International Workshop on Source Term Estimation (STE) Methods for Estimating the Atmospheric Radiation Release from the Fukushima Daiichi Nuclear Power Plant. Boulder, CO. Feb. 22 – 24, 2012

Mesoscale Modeling and Data assimilation for Atmospheric Transport and Fate of Radioactive Materials

Yubao Liu (RAL/NSAP)

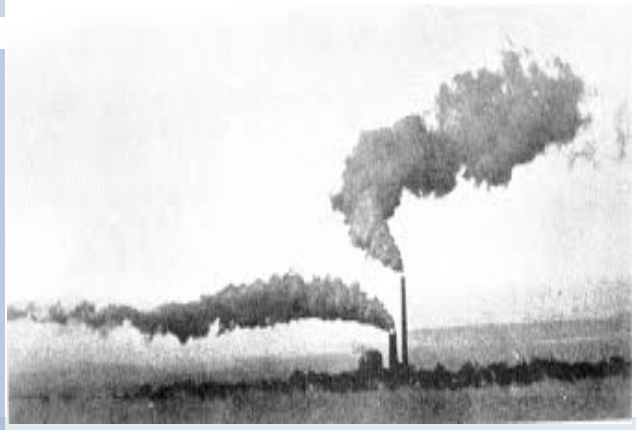
(National Center for Atmospheric Research)

NCAR

NSF

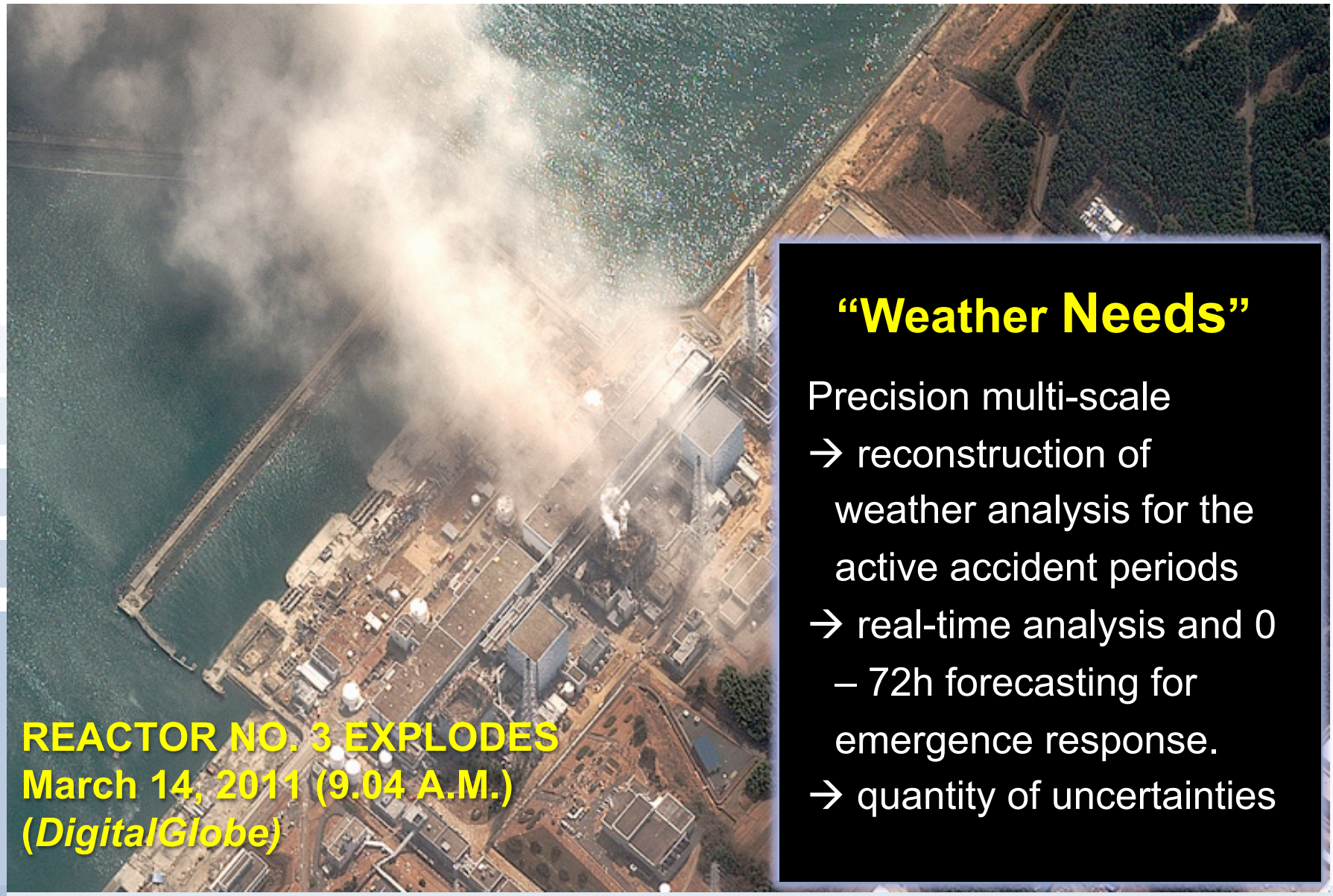
Many Applications Critically Rely on Weather / Atmospheric Flows

