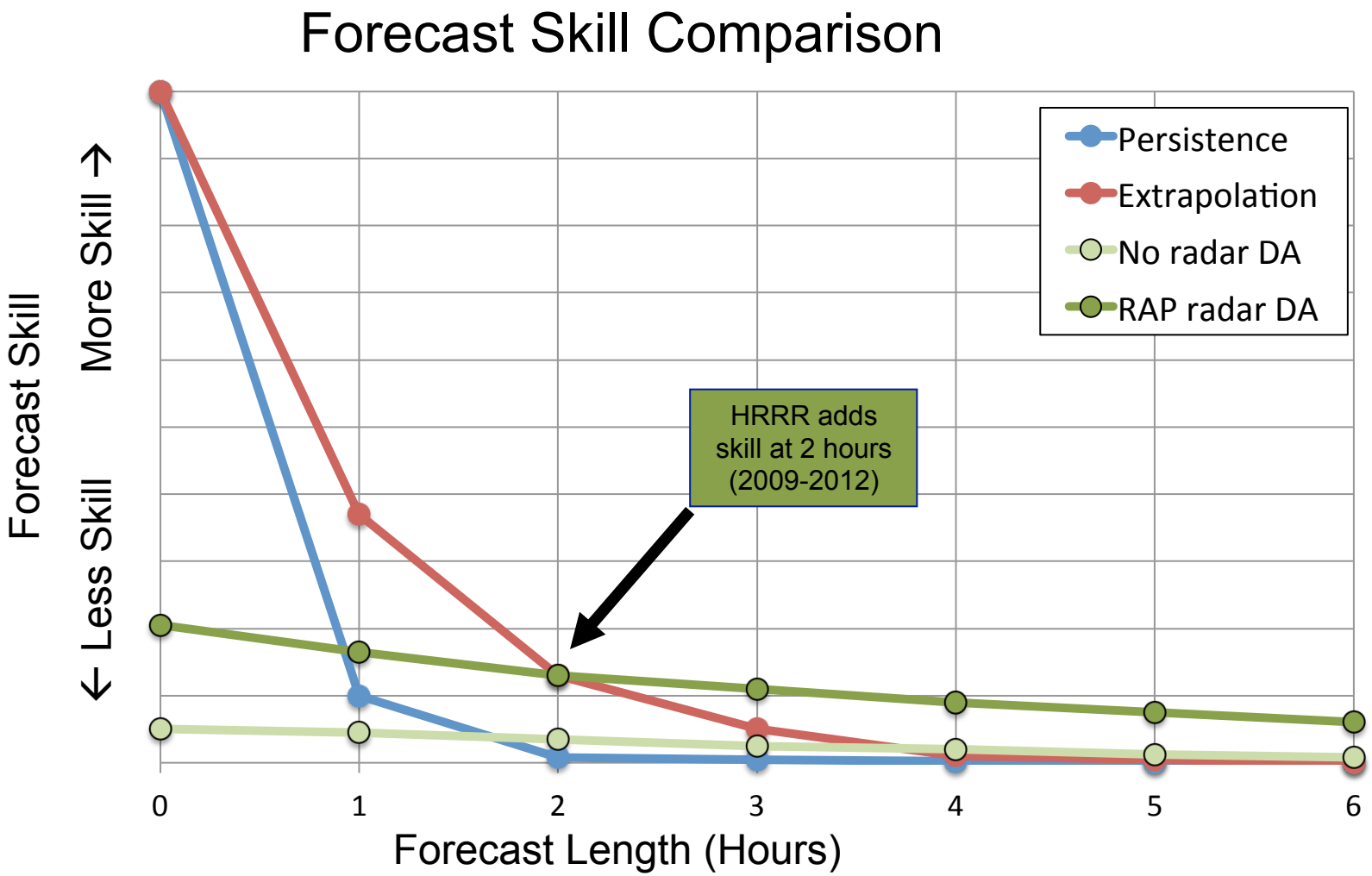
Summary of Forecast Improvements



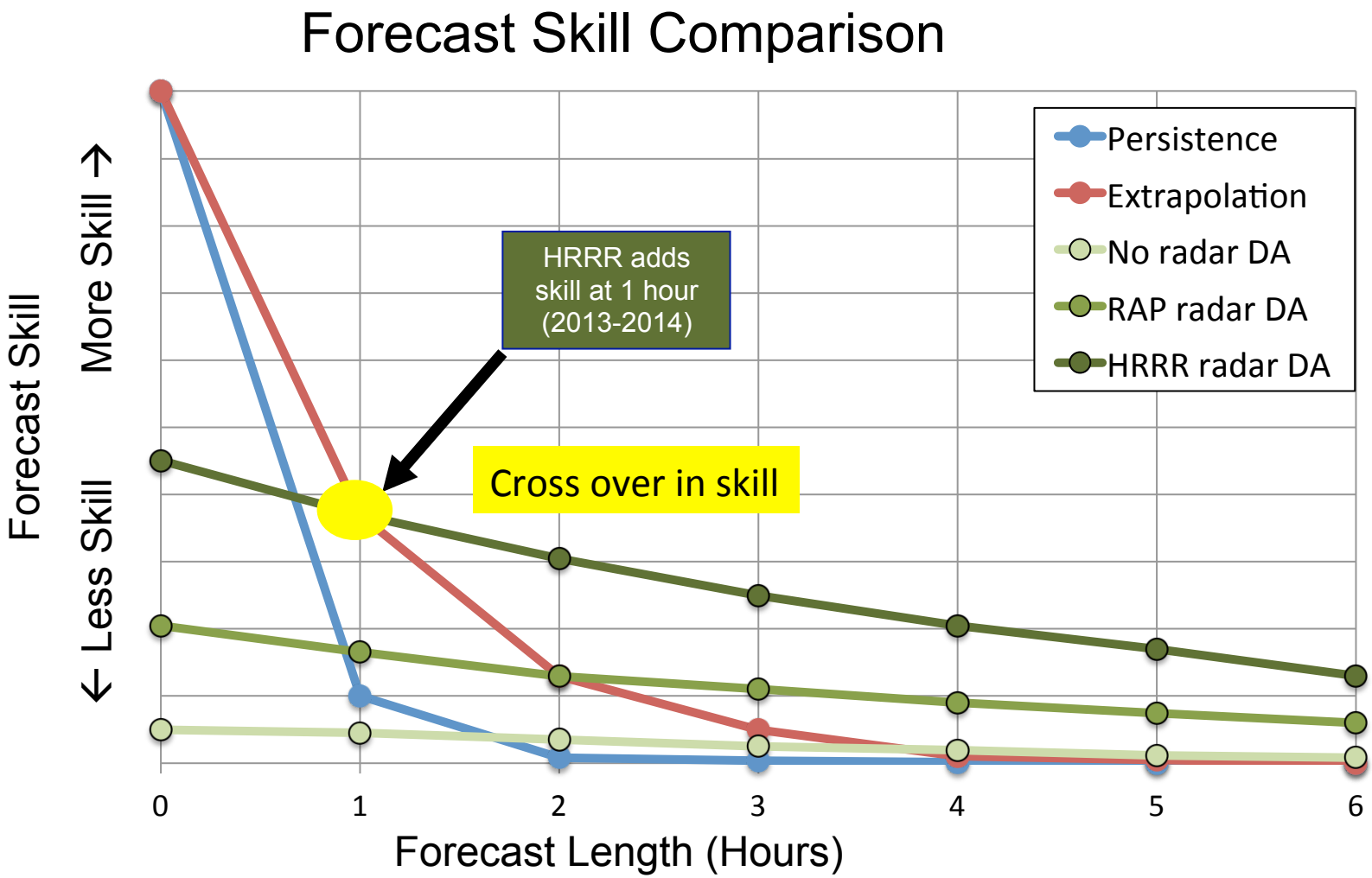
Summary of Forecast Improvements



Summary of Forecast Improvements



Summary of Forecast Improvements



Numerical Weather Prediction skill is moving towards nowcasting techniques.
The radar data assimilation is a large contributor to the improved forecast skill.

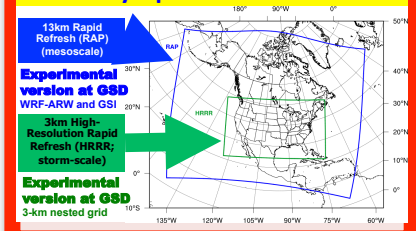
A precipitation climatology from the 3-km High-Resolution Rapid Refresh

Eric James[1,2], Stan Benjamin[2], and Curtis Alexander[1,2]

[1]CIRES/CU, Boulder, Colorado [2]NOAA/OAR/ESRL/GSD/EMB, Boulder, Colorado

HRRR Model

Hourly Updated NOAA NWP

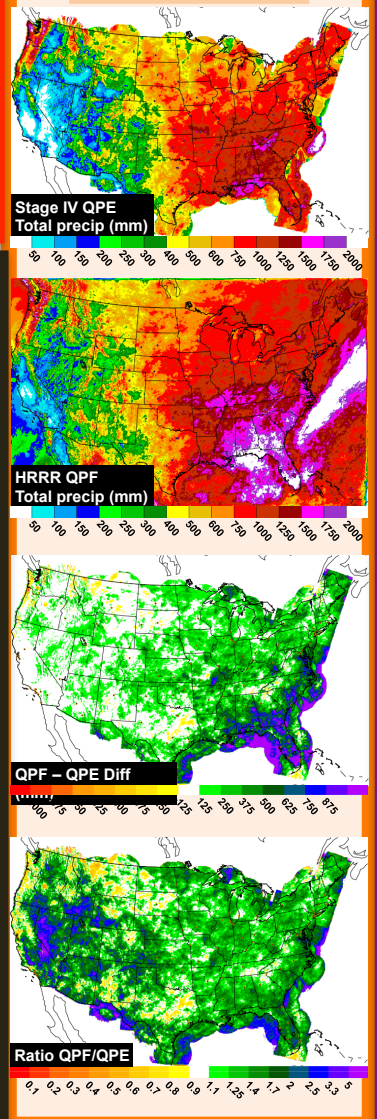


Discussion

- **Significant improvements** took place in HRRR from 2013 to 2014:
  - Hybrid ensemble-3DVAR data assimilation to allow flow-dependent covariances
  - New version of Thompson microphysics scheme
  - Improved parent 13-km RAP
- HRRR is able to capture the year-to-year shifts in precipitation maxima and minima
- HRRR appears to have a high bias in more intense precipitation
- Future work will compare this HRRR "climatology" vs. MRMS data (more accurate in West)

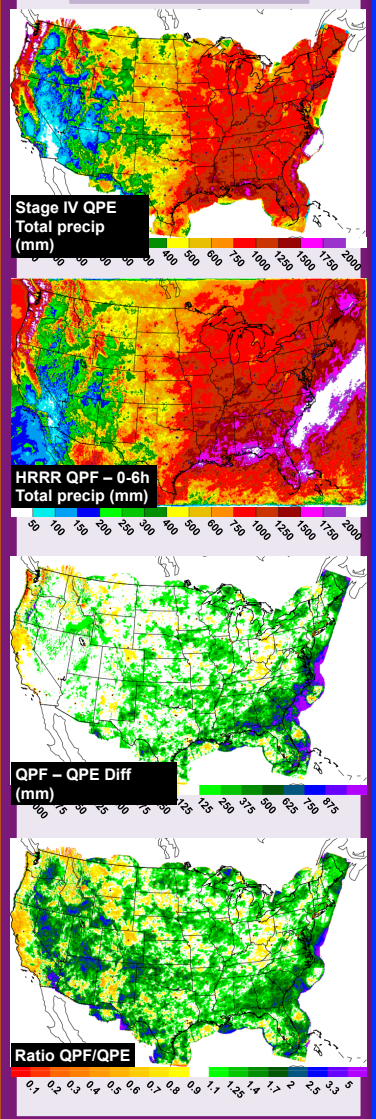
Annual Precipitation

13 Jan – 31 Dec 2013

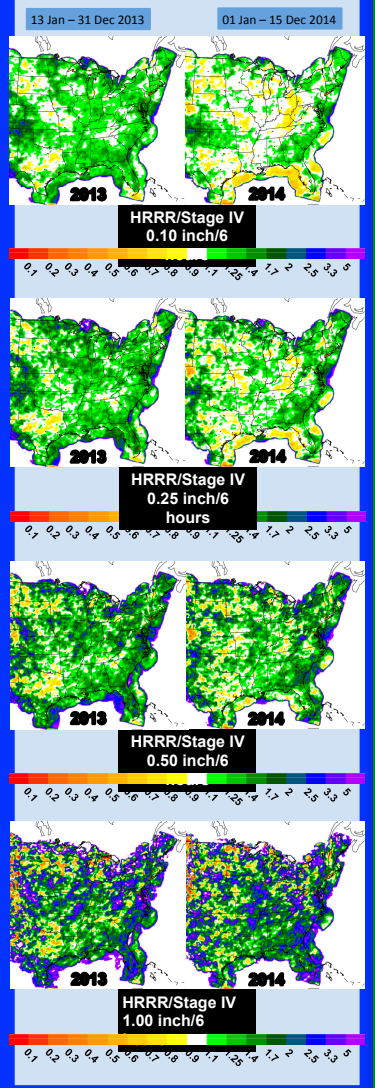


Annual Precipitation

01 Jan – 15 Dec 2014

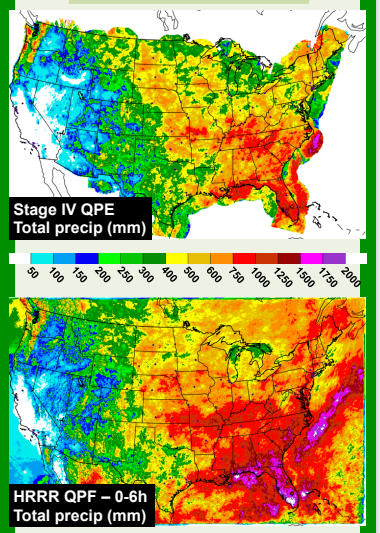


Ratio (QPF/QPE) of Occurrence of Precipitation Thresholds

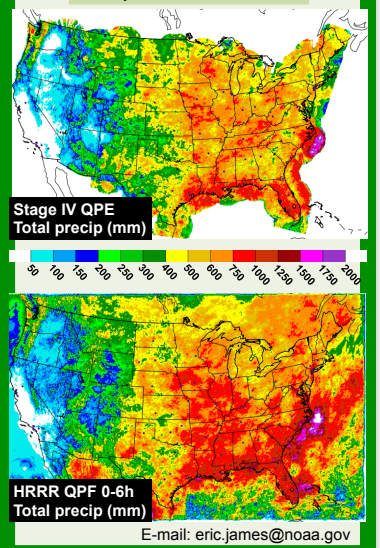


Warm Season Rainfall

16 Apr – 15 Oct 2013



16 Apr – 15 Oct 2014



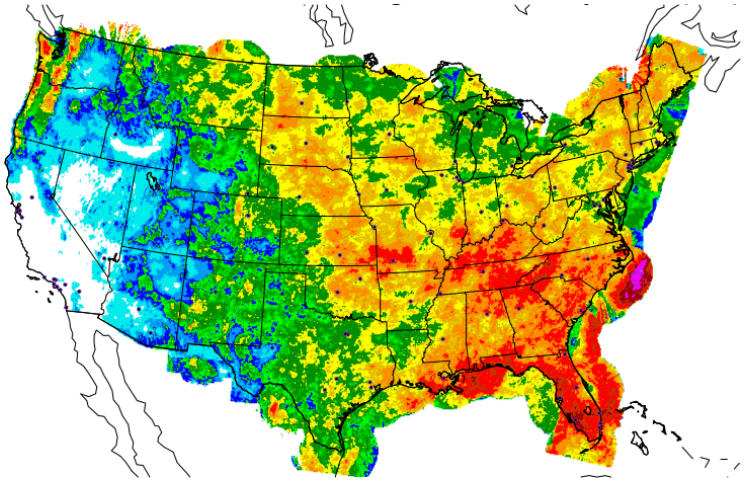
E-mail: eric.james@noaa.gov

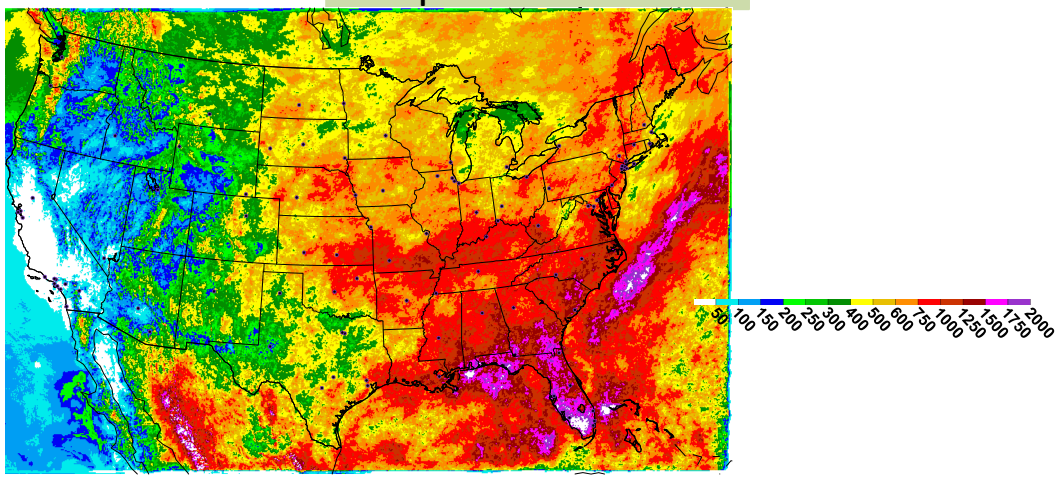
A precipitation climatology from the 3-km High-Resolution Rapid Refresh

Eric James[1,2], Stan Benjamin[2], and Curtis Alexander[1,2]
[1]CIRES/CU, Boulder, Colorado [2]NOAA/OAR/ESRL/GSD/EMB, Boulder, Colorado

Warm Season Rainfall

16 Apr – 15 Oct 2013

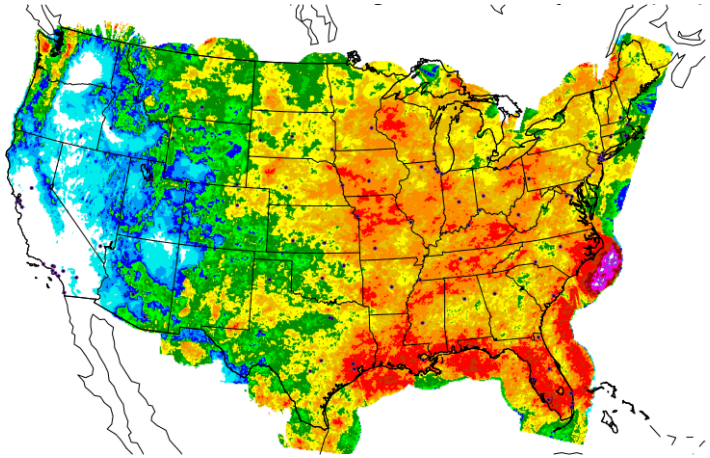


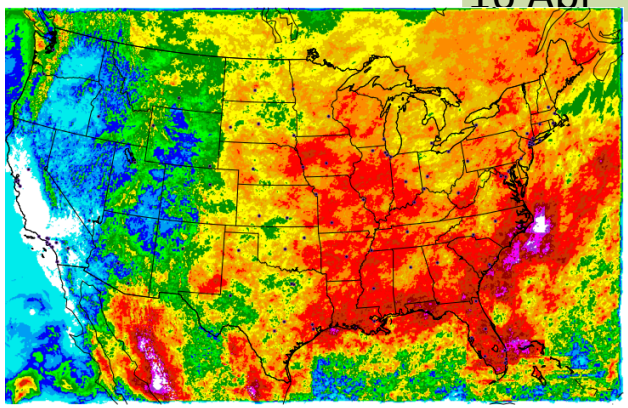


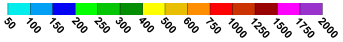
Stage IV QPE
Total precip (mm)

HRRR QPF – 0-6h
Total precip (mm)

16 Apr – 15 Oct 2014







E-mail: eric.james@noaa.gov

RAP/HRRR Implementation Map

ESRL – experimental version

- RAPv1 – used in 2011
  - Initialized 2011 HRRR
- RAPv2 – used in 2012-2013
  - Initialized 2012-2013 HRRR
  - MYNN PBL, 9-layer LSM
  - Hybrid DA, Better surface DA
- HRRR – 2013
  - Initialized from RAPv2-2013
  - 3km/15min radar assimilation
  - Available 45 min earlier, much more accurate 0-15h storm forecasts,

NWS-NCEP - operational

- Implemented 1 May 2012
- RAPv2 – implemented on 25 Feb 2014
- HRRR – Implementation 30 Sept 2014 HRRR testing on WCOSS with real-time end-to-end runs