NCAR



And, of course, Nuclear Releases…

NCAR



REACTOR NO. 3 EXPLODES
March 14, 2011 (9.04 A.M.)
(*DigitalGlobe*)

"Weather Needs"

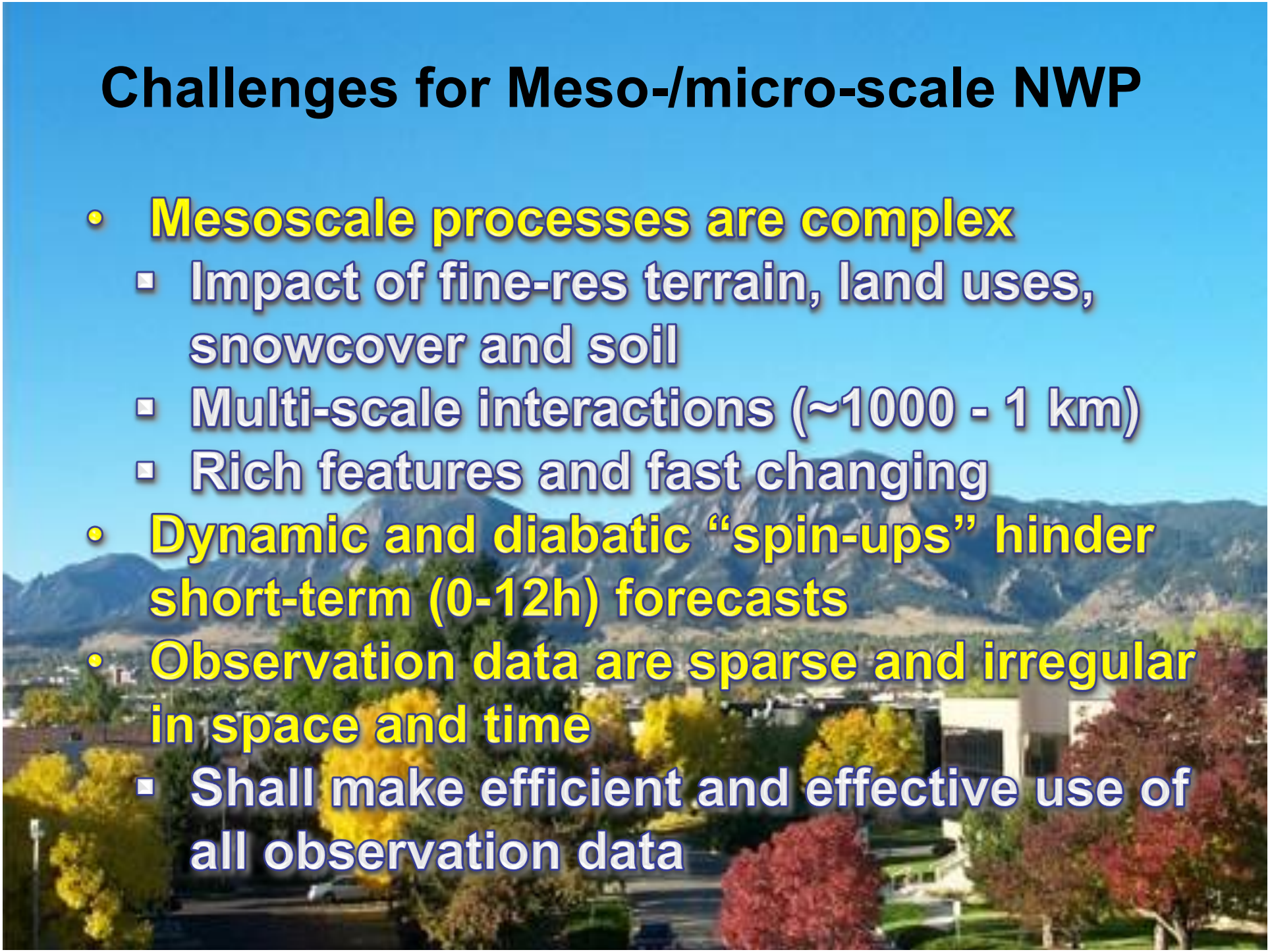
Precision multi-scale

→ reconstruction of weather analysis for the active accident periods

→ real-time analysis and 0 – 72h forecasting for emergence response.