RAP/HRRR Implementation Map

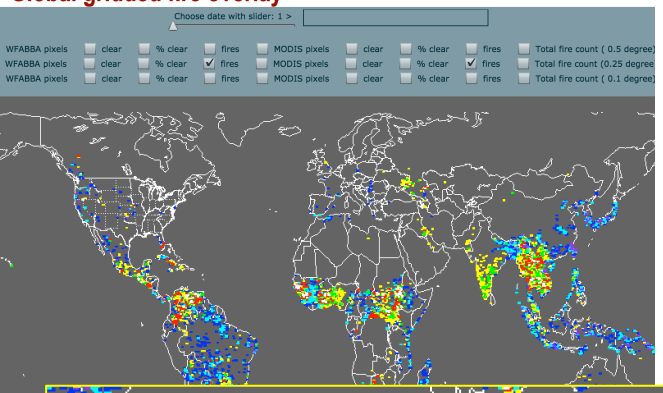
ESRL – experimental version	NWS-NCEP - operational
• **RAPv3 – GSD testing in 2014** – Will initialize 2014 ESRL-HRRR(v2) – Improved PBL, LSM, cu-parm, DA – WRFv3.6.1 w/ Thompson/NCAR aerosol-aware microphysics	• Implement 2015
• **HRRRv2 – GSD testing in 2014** – Initialized by 2014 RAP (v3) – Improved radar assimilation, hybrid assimilation, PBL/cloud physics	• Implement 2015
• **RAPv4 – GSD testing in 2015** – Hourly RAP ensemble data assimilation. – Inline simple chem/fire/smoke for cloud	• Implement 2016
• **HRRRv3 – GSD testing in 2015** – Target: Improved 3km physics/chem/fire + improved data assimilation.	• Implement 2016

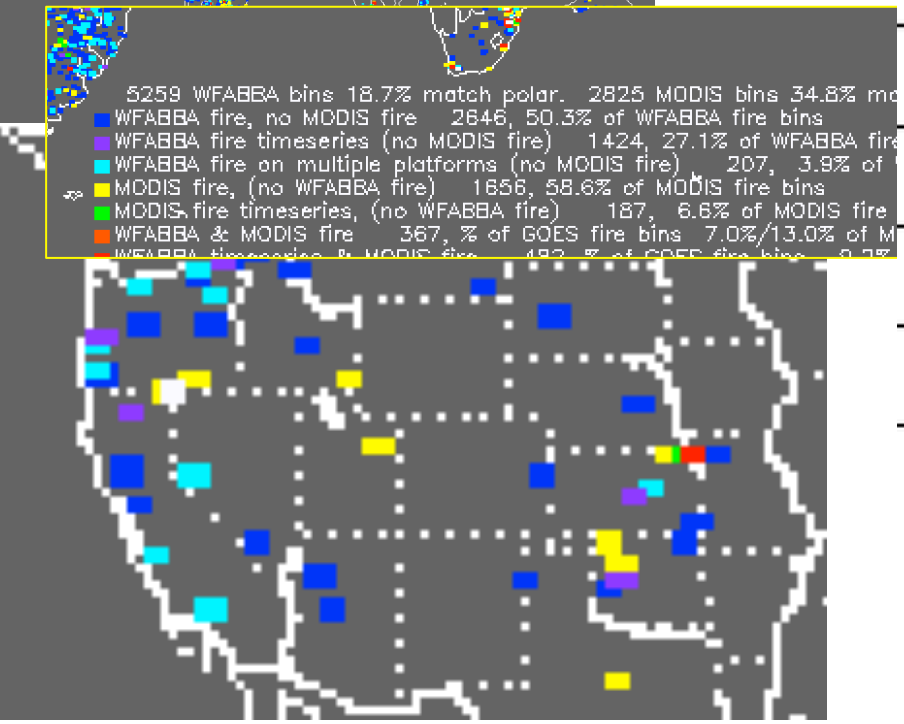
Testing of 3km ensemble DA for HRRR and later HRRRE – case studies only – 2015 onward

HRRR-chem – assimilation of WFABBA

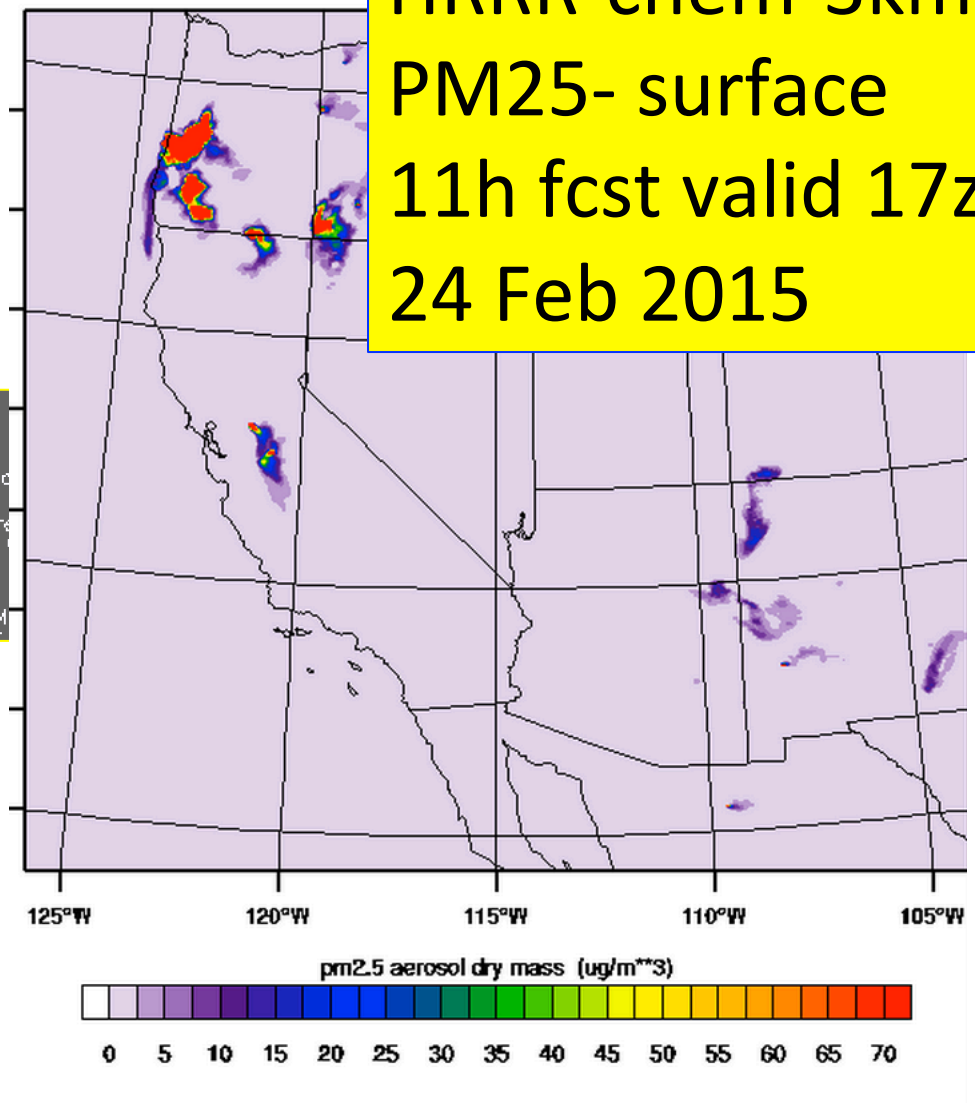
WFABBA WildFire Automated Biomass Burning Algorithm

Global gridded fire overlay

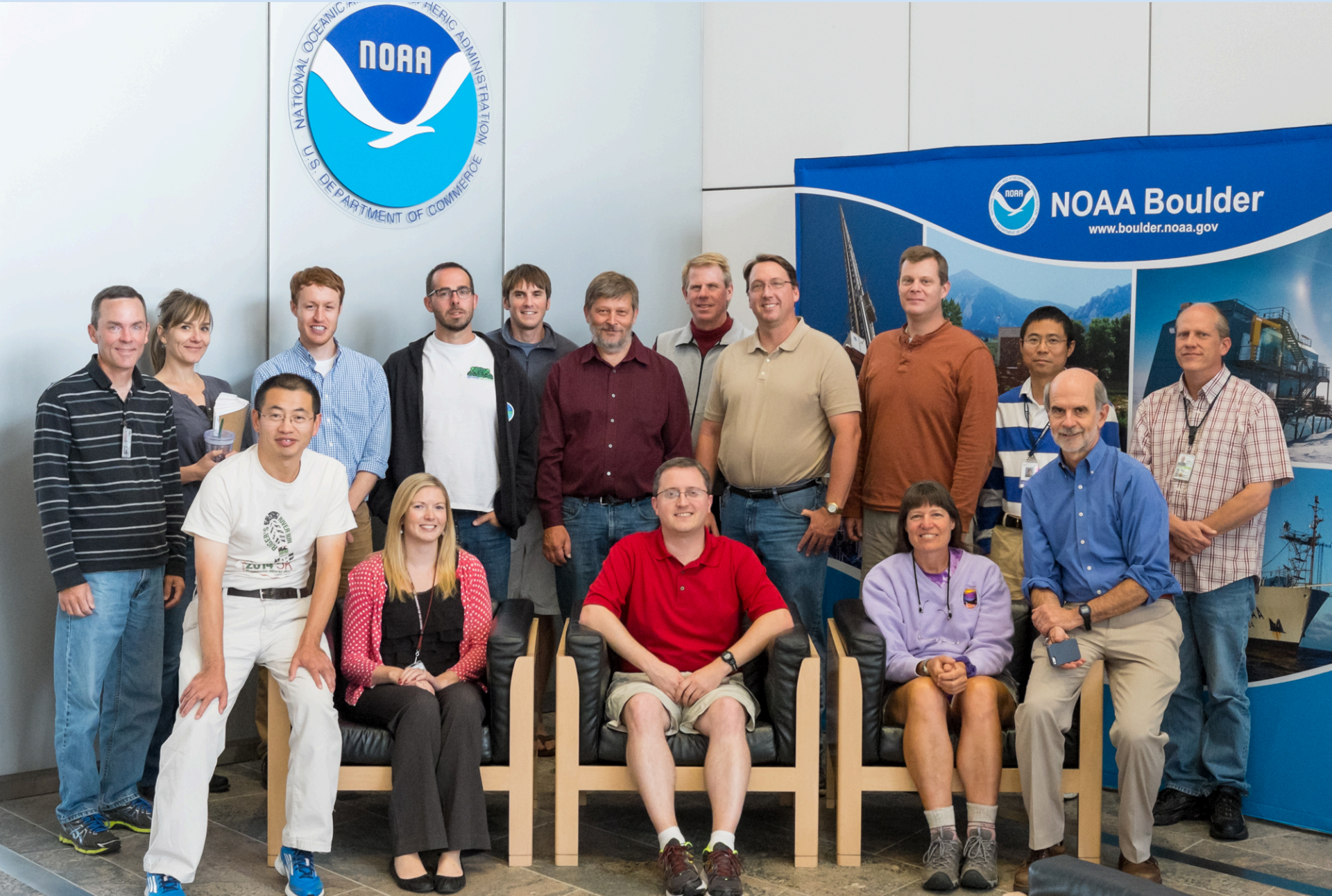




HRRR-chem-3km
PM25- surface
11h fcst valid 17z
24 Feb 2015

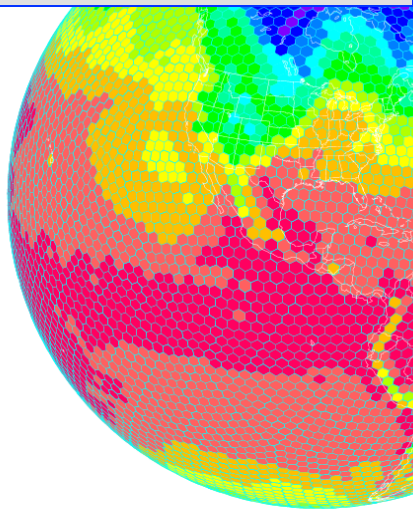


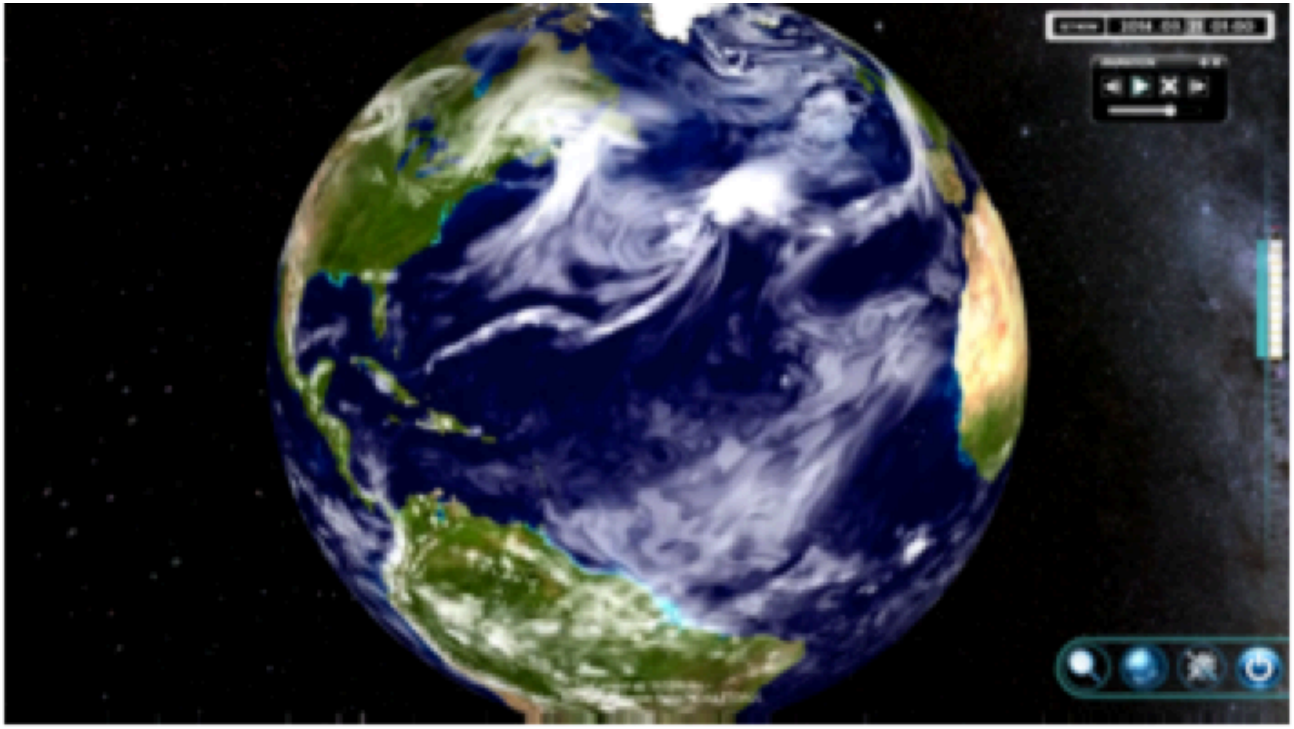
ESRL/GSD HRRR Development Team



Experiments with the FIM θ – global model for medium-range forecast duration

Stan Benjamin, Shan Sun, Rainer Bleck, Georg Grell,
Haiqin Li, Jian-Wen Bao, John Brown
NOAA Earth System Research Laboratory, Boulder CO USA



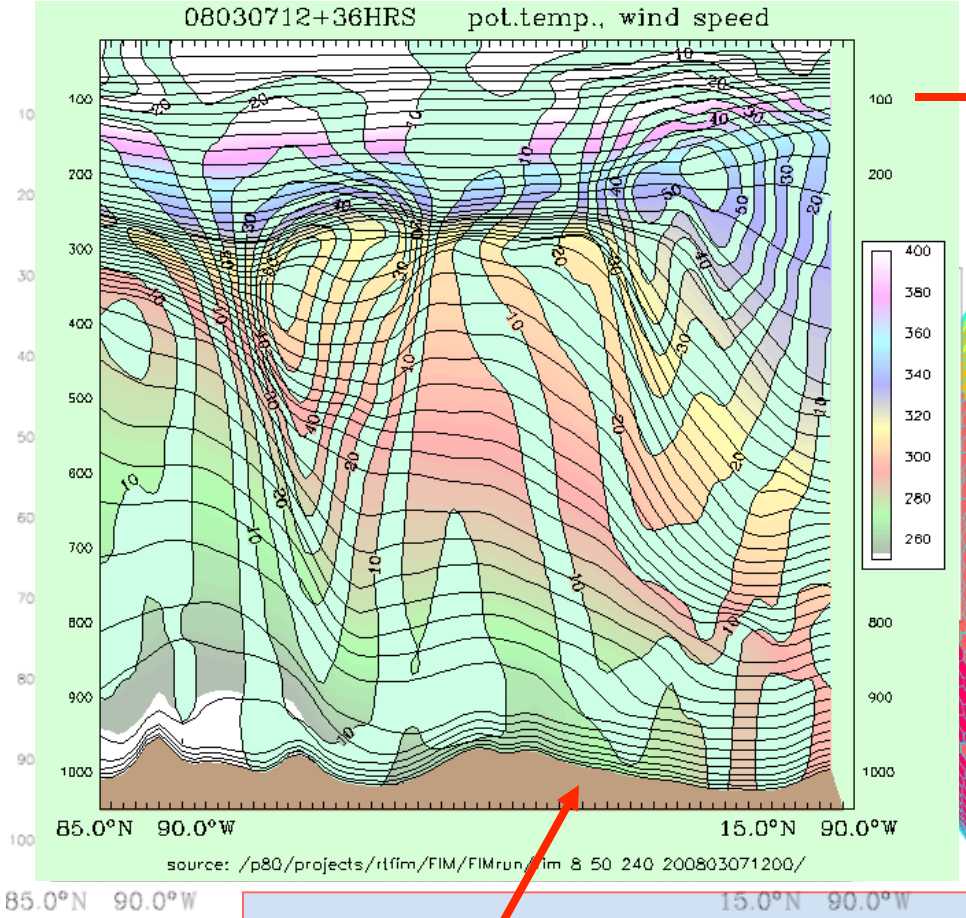


FIM global model – **10km,** 64 levels
Cloud - 10-day forecast init 00z 21 Mar 2014

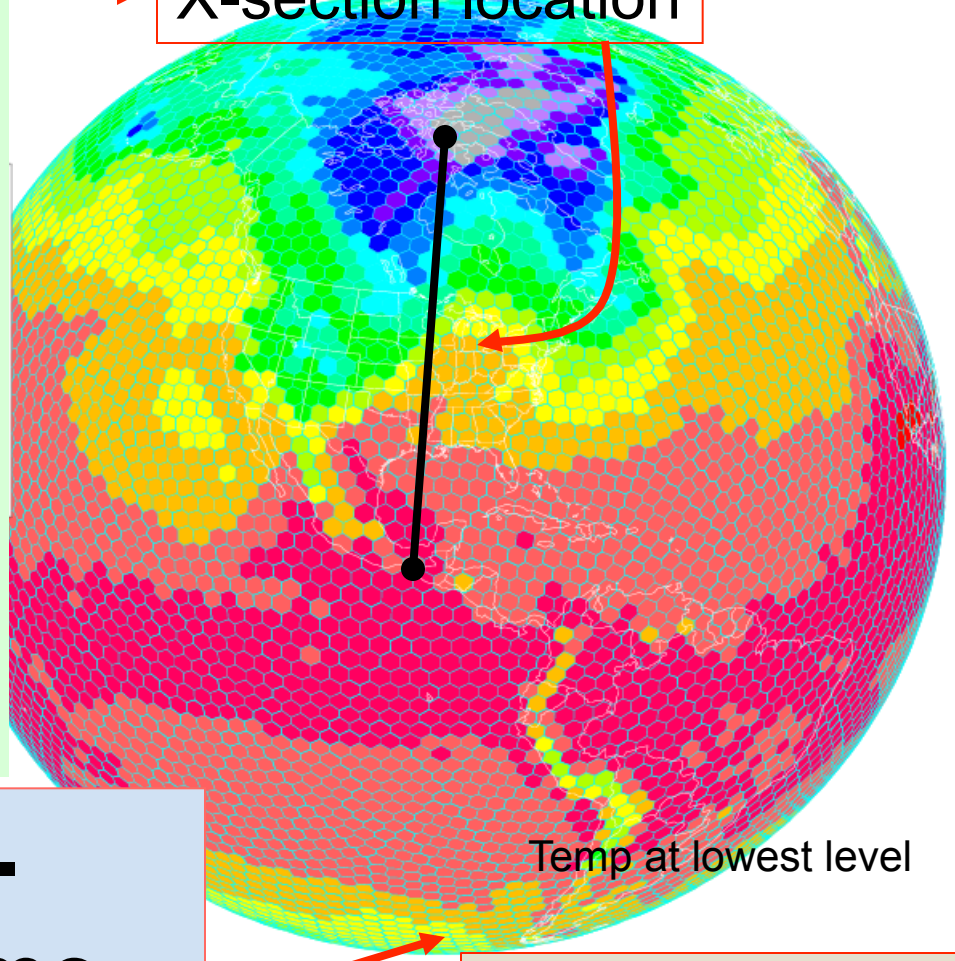
GLERL – Ann Arbor MI - May 2015

FIM model description
Bleck et al., 2015, *Mon.Wea.Rev.*, in press

http://fim.noaa.gov



X-section location



Temp at lowest level

Flow-following-
finite-volume
Icosahedral
Model FIM

1 – FIM desc
2 – NWP skill
3 – experiments
4 - seasonal coupled exps

Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

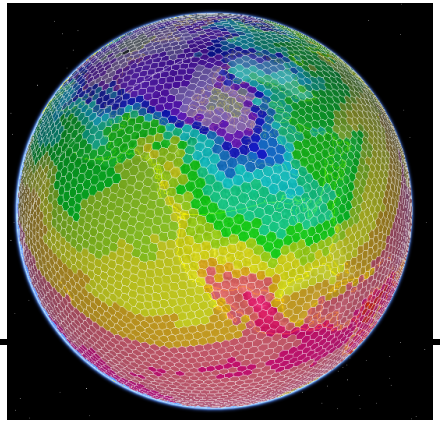
ESRL Finite-volume Icosahedral Models (FIM/NIM)

- **FIM (Flow-following finite-volume Icosahedral Model): A hydrostatic model for NCEP and NOAA research applications.**

- **Target resolution ≥ 10 km**

- **NIM (Nonhydrostatic Icosahedral model): A multi-scale global model for weather and intra-seasonal climate predictions.**

- **Target resolution : O(1 km) ~O(100 km)**



Novel features of FIM/NIM:

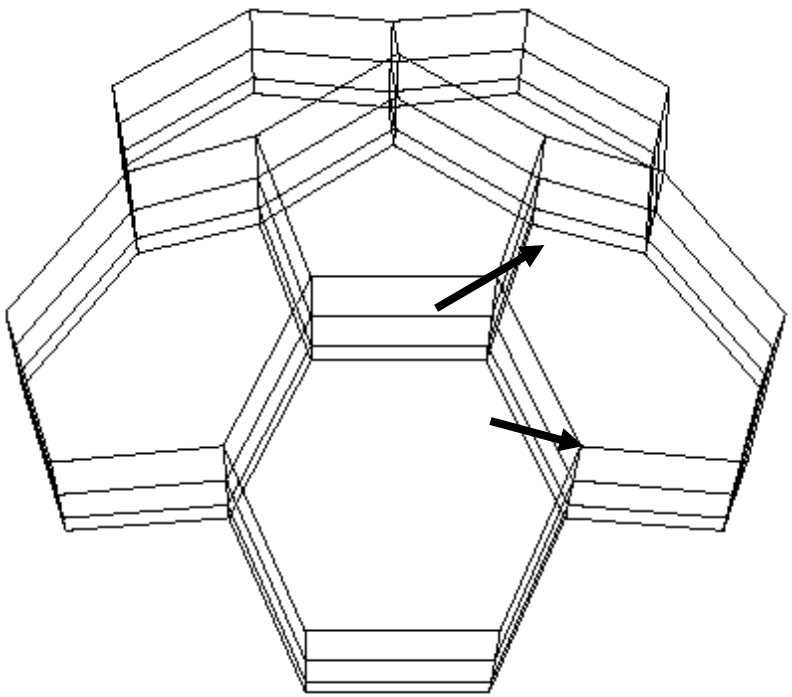
- **Finite-volume Integrations on *Local Coordinate***
- **FIM: Hybrid σ-θ Coordinate w/ GFS Physics**
- **Efficient Indirect Addressing Scheme on Irregular Grid**
- **Conservative and Monotonic Adams-Bashforth 3rd-order FCT Scheme**
- **Grid Optimization for Efficiency and Accuracy**
- **Novel Features of NIM:**

-Use of Three-dimensional Control Volume in Height Coordinate

-3-D Volume Integration to Improve pressure gradient force (PGF) accuracy

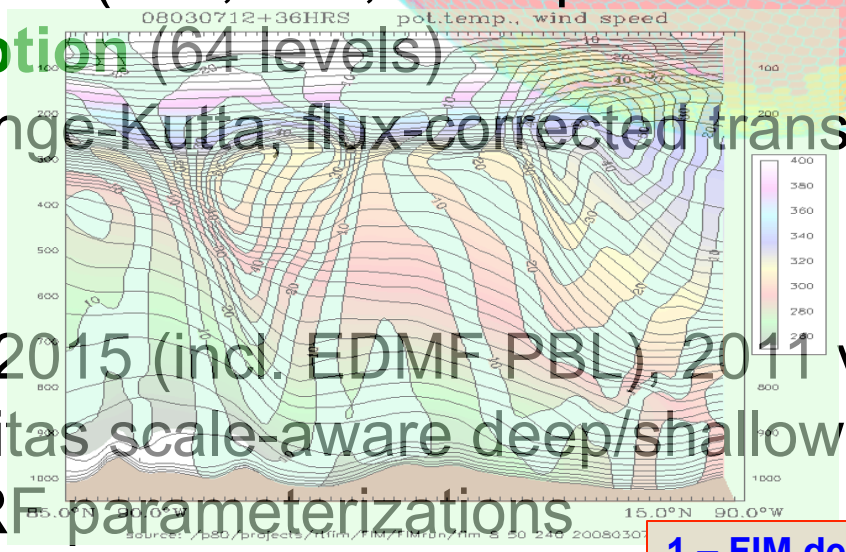
* extend surface integration to volume integration (S.-J. Lin, QJRMS,1997)

* use smooth terrain transformation (Klemp,MWR, 2011)



FIM numerical atmospheric model

- Horizontal grid
  - **Icosahedral,** Δx=240km/120km / 60km/30km/15km/10km
- Vertical grid
  - ptop = 0.5 hPa, θtop ~2200K
  - **Generalized vertical coordinate**
    - **Hybrid θ−σ** option (64L, 38L, 21L options currently)
    - **GFS-like σ-p option** (64 levels)
  - A-grid, 3rd-order Runge-Kutta, flux-corrected transport



- Physics
  - GFS physics suite: 2015 (incl. EDMF PBL), 2011 versions
  - Option for Grell-Freitas scale-aware deep/shallow cumulus
  - Option for other WRF parameterizations
- Coupled model extensions
  - Chem – WRF-chem/GOCART
  - Ocean – icosahedral HYCOM (no coupler), tri-polar HYCOM (with coupler)

1 – FIM desc
2 – NWP skill
3 – experiments
4 - seasonal coupled exps

FIM design – adaptive vertical coordinate

Hybrid (sigma/ isentropic) vertical coordinate

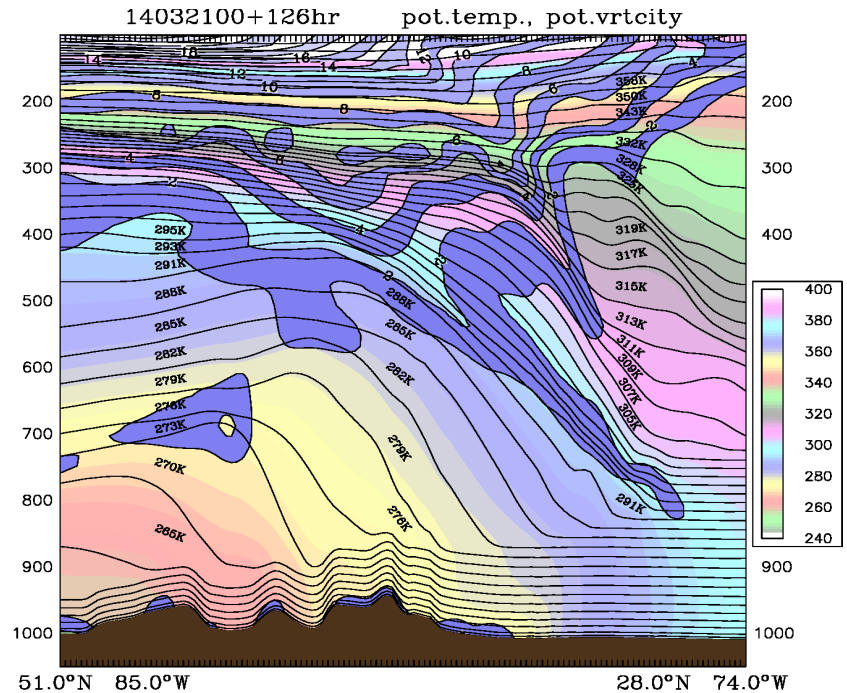
- Improved conservation using quasi-material surfaces, reduced vertical dispersion.

Improved transport by reducing numerical dispersion from vertical cross-coordinate transport, ***improved stratospheric/tropospheric exchange.***

- Used in NCEP Rapid Update Cycle (RUC) model
- Used in HYCOM ocean model

Installed as generalized "s" vertical coordinate

- can be replaced with sigma-p or other coordinates.



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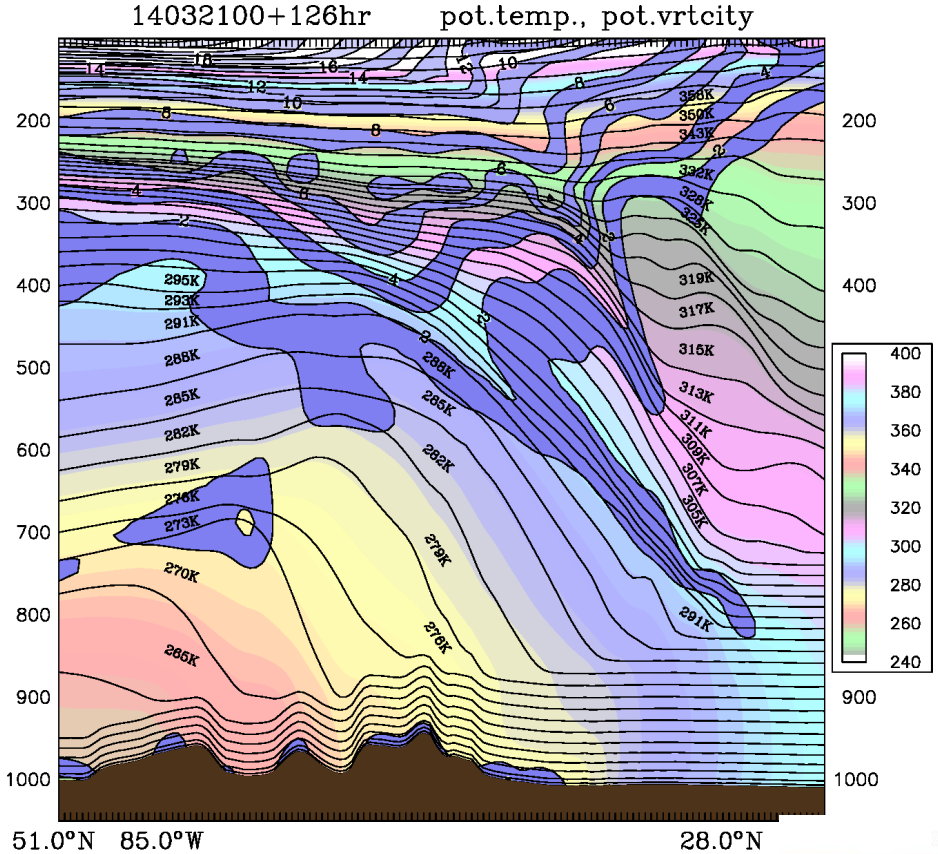
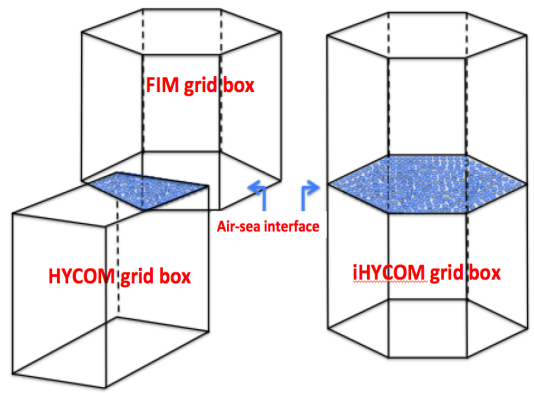


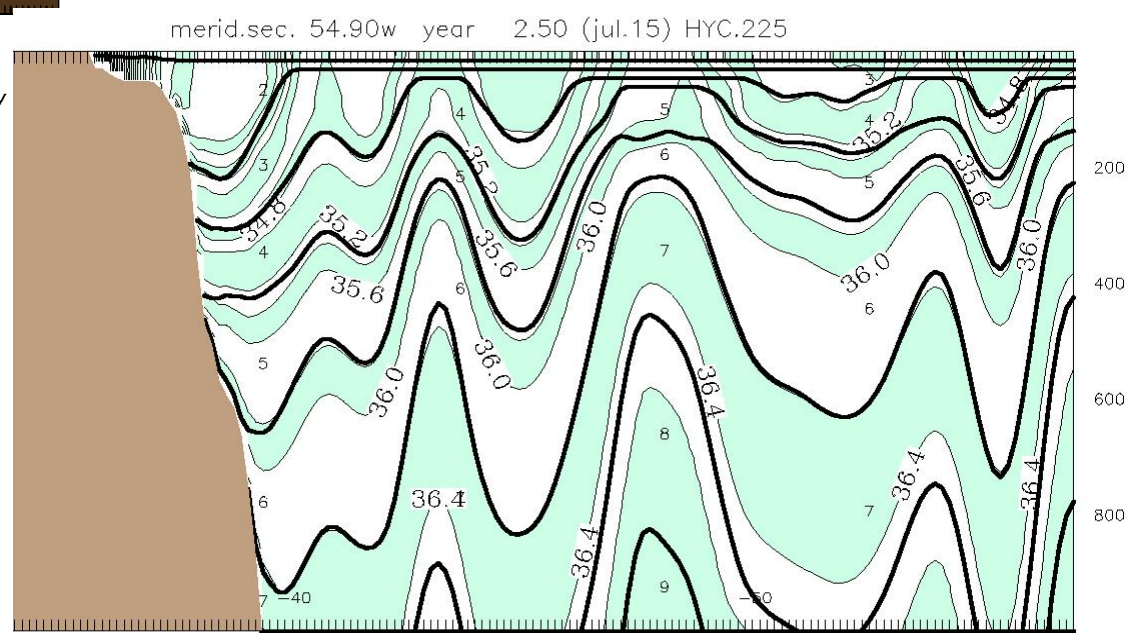
FIM vertical section. Heavy black lines: coordinate surfaces. Colored field: pot.temperature (K). Shaded contours: potential vorticity.



fimG8

source: .../BMC/fim/bleck/trunk/FIMrun/zeussubfim 5725/fim8 64 480/fim/

iHYCOM vertical section. Heavy black lines: coordinate surfaces. Shaded contours: potential density ($\sigma 2$)

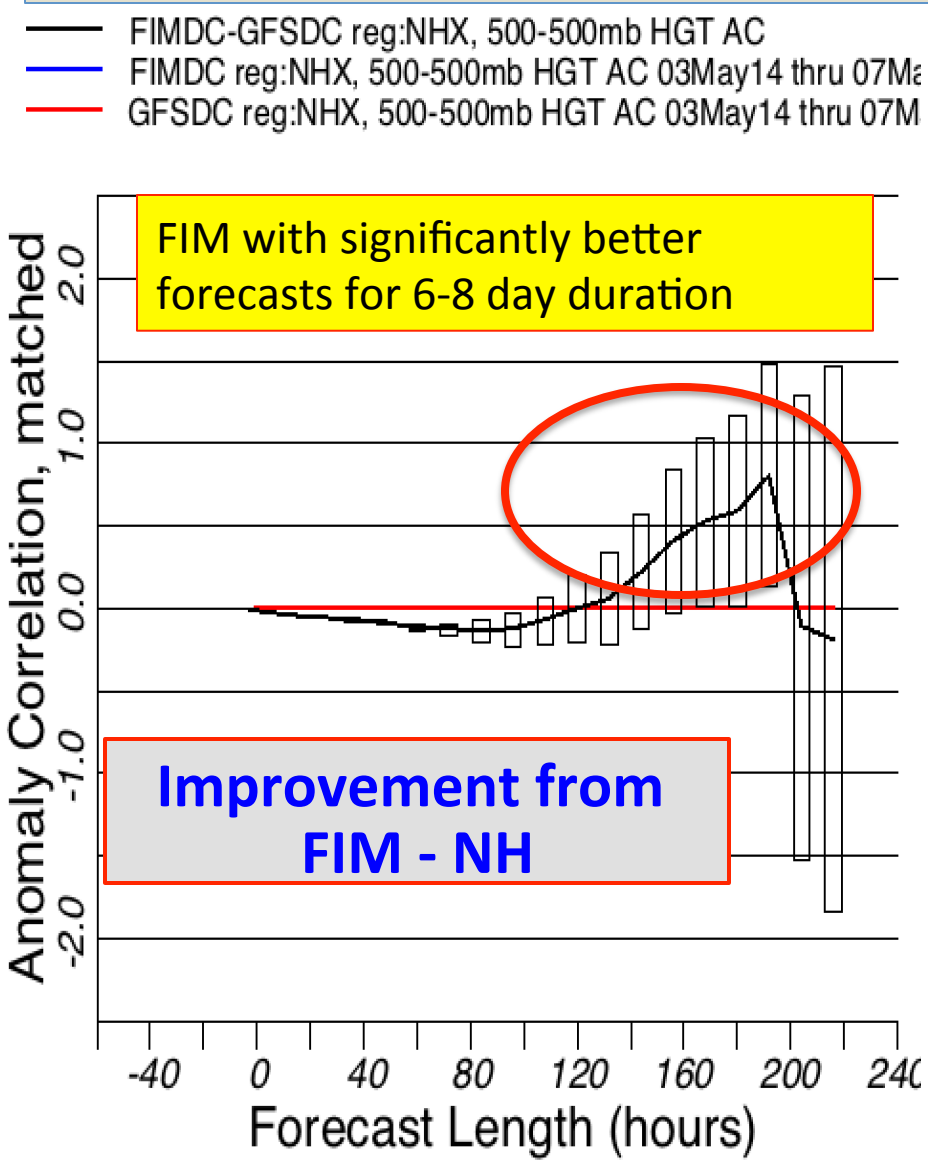


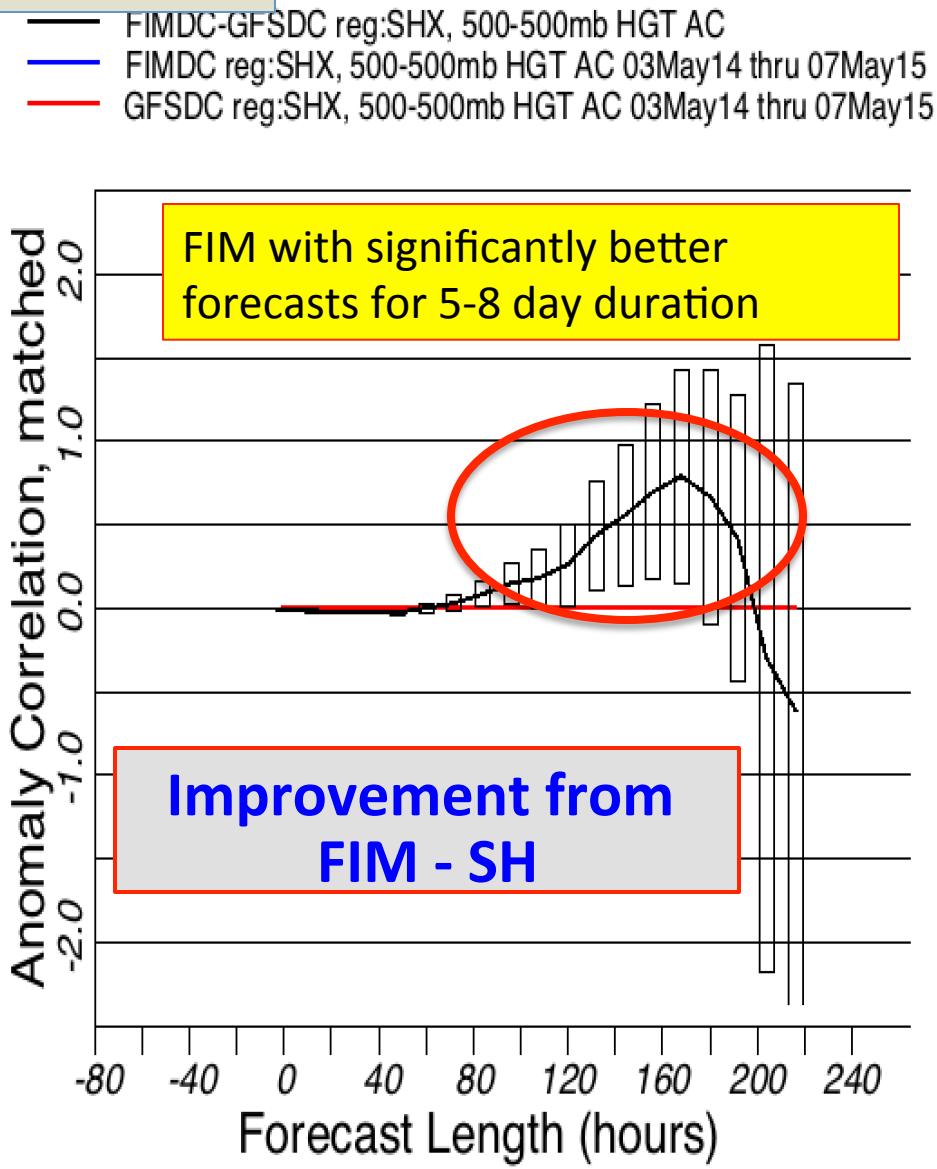
Coupled atm/ocean model with

- *matched icosahedral grid*
- *adaptive vert coord in both atmsphere and ocean*

500-hPa Height Anomaly Correlation FIM-30km (GFS init, GFS phys) vs. GFS NCEP operational