→ quantity of uncertainties

Challenges for Meso-/micro-scale NWP



- Mesoscale processes are complex
  - Impact of fine-res terrain, land uses, snowcover and soil
  - Multi-scale interactions (~1000 - 1 km)
  - Rich features and fast changing
- Dynamic and diabatic "spin-ups" hinder short-term (0-12h) forecasts
- Observation data are sparse and irregular in space and time
  - Shall make efficient and effective use of all observation data

The NCAR RTFDDA System

RTFDDA: Real-Time Four Dimensional Data Assimilation and forecasting system

(Liu et al. 2008a,b JAMC; 2011 JWEIA)

* Original developed for US Army test ranges, this system has been deployed for 30+ weather-critical applications of US governments and industrial entities and international organizations.

1. **Description of the RTFDDA Technology**
2. **Introduction to the Advanced RTFDDA Technologies**

*Thanks to the RTFDDA R&D team, sponsors and users.

WRF: Weather Research and Forecasting

NCAR

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} + \frac{uv\tan\phi}{a} - \frac{uw}{a} - \frac{1}{\rho}\frac{\partial p}{\partial x} - 2\Omega(w\cos\phi - v\sin\phi) + Fr_x$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \frac{u^2\tan\phi}{a} - \frac{uw}{a} - \frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega u\sin\phi + Fr_y$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \frac{u^2+v^2}{a} - \frac{1}{\rho}\frac{\partial p}{\partial z} + 2\Omega u\cos\phi - g + Fr_z$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} + (\gamma - \gamma_d)w + \frac{1}{c_p}\frac{dH}{dt}$$

$$\frac{\partial \rho}{\partial t} = -u\frac{\partial \rho}{\partial x} - v\frac{\partial \rho}{\partial y} + -w\frac{\partial \rho}{\partial z} - \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial q_v}{\partial t} = -u\frac{\partial q_v}{\partial x} - v\frac{\partial q_v}{\partial y} - w\frac{\partial q_v}{\partial z} + Q_v$$

$$P = \rho RT$$

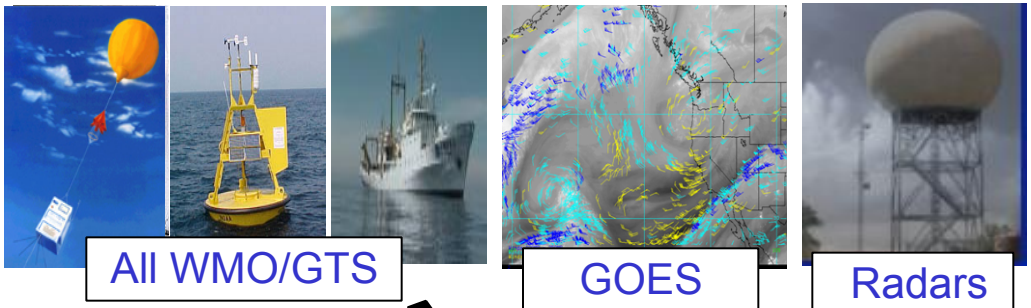
One of the most advanced NWP models, with thousands of users over the globe.

- Land-surface processes
- Cloud microphysics
- Radiation – long and shortwave
- PBL Turbulent fluxes - heat, moisture, momentum
- Cumulus convection
- Sub-grid diffusion

WRF has been broadly utilized by various academia and industries.

NCAR RTFDDA and Forecasting System

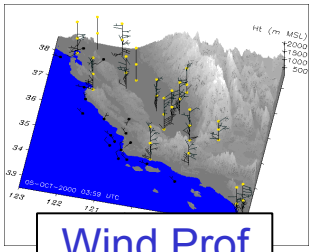
NCAR



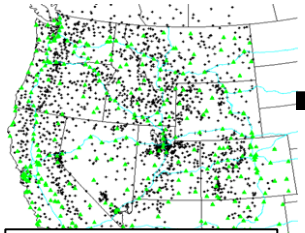
All WMO/GTS

GOES

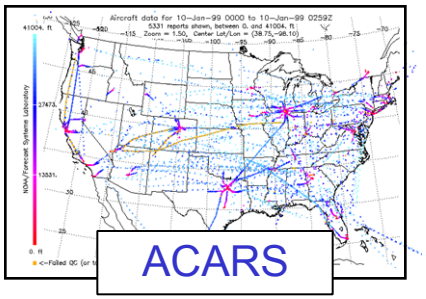
Radars



Wind Prof



MESONETs



ACARS

Etc.