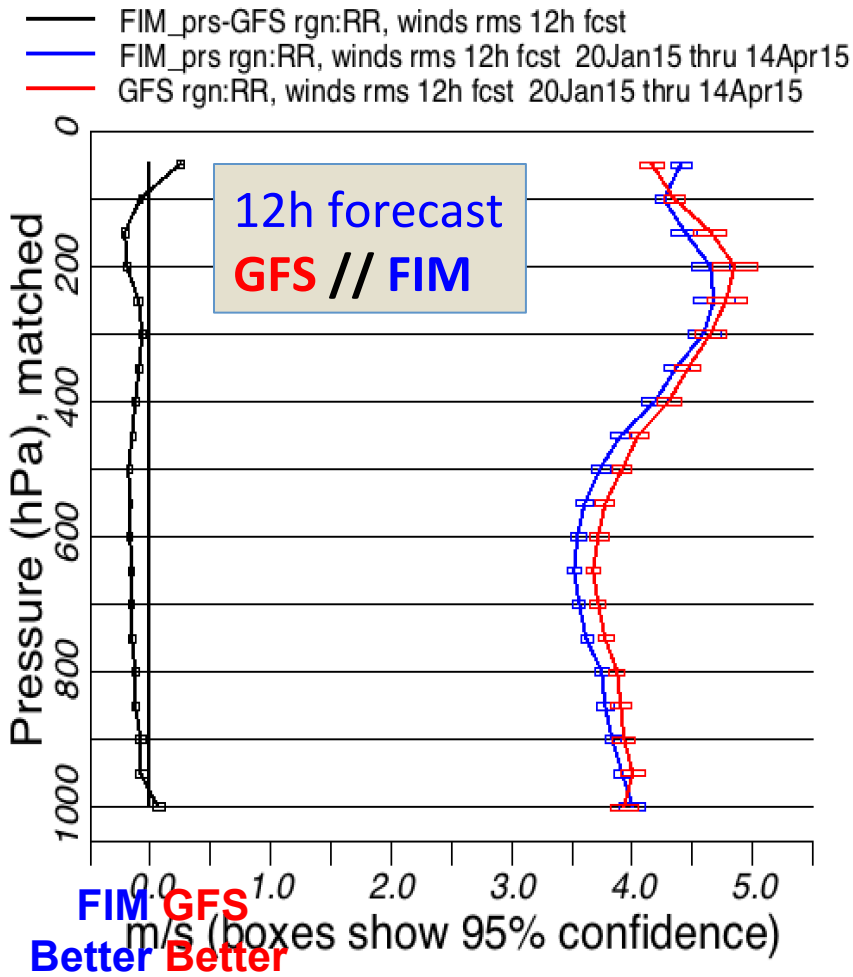
12-month NWP test May 2014 -May 2015

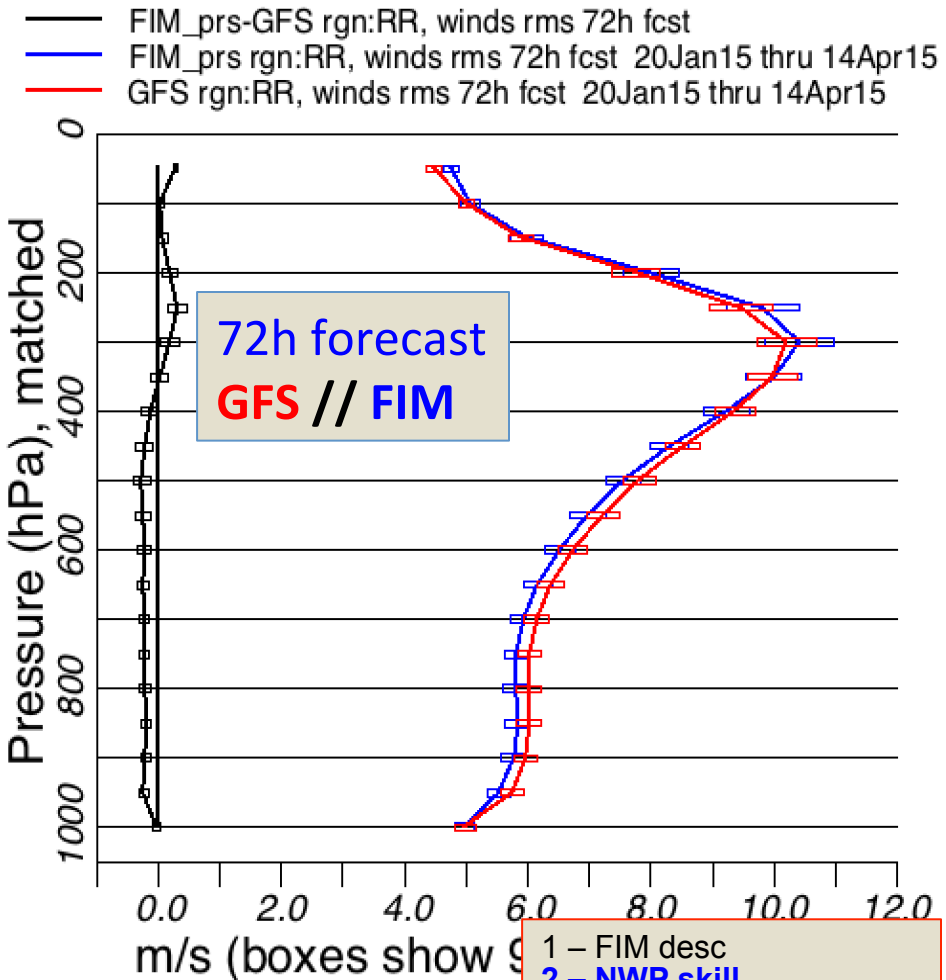




Wind RMS error vs. raobs
N. America
GFS (T1534) // FIM-30km
Both using 0.5 lat/lon

RMS errors (smaller better) - verification with rawinsonde observations
–Jan-April 2015

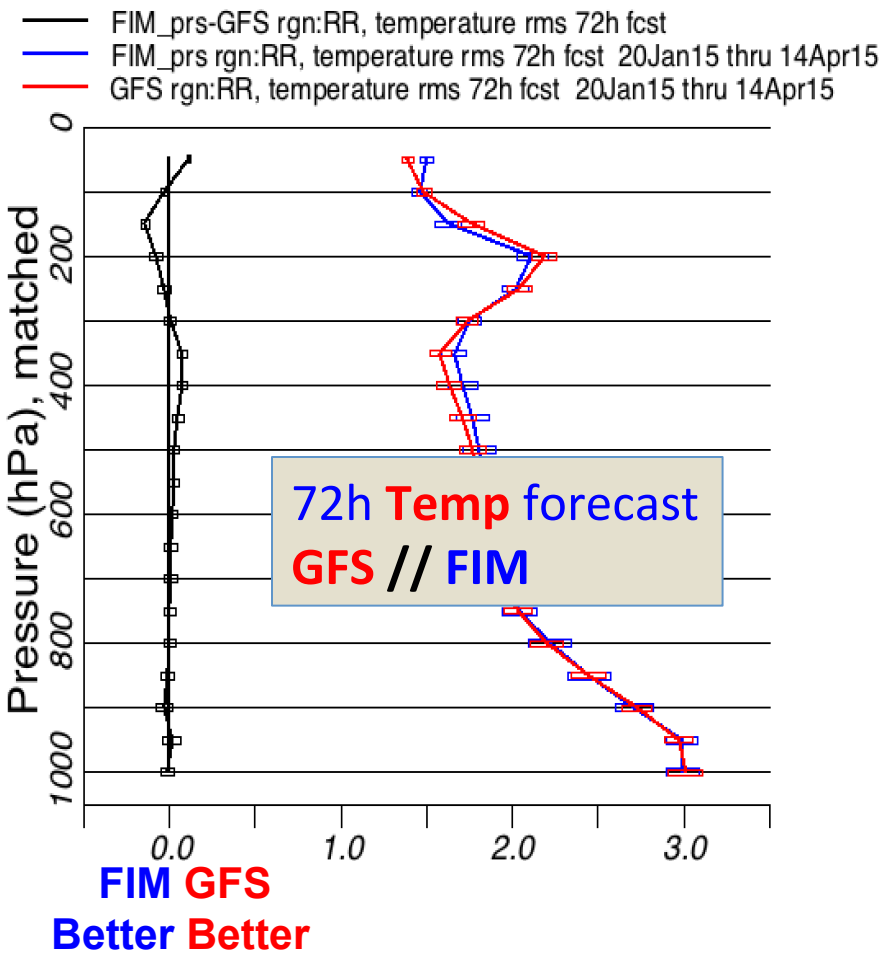


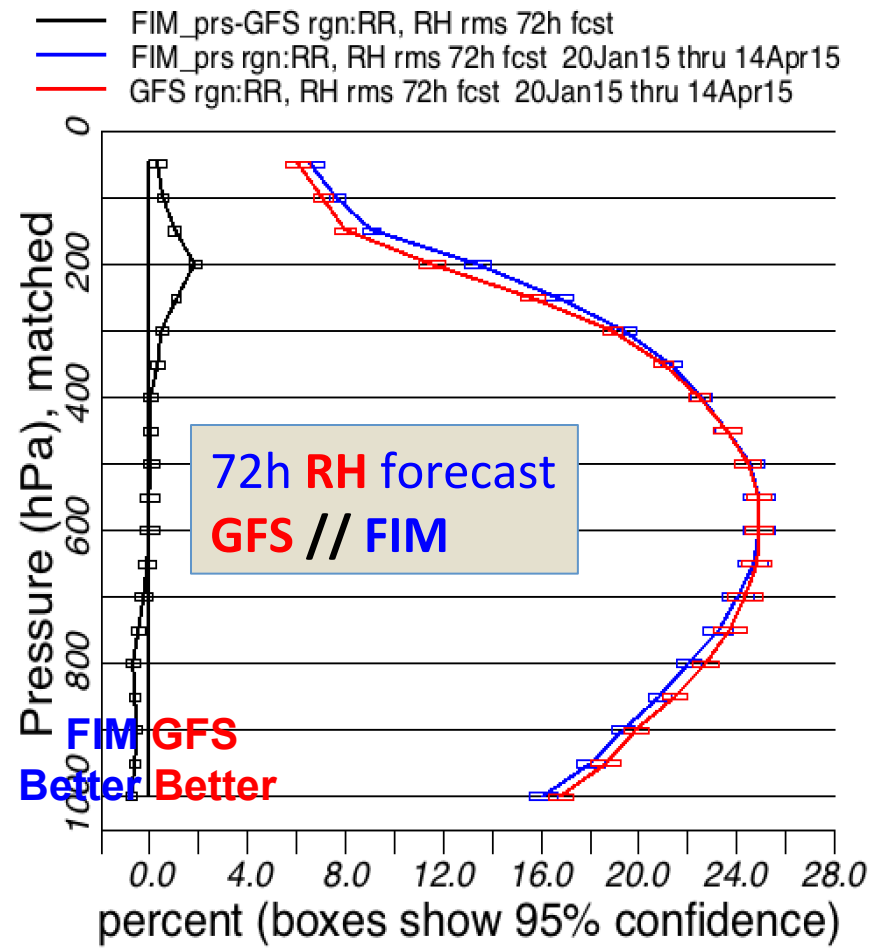


1 – FIM desc
2 – NWP skill
3 – experiments
4 - seasonal coupled exps

Temp/RH RMS error vs. raobs
N. America
GFS (T1534) // FIM-30km

RMS errors (smaller better) - verification with rawinsonde observations
–Jan-April 2015

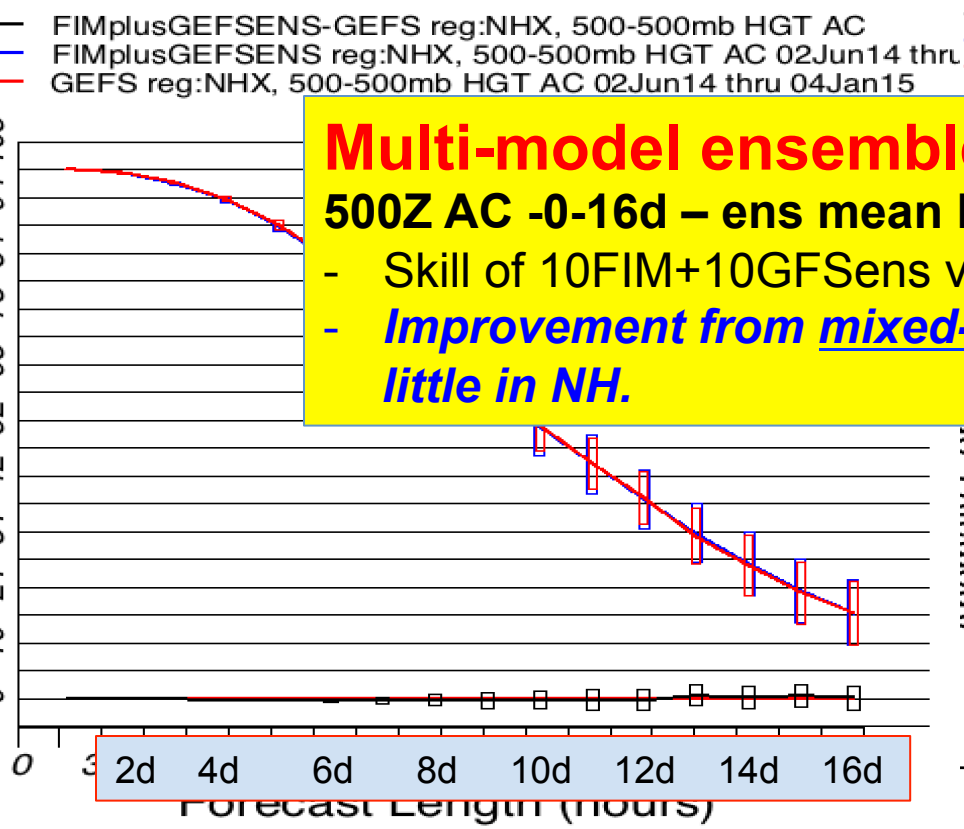


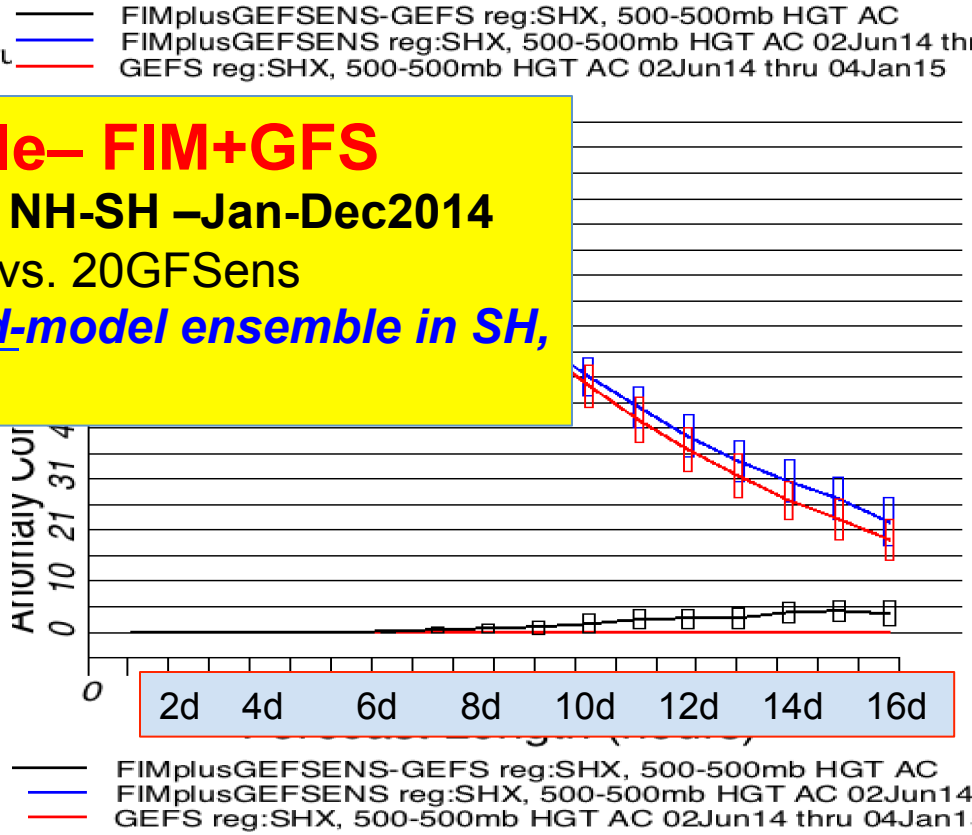


Multi-model ensemble– FIM+GFS

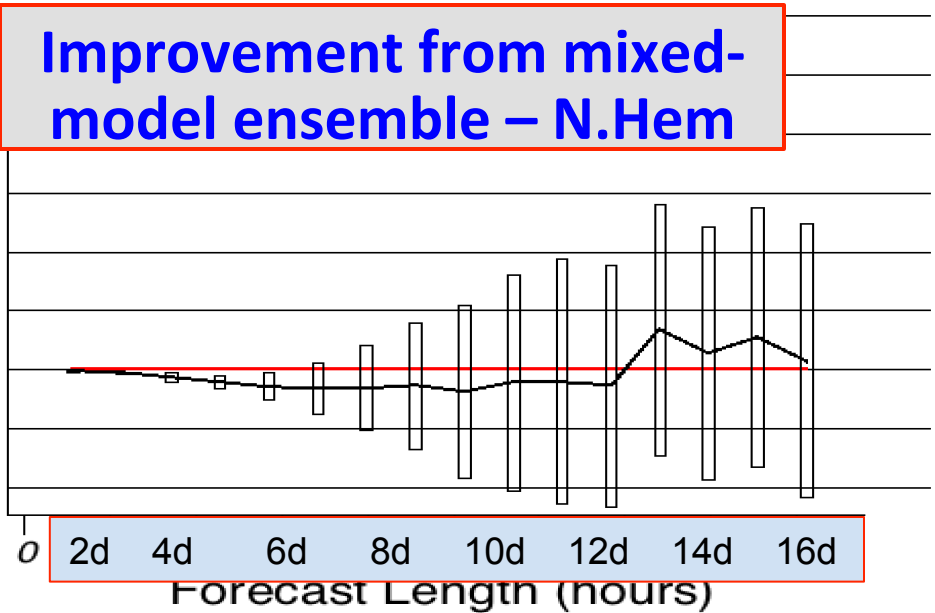
500Z AC -0-16d – ens mean NH-SH –Jan-Dec2014

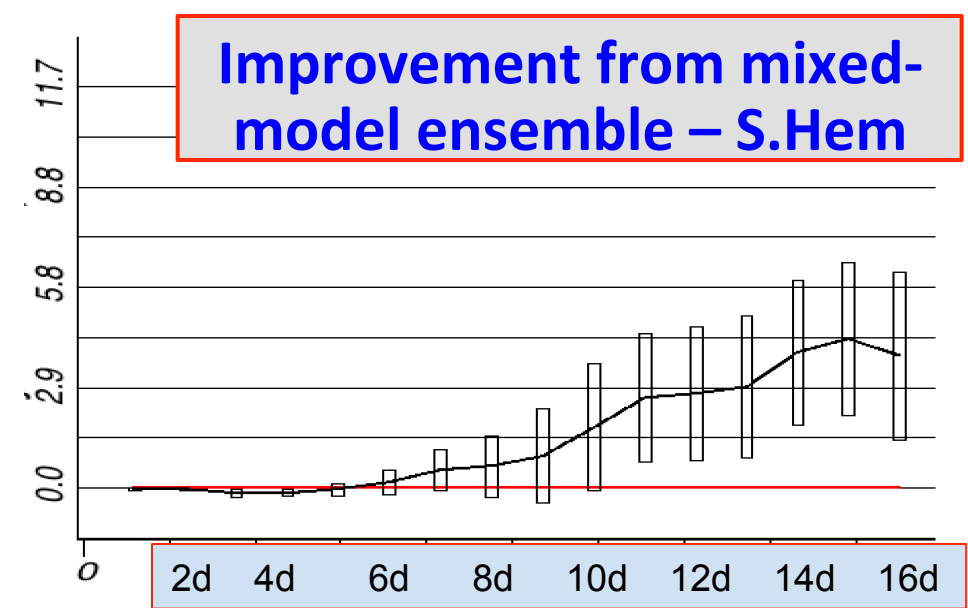
- Skill of 10FIM+10GFSens vs. 20GFSens
- ***Improvement from mixed-model ensemble in SH, little in NH.***



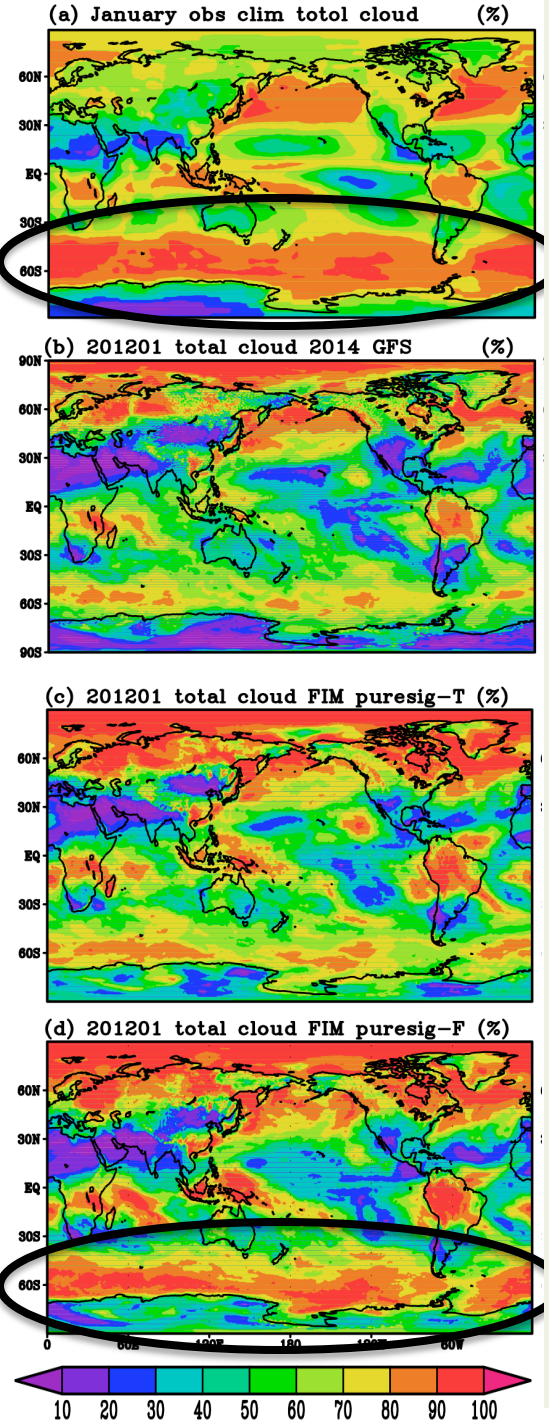


Improvement from mixed-model ensemble – N.Hem





Improvement from mixed-model ensemble – S.Hem



1-month – Jan 2012

Obs clouds

GFS with 2014 physics – T574

FIM with GFS-like sigma vert coord

FIM with θ−σ vert coord

Much better clouds, critical for coupled application esp. in southern oceans.

Atmos-only (AMIP) tests FIM/HYCOM coupled atmos/ ocean model – 1-month fcst

- Horizontal grid
  - **Icosahedral,** Δx=30km
- Vertical grid
  - **Hybrid θ−σ** option (64L)
  - **GFS-like σ-p opt** (64L)
- Physics - 2014-GFS, Grell-Freitas scale-aware cumulus

1 – FIM desc
2 – NWP skill
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Experiments – Coupled model – FIM-HYCOM – MJO case

- Horizontal resolution: 30km.
- Vertical: Atmos: 64 layers.
    - Ocean: 26 layers
  - Both using vertically adaptive grid
- Physics – atmos: GFS 2015 update physics
- Initial conditions: CFSR atmos & ocean
- Initial time: Dec 11, Jan 12, Feb 12
- Ensemble members 3 for each month
- Forecast duration: 2 months

For next slide…..

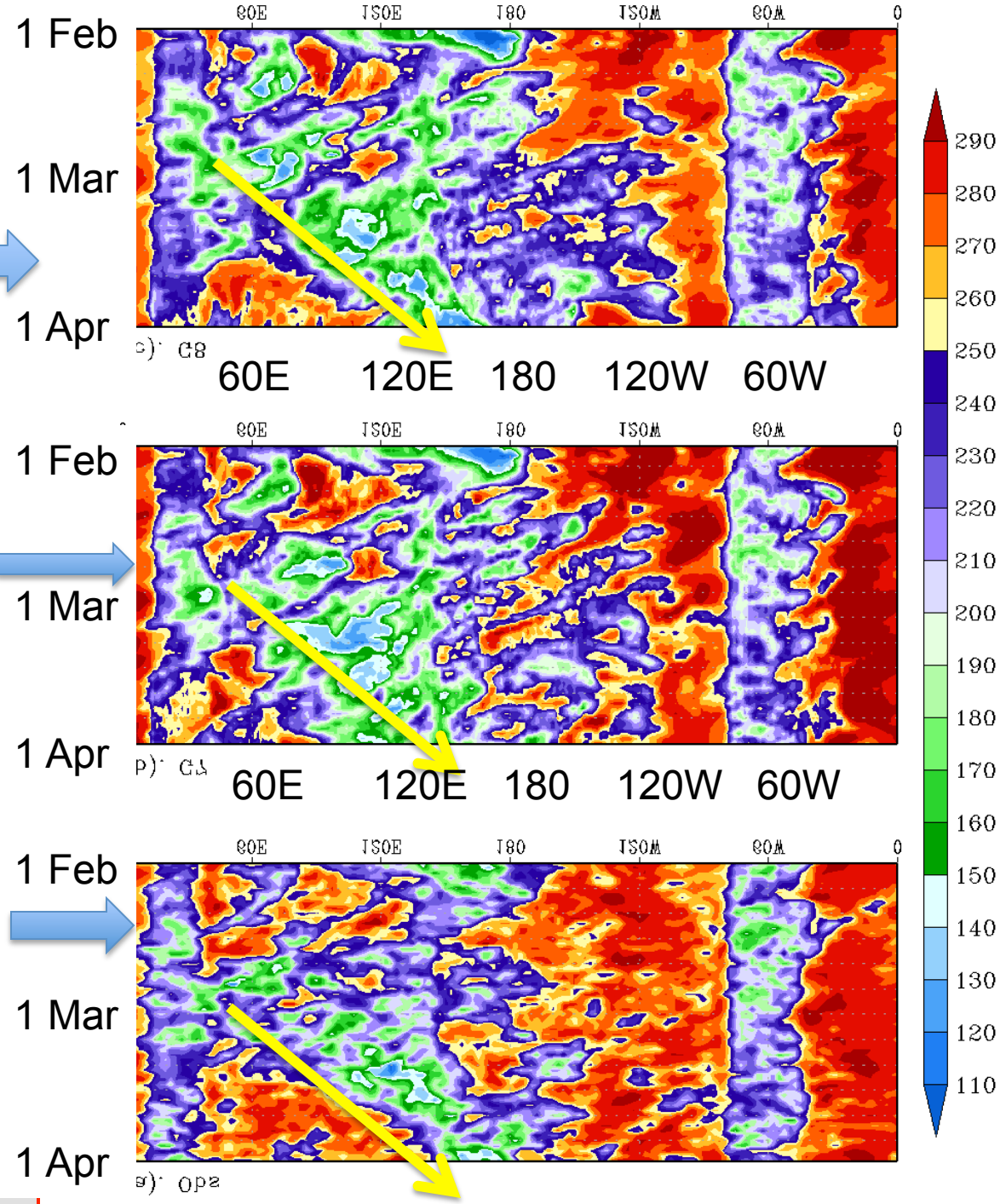
MJO event – OLR Outgoing Longwave Radiation

1Feb-1Apr 2012

Observed

60-day ens fcst - Coupled FIM-iHYCOM -60km (G7)

60-day ens fcst - Coupled FIM-iHYCOM -30km (G8)



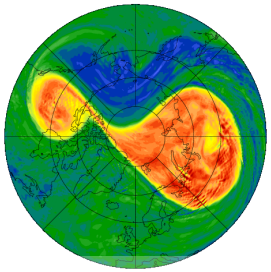
Improved MJO depiction 30km (vs. 60km)

Applications of FIM-HYCOM

- NWP application – AMIP only –
  - extensive real-time and retrospective runs
  - 15km FIM to 14d for 1-year HIWPP experiment to public
- Week 3-4 experiments – just starting
  - AMIP only but could do CMIP
- Seasonal experiments
- Next:
  - 30-year free run for ENSO frequency, 30y hindcasts

- **Physics option: Scale-aware/aerosol-aware convective parameterization (Grell and Freitas, 2014, AtmosChemPhys)**
  - Stochastic approach for closures adapted from the Grell-Devenyi convective scheme
  - Scale awareness through Arakawa (2011) approach (fractional coverage of sub-grid-scale updrafts/downdrafts) or spreading of subsidence
  - Transitions to shallow-cu scheme as grid spacing decreases

Key aspects of FIM global model



- **Characteristics**
  - Quasi-uniform icosahedral grid (run at 60-30-15-10km)
  - Quasi-lagrangian **θ-σ** vertical coordinate, **reduced vertical diffusion**
  - Coupled with icos-grid-matched HYCOM and inline atmospheric chemistry (WRF-chem)

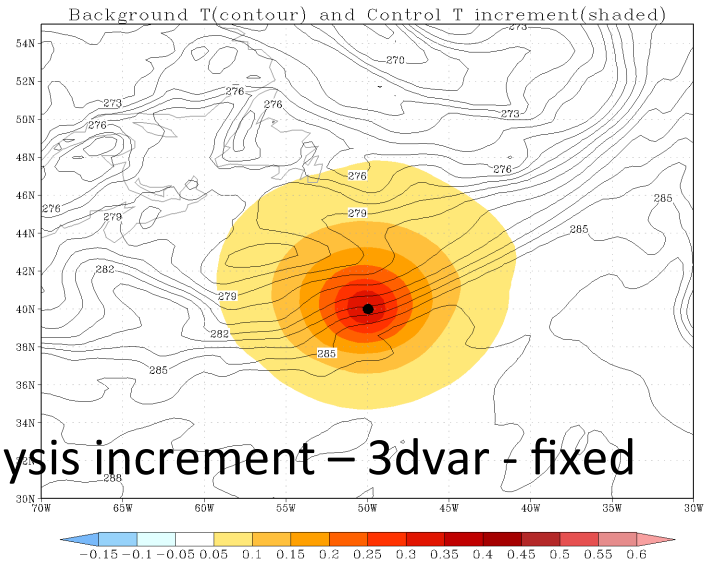
FIM model description
Bleck et al., 2015, *Mon.Wea.Rev.*, in press

- **Results**
  - Wind, RH forecasts improved over NCEP GFS
  - Improved 500z AC for S.Hem and N.Hemis for 6-8 days
  - **FIM+GFS mixed-model (10+10) ensemble better in S.Hem than current operational GFS-only NCEP global ensemble (20 mem)**
  - Improved 500h AC, stratospheric sudden warming, MJO, event, seasonal prediction with θ-σ vertical coordinate
- **Plans**
  - Testing with NCEP for mixed-model NWP ensemble, subseasonal- to–seasonal ensemble forecasts. 16-year hindcast starting – 30km
  - Earth system experiments with full atmospheric-ocean-inline-chem configuration,

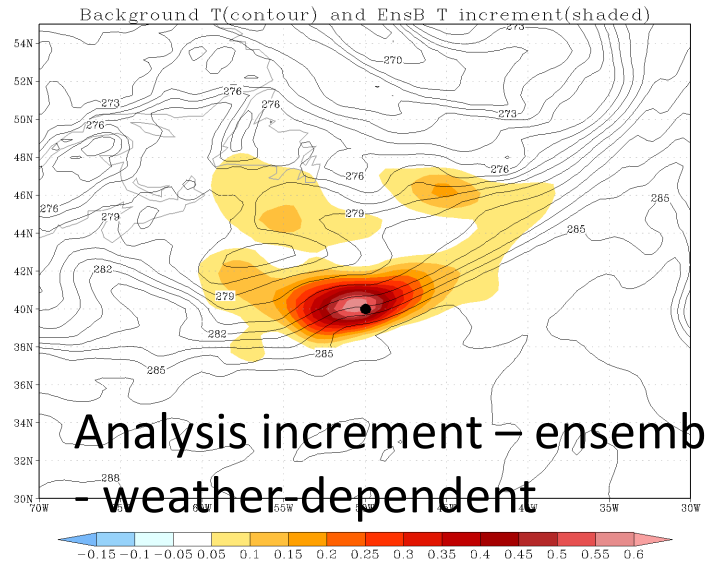
NOAA/ESRL/GSD/ Earth Modeling Branch grand challenges

- Storm-scale CONUS-wide 3km ens-based data assimilation and ensemble forecast modeling
- Earth-system global modeling capability with atmosphere, ocean, chemistry, ice, and land-surface components for research and potential operational applications.
- Common issues for 6h/3km and 6-mon/30km: subgrid-scale clouds, atmospheric chemistry, coupling with hydrology
- Collaboration with NOAA laboratories

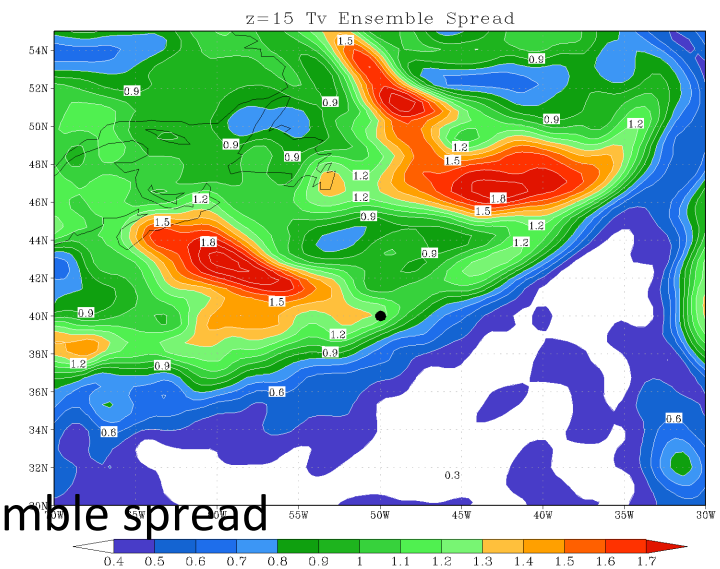
Use of Ensemble in Data Assimilation (different from ensemble forecasting)



Analysis increment – 3dvar - fixed



Analysis increment – ensemble - weather-dependent



Ensemble spread

RAP assimilation development

- Large improvement for winds /turbulence esp. from ensemble DA (from global ensemble)
- Need regional ens DA for improved clouds, radar, near-surface assimilation

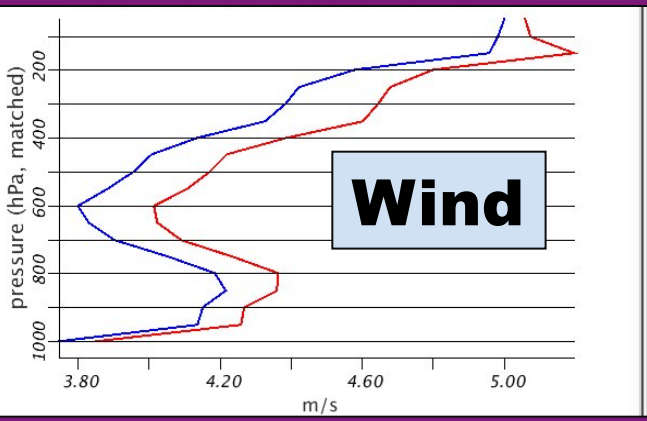
Single 850mb Tv observation (1K O-F, 1K error)

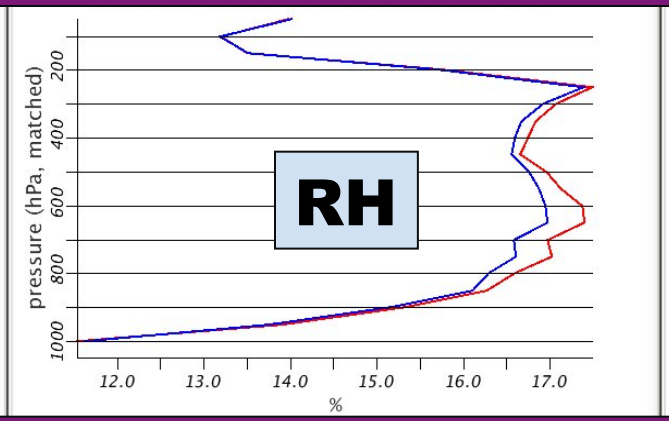
RAP Hybrid Data Assimilation

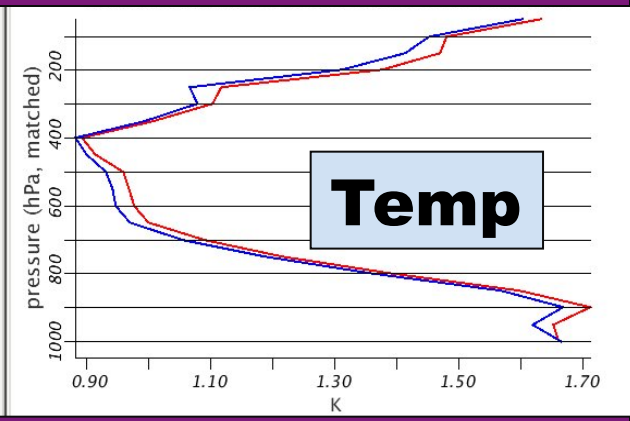
RMSE Vertical Profiles -- 22 Nov – 22 Dec 2012

RAP Hybrid **RAP No Hybrid (3D-VAR)**

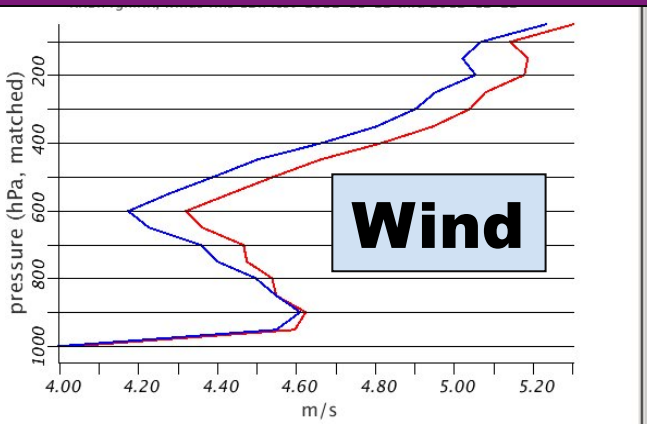
03-hr Forecast

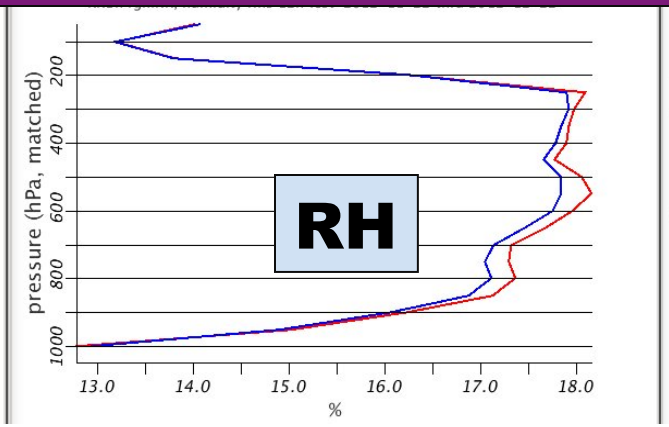


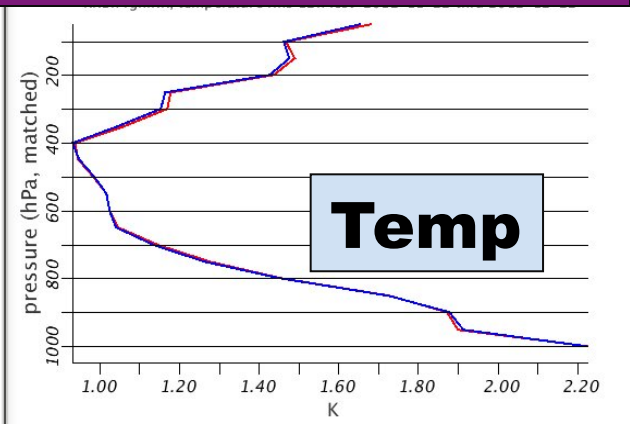




12-hr Forecast



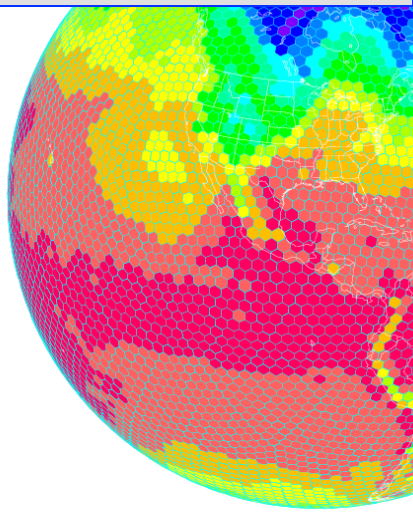


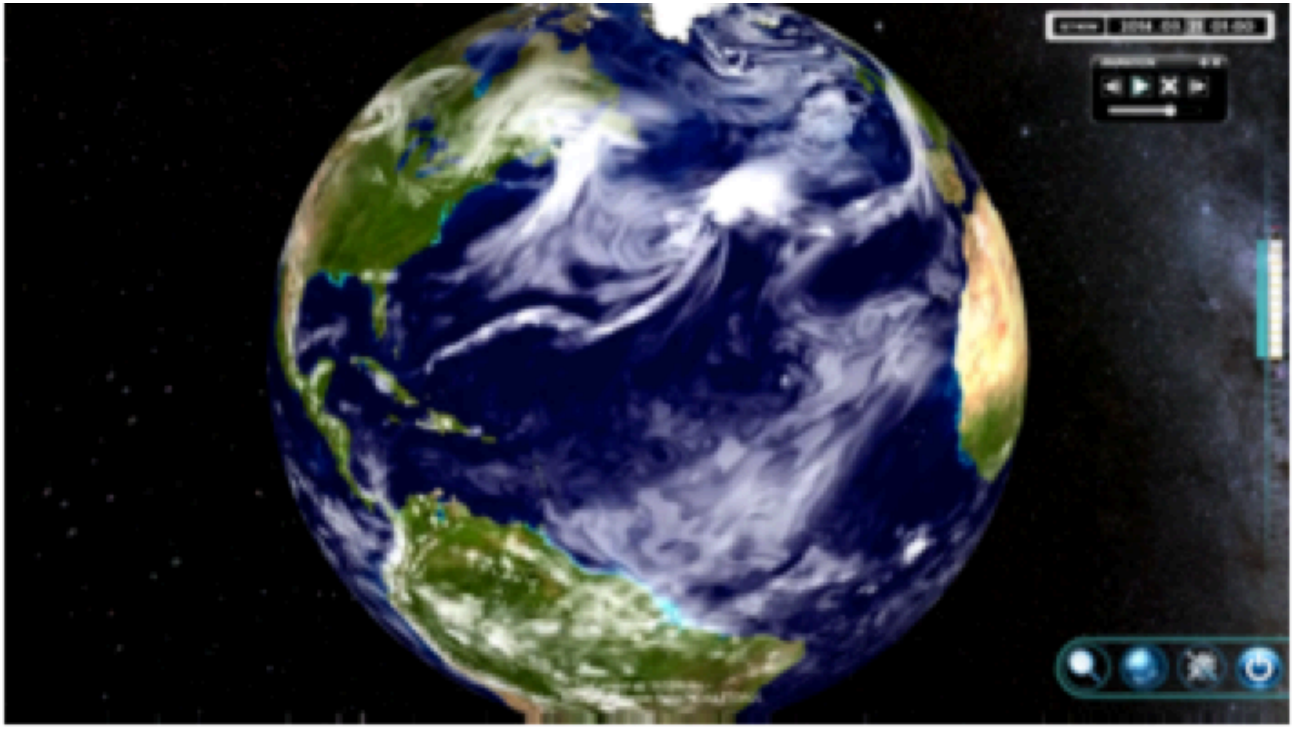


Improved upper-air fields, crucial for RAP / HRRR

Experiments with the FIM θ – global model for medium-range forecast duration

Stan Benjamin, Shan Sun, Rainer Bleck, Georg Grell,
Haiqin Li, Jian-Wen Bao, John Brown
NOAA Earth System Research Laboratory, Boulder CO USA



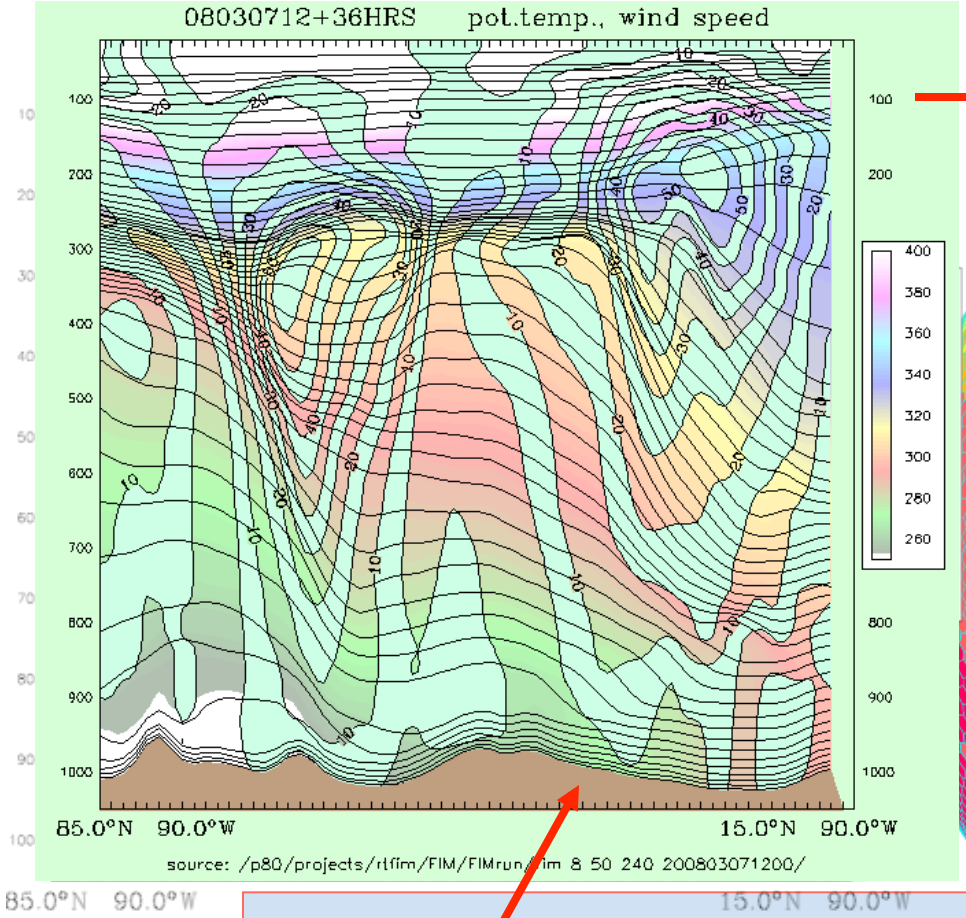


FIM global model – **10km,** 64 levels
Cloud - 10-day forecast init 00z 21 Mar 2014

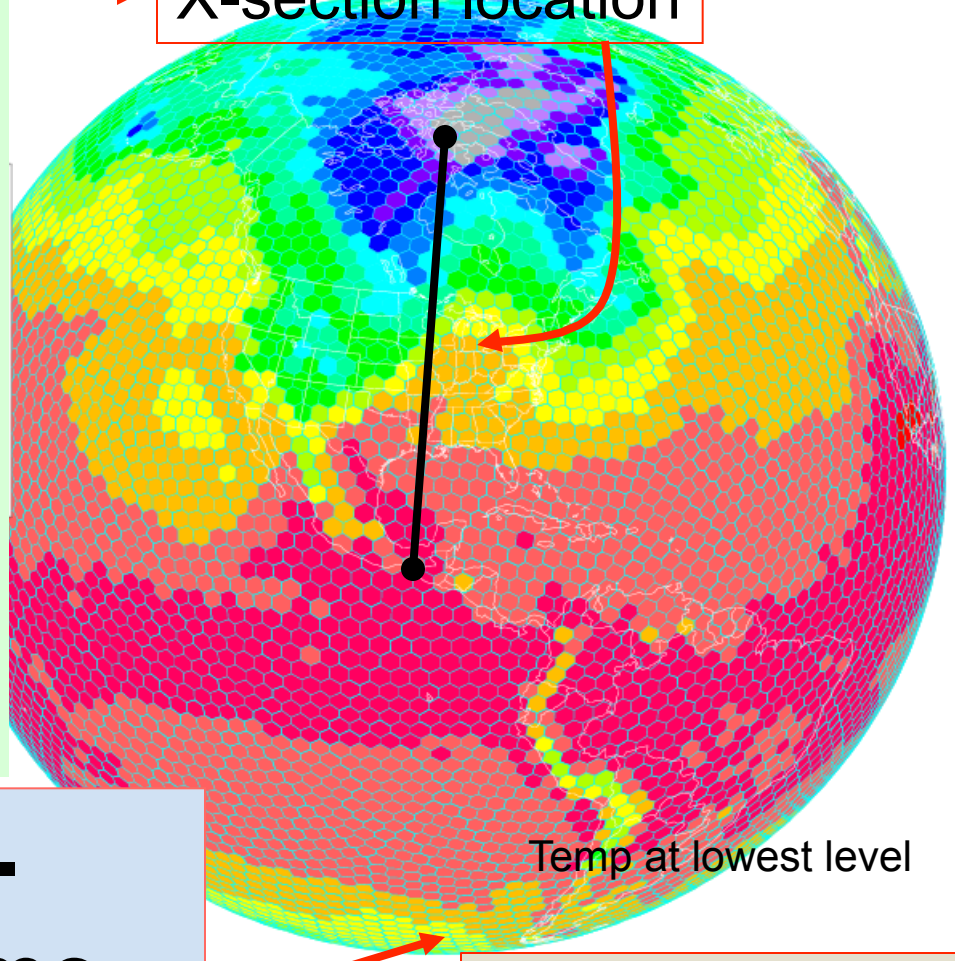
GLERL – Ann Arbor MI - May 2015

FIM model description
Bleck et al., 2015, *Mon.Wea.Rev.*, in press

http://fim.noaa.gov



X-section location



Temp at lowest level

Flow-following-
finite-volume
Icosahedral
Model FIM

1 – FIM desc
2 – NWP skill
3 – experiments
4 - seasonal coupled exps

Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

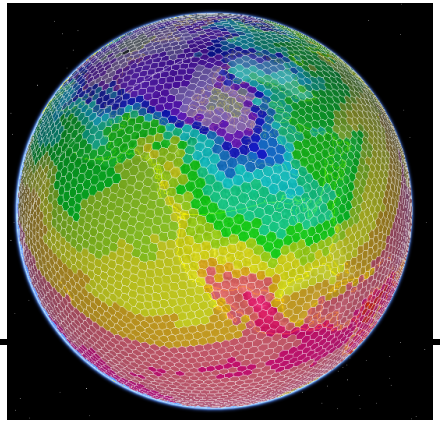
ESRL Finite-volume Icosahedral Models (FIM/NIM)

- **FIM (Flow-following finite-volume Icosahedral Model): A hydrostatic model for NCEP and NOAA research applications.**

- **Target resolution ≥ 10 km**

- **NIM (Nonhydrostatic Icosahedral model): A multi-scale global model for weather and intra-seasonal climate predictions.**

- **Target resolution : O(1 km) ~O(100 km)**



Novel features of FIM/NIM:

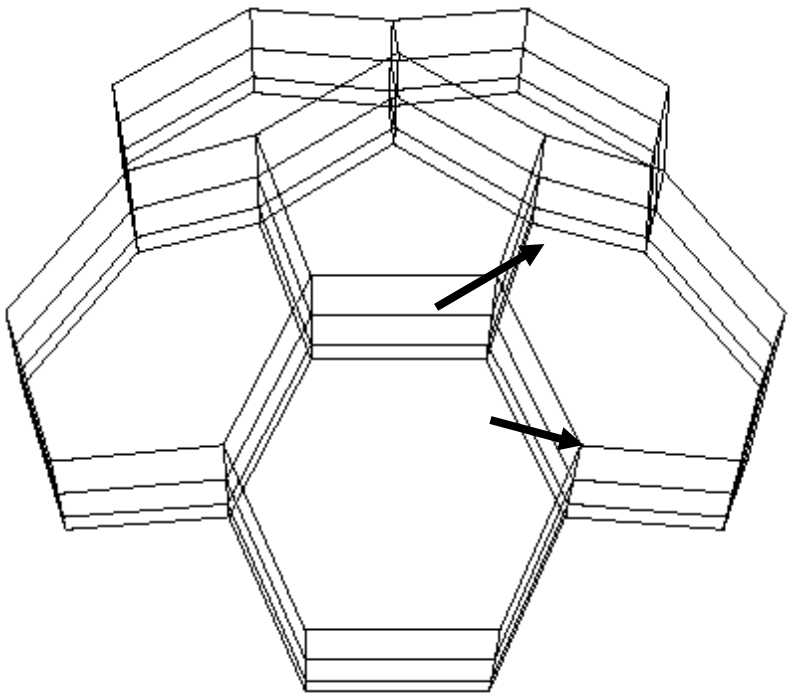
- **Finite-volume Integrations on *Local Coordinate***
- **FIM: Hybrid σ-θ Coordinate w/ GFS Physics**
- **Efficient Indirect Addressing Scheme on Irregular Grid**
- **Conservative and Monotonic Adams-Bashforth 3rd-order FCT Scheme**
- **Grid Optimization for Efficiency and Accuracy**
- **Novel Features of NIM:**

-Use of Three-dimensional Control Volume in Height Coordinate

-3-D Volume Integration to Improve pressure gradient force (PGF) accuracy

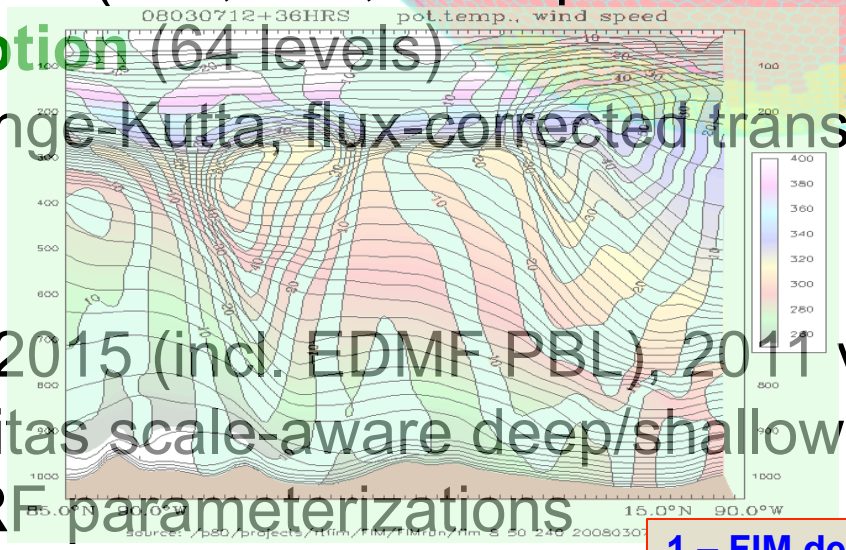
* extend surface integration to volume integration (S.-J. Lin, QJRMS,1997)

* use smooth terrain transformation (Klemp,MWR, 2011)



FIM numerical atmospheric model

- Horizontal grid
  - **Icosahedral,** Δx=240km/120km / 60km/30km/15km/10km
- Vertical grid
  - ptop = 0.5 hPa, θtop ~2200K
  - **Generalized vertical coordinate**
    - **Hybrid θ−σ** option (64L, 38L, 21L options currently)
    - **GFS-like σ-p option** (64 levels)
  - A-grid, 3rd-order Runge-Kutta, flux-corrected transport



- Physics
  - GFS physics suite: 2015 (incl. EDMF PBL), 2011 versions
  - Option for Grell-Freitas scale-aware deep/shallow cumulus
  - Option for other WRF parameterizations
- Coupled model extensions
  - Chem – WRF-chem/GOCART
  - Ocean – icosahedral HYCOM (no coupler), tri-polar HYCOM (with coupler)

1 – FIM desc
2 – NWP skill
3 – experiments
4 - seasonal coupled exps

FIM design – adaptive vertical coordinate

Hybrid (sigma/ isentropic) vertical coordinate

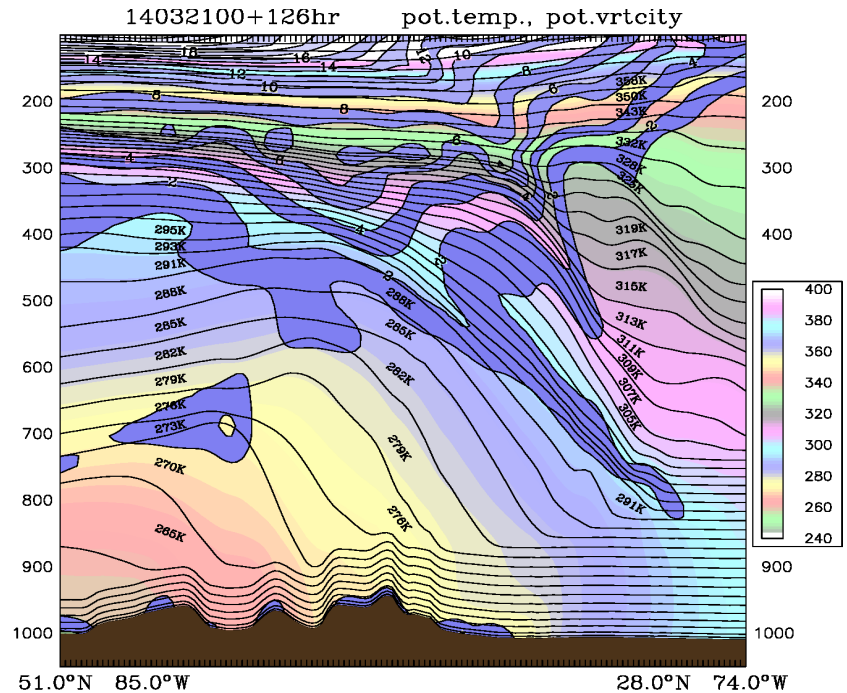
- Improved conservation using quasi-material surfaces, reduced vertical dispersion.

Improved transport by reducing numerical dispersion from vertical cross-coordinate transport, ***improved stratospheric/tropospheric exchange.***

- Used in NCEP Rapid Update Cycle (RUC) model
- Used in HYCOM ocean model

Installed as generalized "s" vertical coordinate

- can be replaced with sigma-p or other coordinates.



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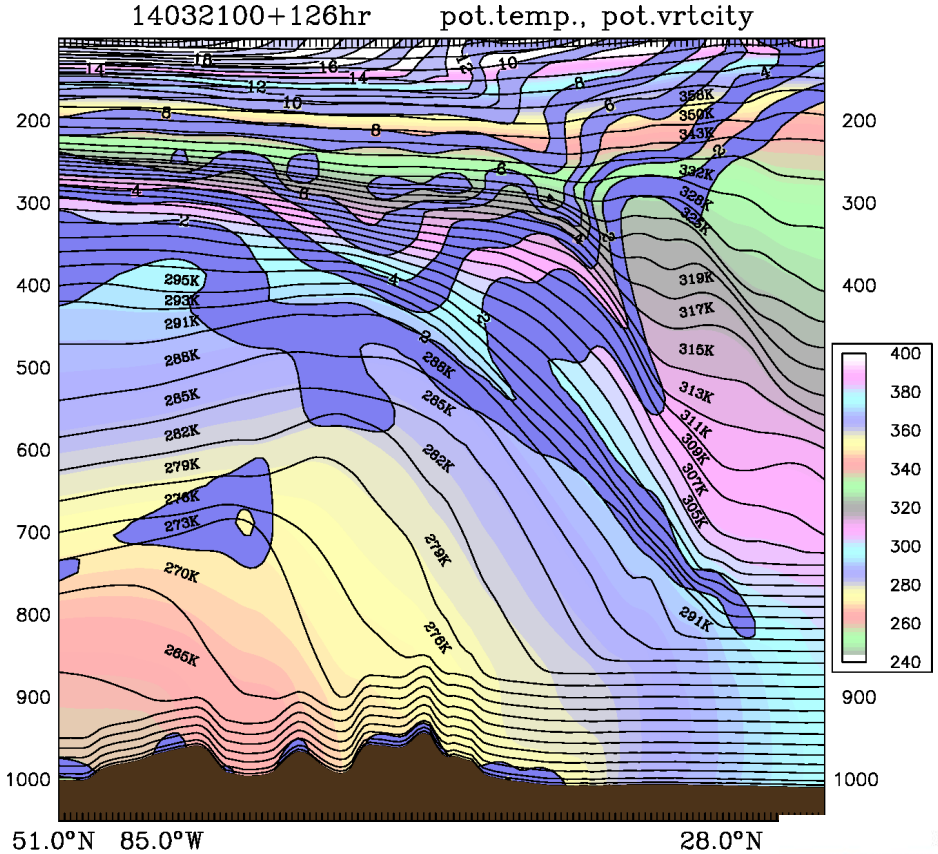
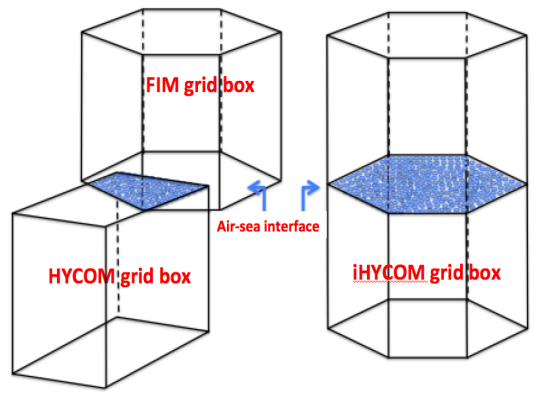


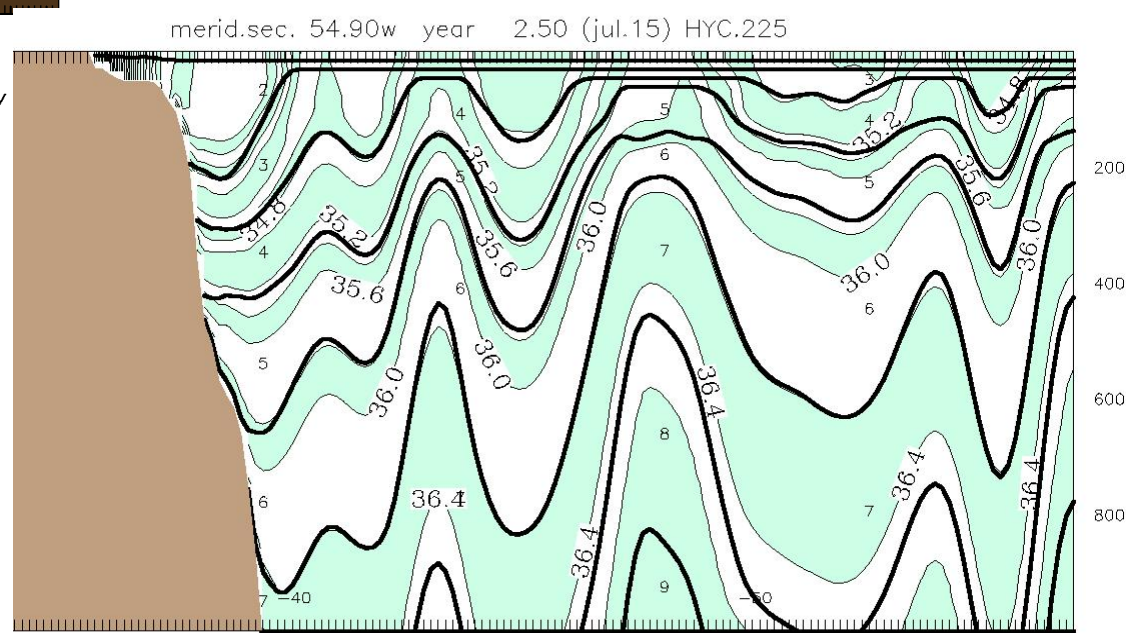
FIM vertical section. Heavy black lines: coordinate surfaces. Colored field: pot.temperature (K). Shaded contours: potential vorticity.



fimG8

source: .../BMC/fim/bleck/trunk/FIMrun/zeussubfim 5725/fim8 64 480/fim/

iHYCOM vertical section. Heavy black lines: coordinate surfaces. Shaded contours: potential density ($\sigma 2$)

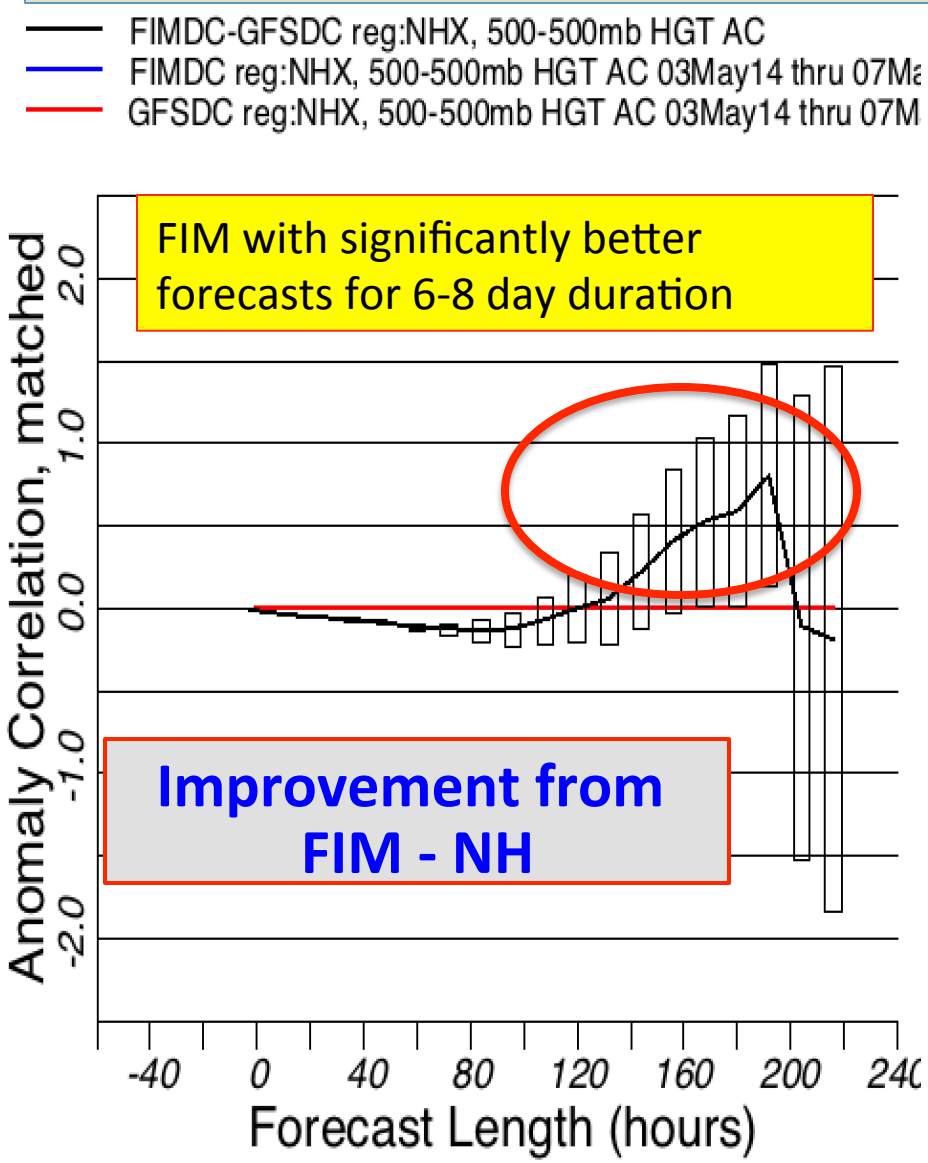


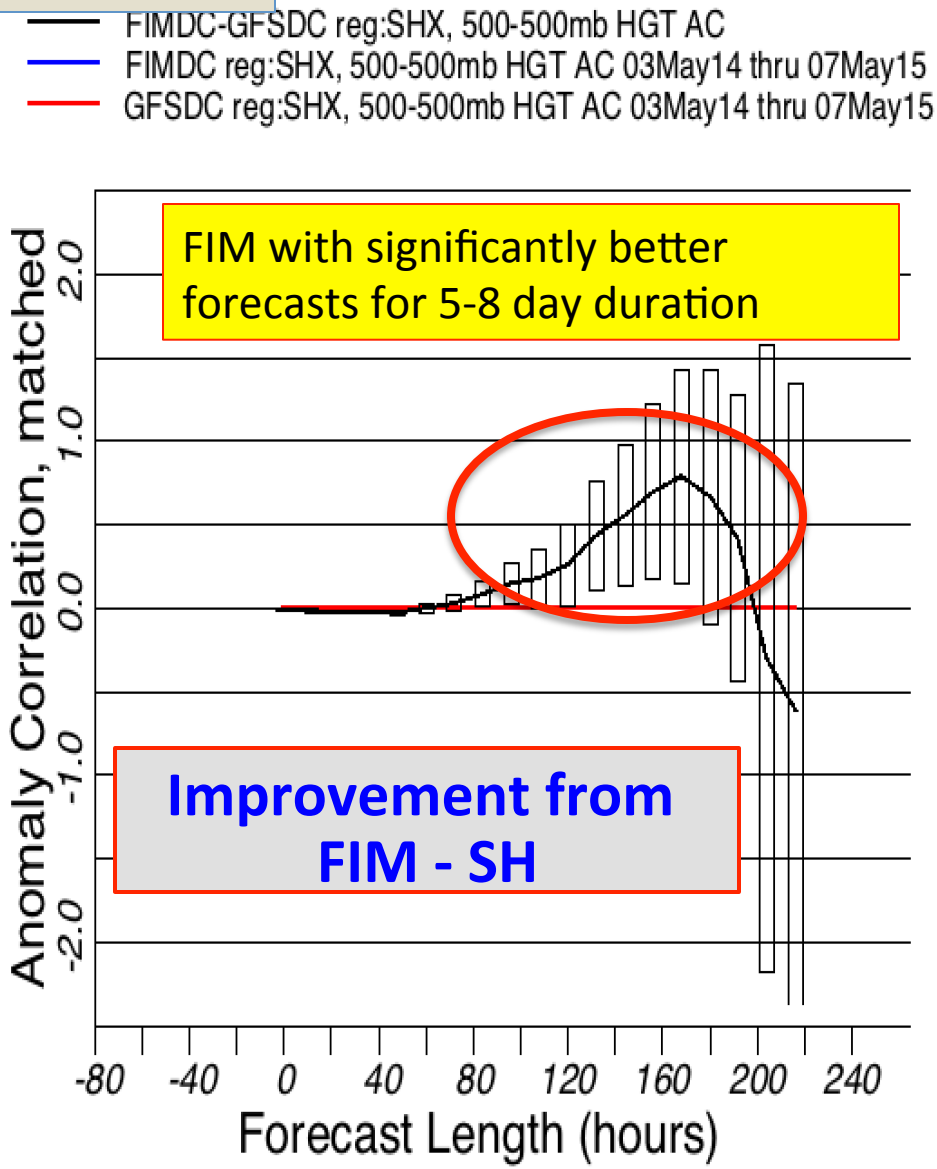
Coupled atm/ocean model with

- *matched icosahedral grid*
- *adaptive vert coord in both atmsphere and ocean*

500-hPa Height Anomaly Correlation FIM-30km (GFS init, GFS phys) vs. GFS NCEP operational

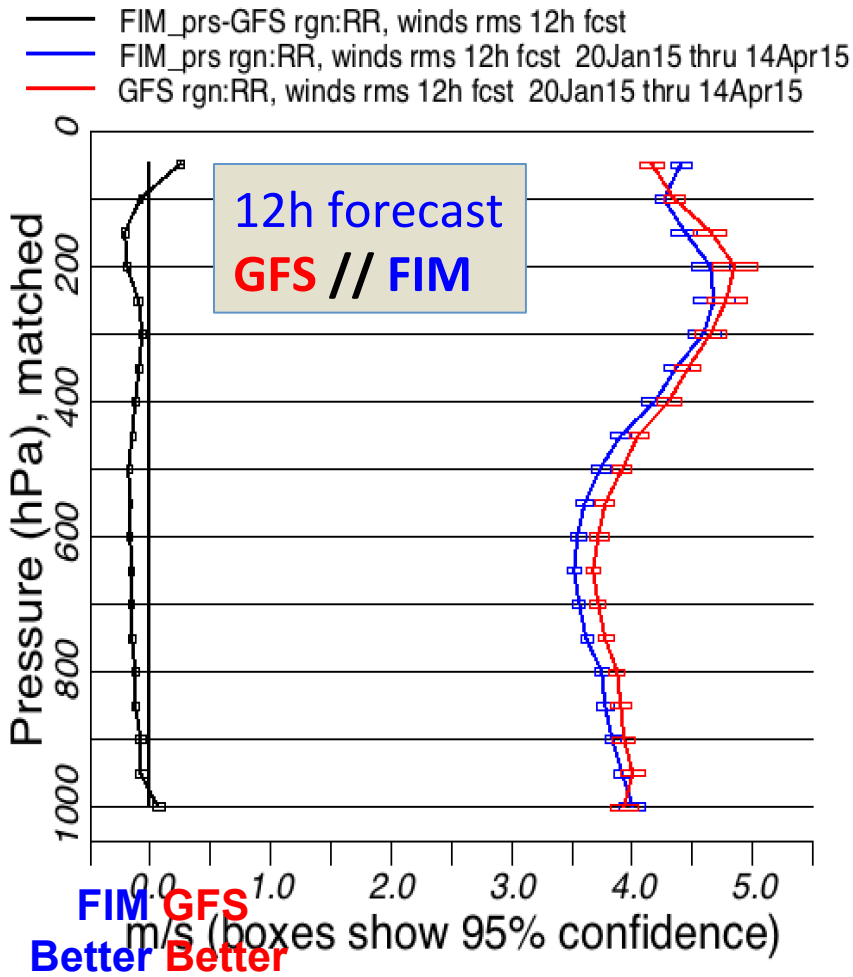
12-month NWP test May 2014 -May 2015

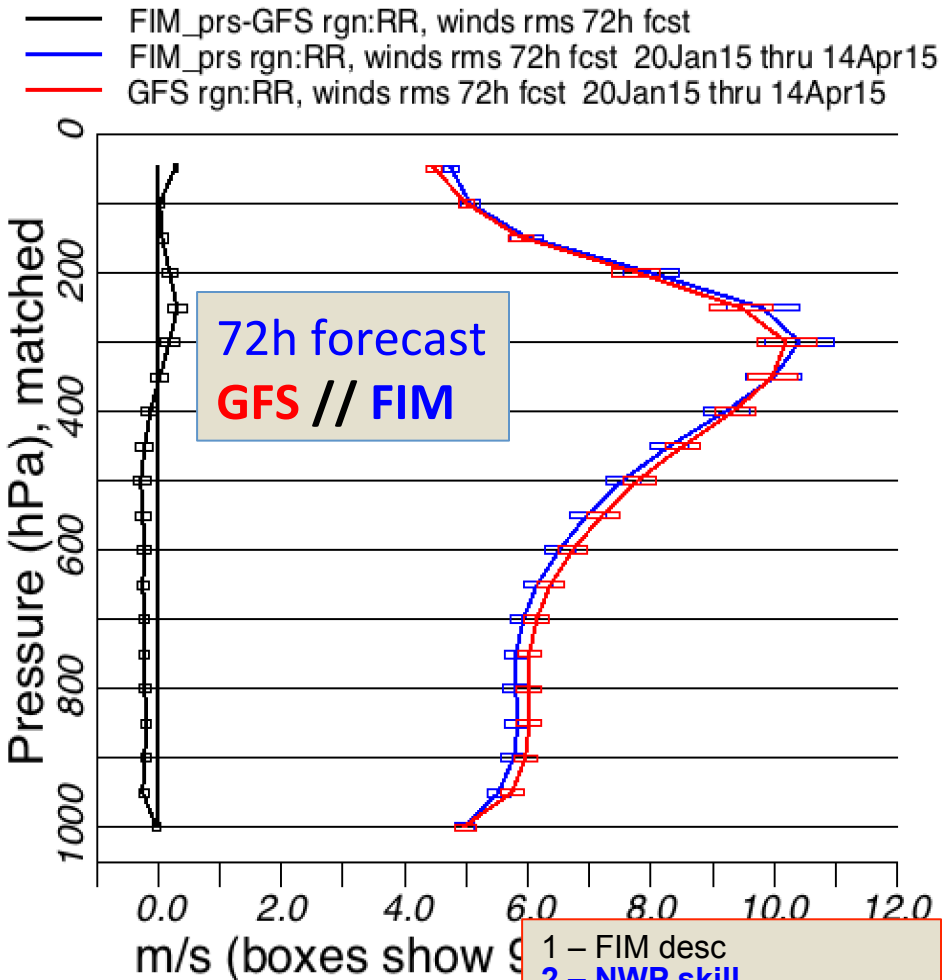




Wind RMS error vs. raobs
N. America
GFS (T1534) // FIM-30km
Both using 0.5 lat/lon

RMS errors (smaller better) - verification with rawinsonde observations
–Jan-April 2015





1 – FIM desc
2 – NWP skill
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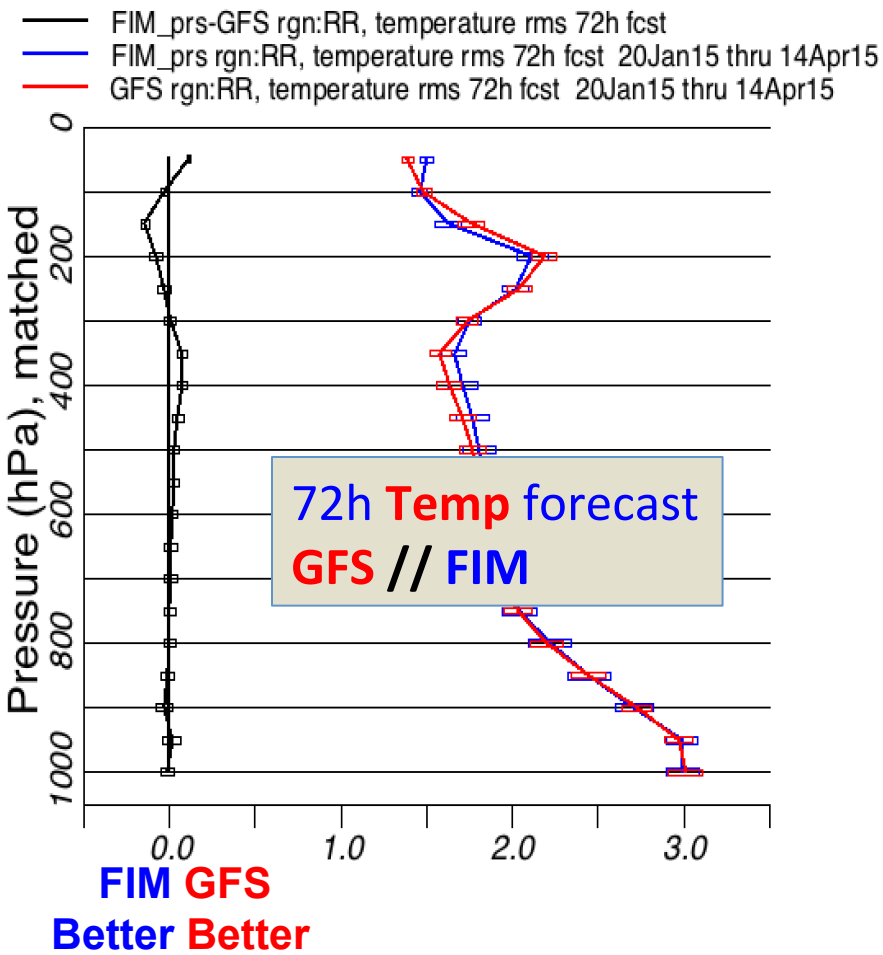
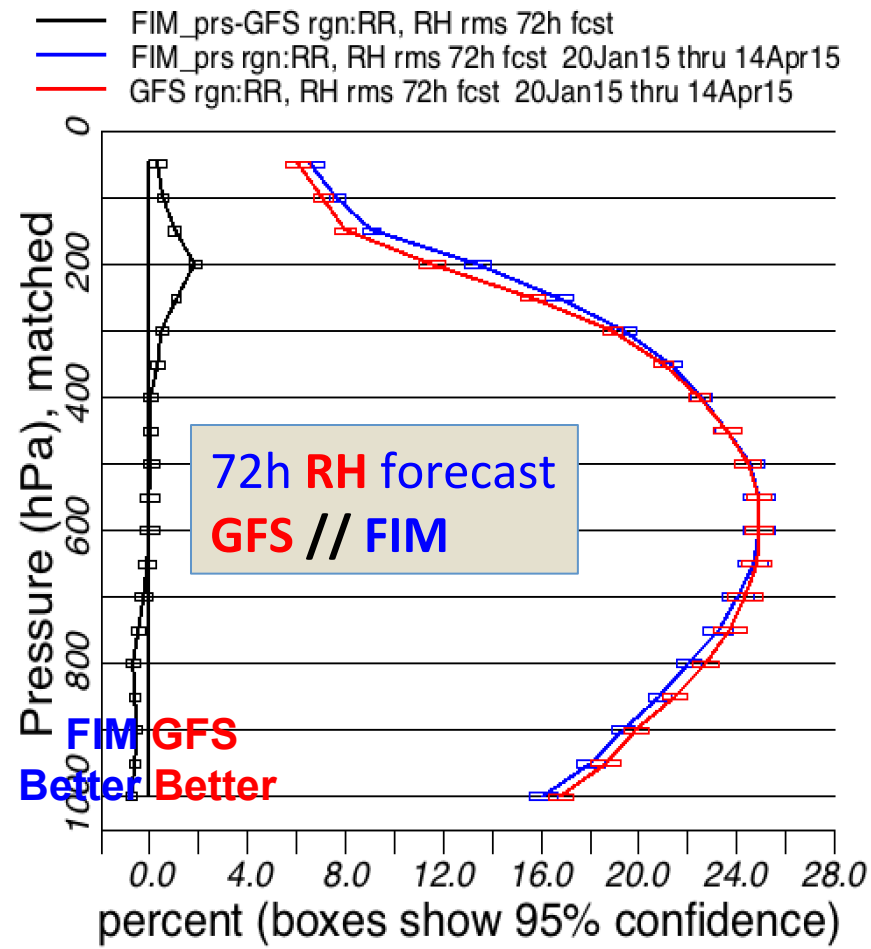
Temp/RH RMS error vs. raobs
N. America
GFS (T1534) // FIM-30km

RMS errors (smaller better) - verification with rawinsonde observations
–Jan-April 2015

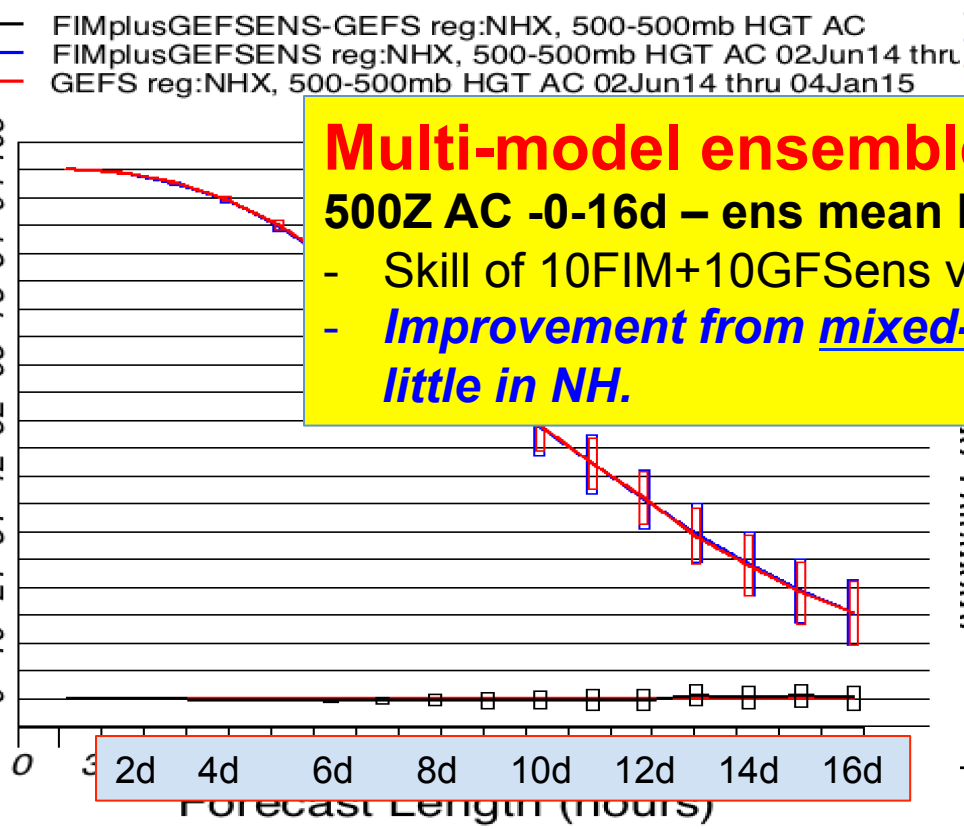


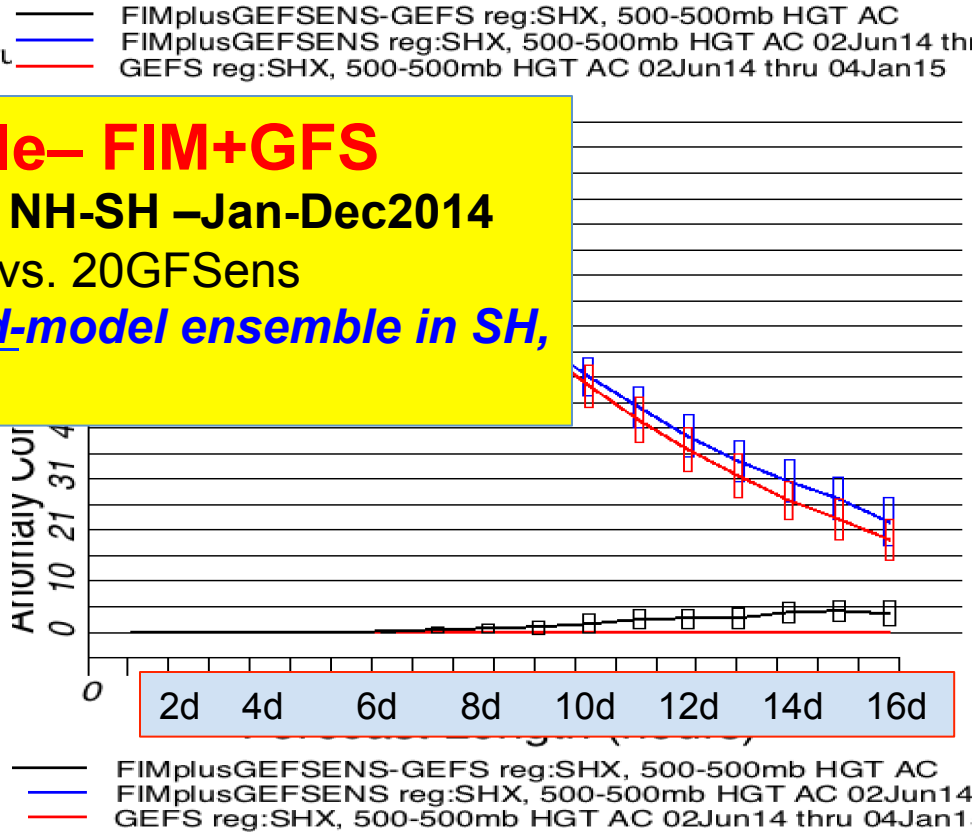


Multi-model ensemble– FIM+GFS

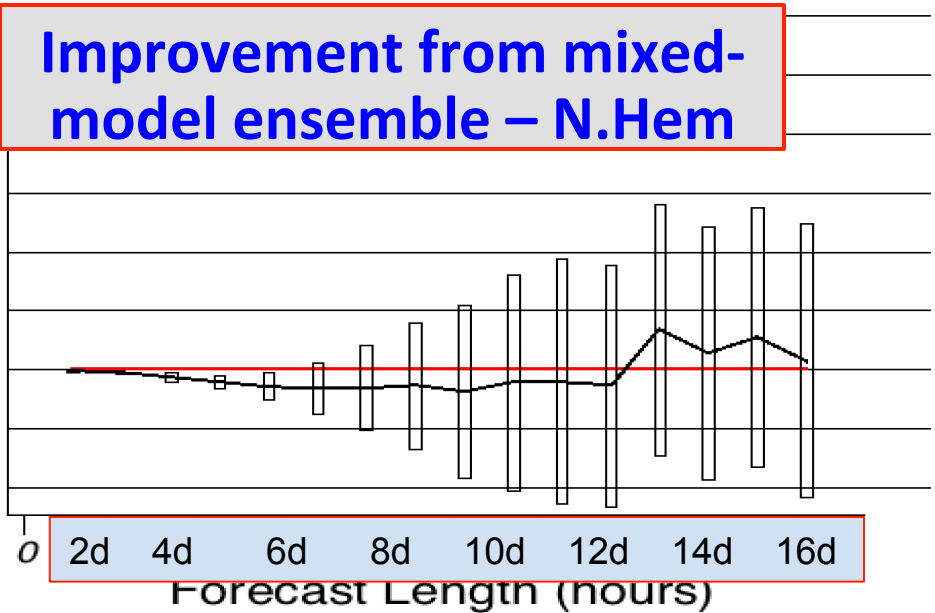
500Z AC -0-16d – ens mean NH-SH –Jan-Dec2014

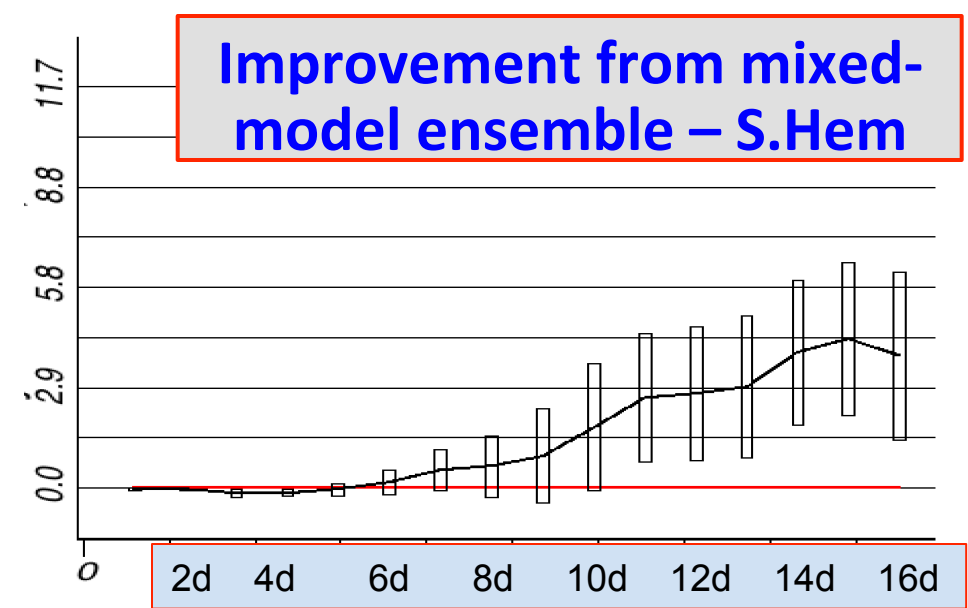
- Skill of 10FIM+10GFSens vs. 20GFSens
- ***Improvement from mixed-model ensemble in SH, little in NH.***



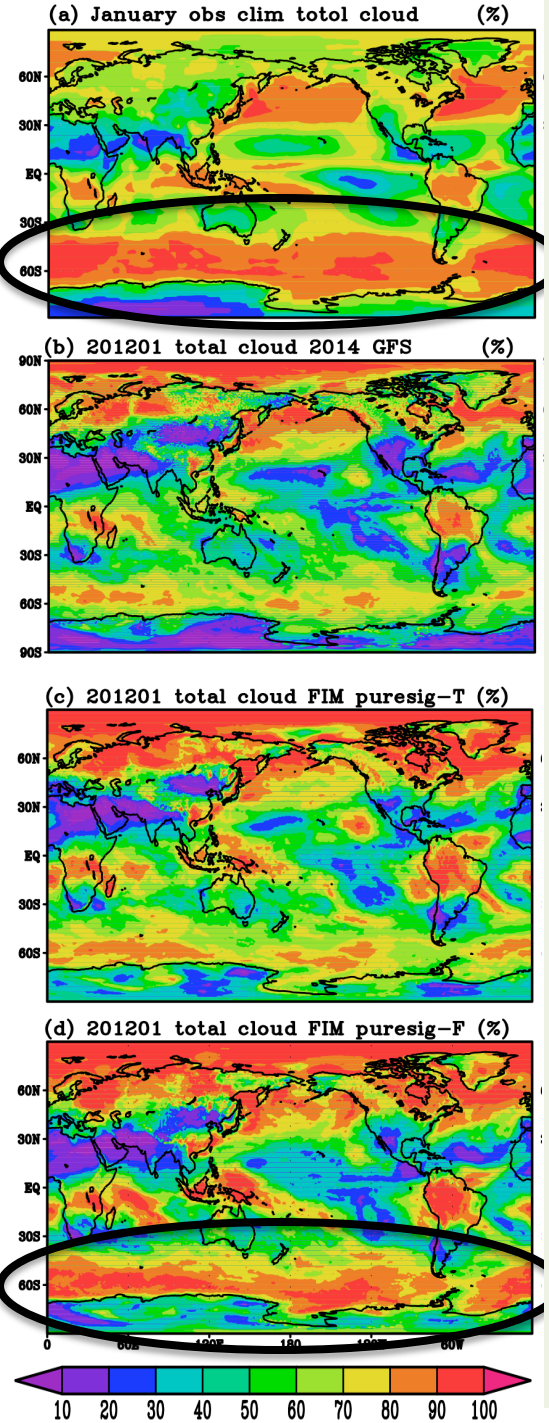


Improvement from mixed-model ensemble – N.Hem





Improvement from mixed-model ensemble – S.Hem



1-month – Jan 2012

Obs clouds

GFS with 2014 physics – T574

FIM with GFS-like sigma vert coord

FIM with θ−σ vert coord

Much better clouds, critical for coupled application esp. in southern oceans.

Atmos-only (AMIP) tests FIM/HYCOM coupled atmos/ ocean model – 1-month fcst

- Horizontal grid
  - **Icosahedral,** Δx=30km
- Vertical grid
  - **Hybrid θ−σ** option (64L)
  - **GFS-like σ-p opt** (64L)
- Physics - 2014-GFS, Grell-Freitas scale-aware cumulus

1 – FIM desc
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Experiments – Coupled model – FIM-HYCOM – MJO case

- Horizontal resolution: 30km.
- Vertical: Atmos: 64 layers.
    - Ocean: 26 layers
  - Both using vertically adaptive grid
- Physics – atmos: GFS 2015 update physics
- Initial conditions: CFSR atmos & ocean
- Initial time: Dec 11, Jan 12, Feb 12
- Ensemble members 3 for each month
- Forecast duration: 2 months

For next slide…..

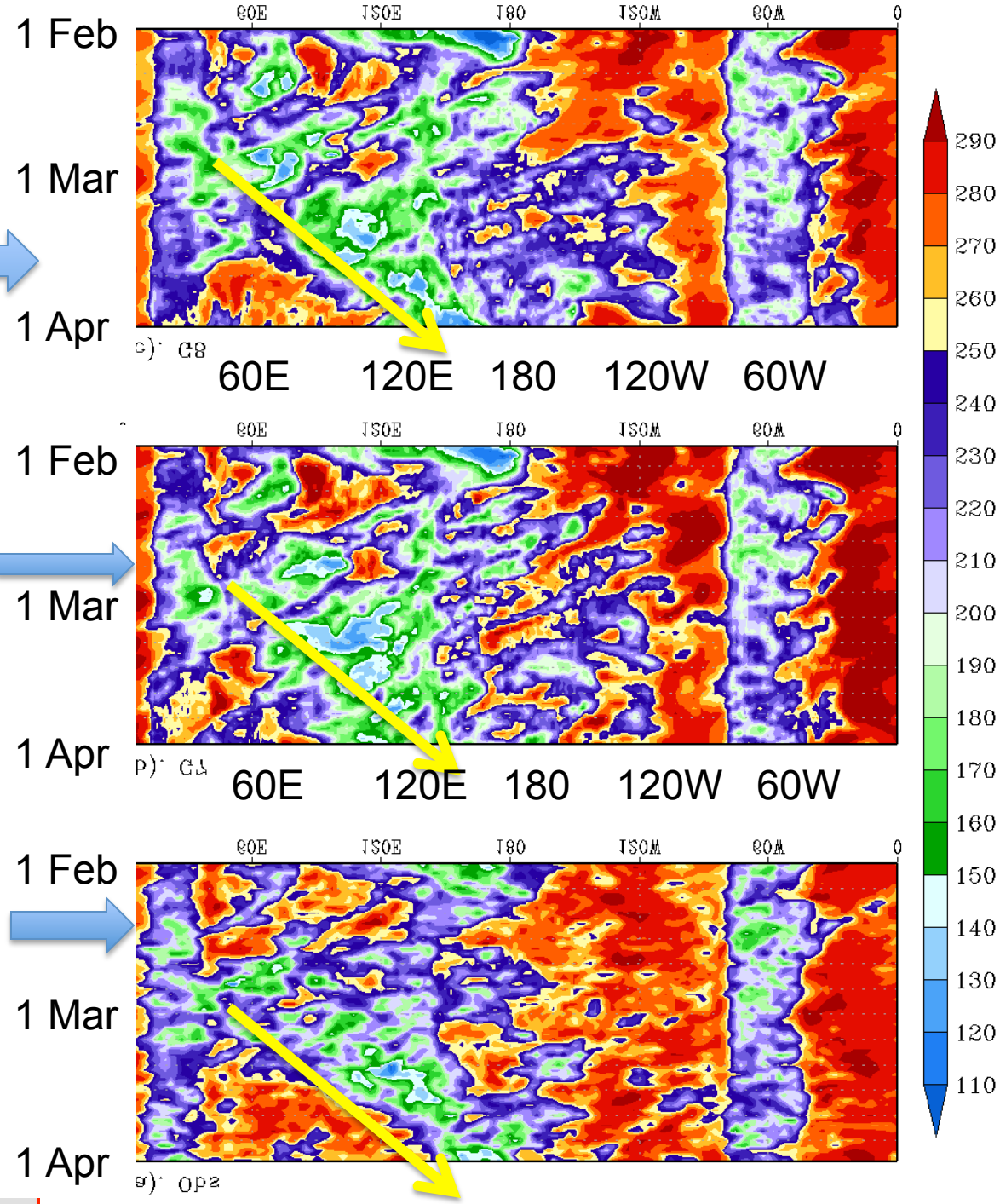
MJO event – OLR Outgoing Longwave Radiation

1Feb-1Apr 2012

Observed

60-day ens fcst - Coupled FIM-iHYCOM -60km (G7)

60-day ens fcst - Coupled FIM-iHYCOM -30km (G8)



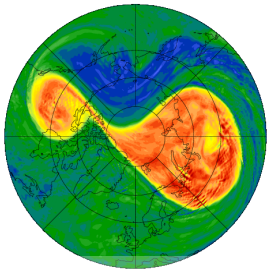
Improved MJO depiction 30km (vs. 60km)

Applications of FIM-HYCOM

- NWP application – AMIP only –
  - extensive real-time and retrospective runs
  - 15km FIM to 14d for 1-year HIWPP experiment to public
- Week 3-4 experiments – just starting
  - AMIP only but could do CMIP
- Seasonal experiments
- Next:
  - 30-year free run for ENSO frequency, 30y hindcasts

- **Physics option: Scale-aware/aerosol-aware convective parameterization (Grell and Freitas, 2014, AtmosChemPhys)**
  - Stochastic approach for closures adapted from the Grell-Devenyi convective scheme
  - Scale awareness through Arakawa (2011) approach (fractional coverage of sub-grid-scale updrafts/downdrafts) or spreading of subsidence
  - Transitions to shallow-cu scheme as grid spacing decreases

Key aspects of FIM global model



- **Characteristics**
  - Quasi-uniform icosahedral grid (run at 60-30-15-10km)
  - Quasi-lagrangian **θ-σ** vertical coordinate, **reduced vertical diffusion**
  - Coupled with icos-grid-matched HYCOM and inline atmospheric chemistry (WRF-chem)

FIM model description
Bleck et al., 2015, *Mon.Wea.Rev.*, in press

- **Results**
  - Wind, RH forecasts improved over NCEP GFS
  - Improved 500z AC for S.Hem and N.Hemis for 6-8 days
  - **FIM+GFS mixed-model (10+10) ensemble better in S.Hem than current operational GFS-only NCEP global ensemble (20 mem)**
  - Improved 500h AC, stratospheric sudden warming, MJO, event, seasonal prediction with θ-σ vertical coordinate
- **Plans**
  - Testing with NCEP for mixed-model NWP ensemble, subseasonal- to–seasonal ensemble forecasts. 16-year hindcast starting – 30km
  - Earth system experiments with full atmospheric-ocean-inline-chem configuration,

NOAA/ESRL/GSD/ Earth Modeling Branch grand challenges

- Storm-scale CONUS-wide 3km ens-based data assimilation and ensemble forecast modeling
- Earth-system global modeling capability with atmosphere, ocean, chemistry, ice, and land-surface components for research and potential operational applications.
- Common issues for 6h/3km and 6-mon/30km: subgrid-scale clouds, atmospheric chemistry, coupling with hydrology
- Collaboration with NOAA laboratories