Farm Met

RTFDDA

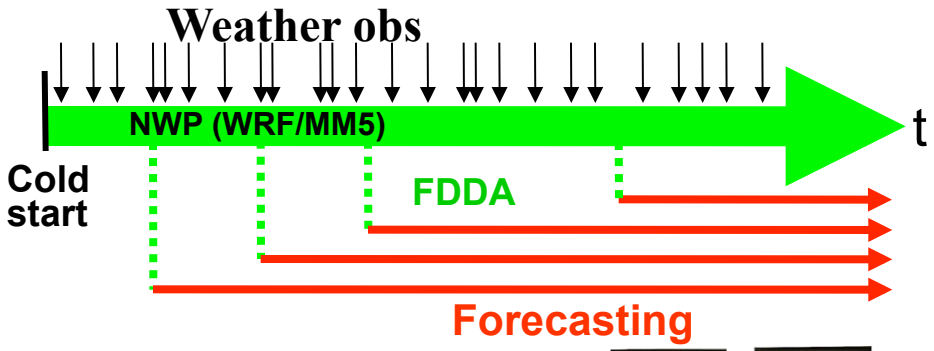
Regional-scale model, based on **WRF / MM5**

Modified NWP (WRF/MM5):

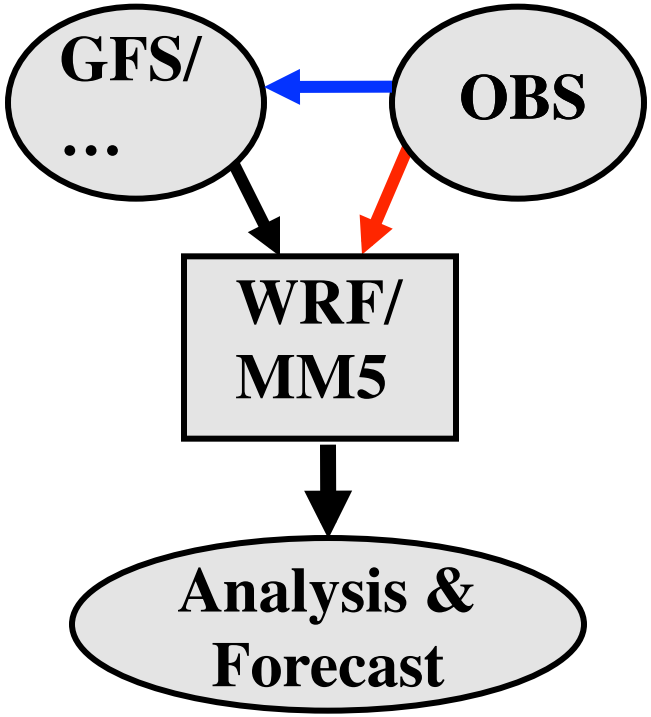
$$Dx/Dt = \ldots + GW\,(x_{obs} - x_{model})$$

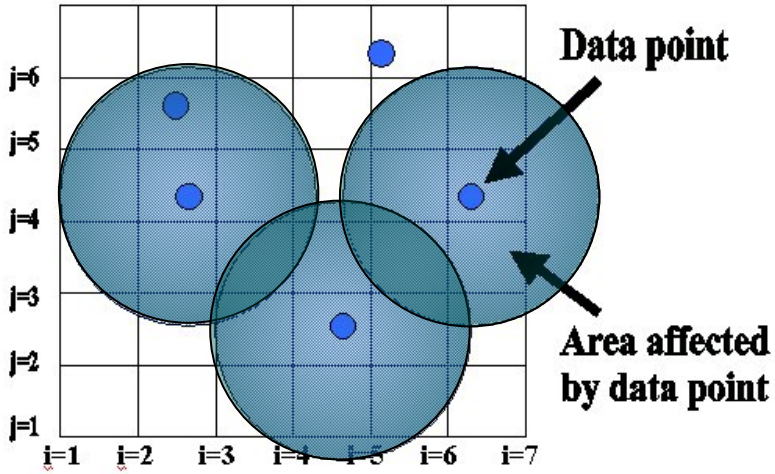
where x = T, U, V, Q, P1, P2 …

W is weight function

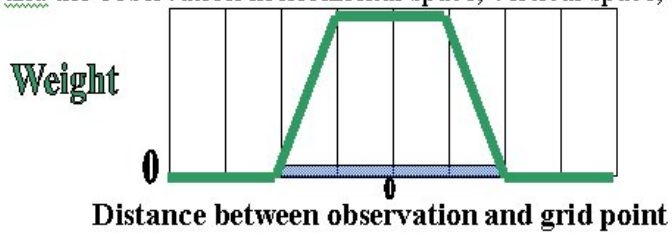


(E-)RTFDDA: Data Assimilation – 4DWX





The weights can vary with the distance between the grid points and the observation in horizontal space, vertical space, and time.



Incorporate observation data into a full-physics mesoscale model to produce 4-D synthetic (model and obs) weather at given locations.

Advanced FDDA: 4D-REKF

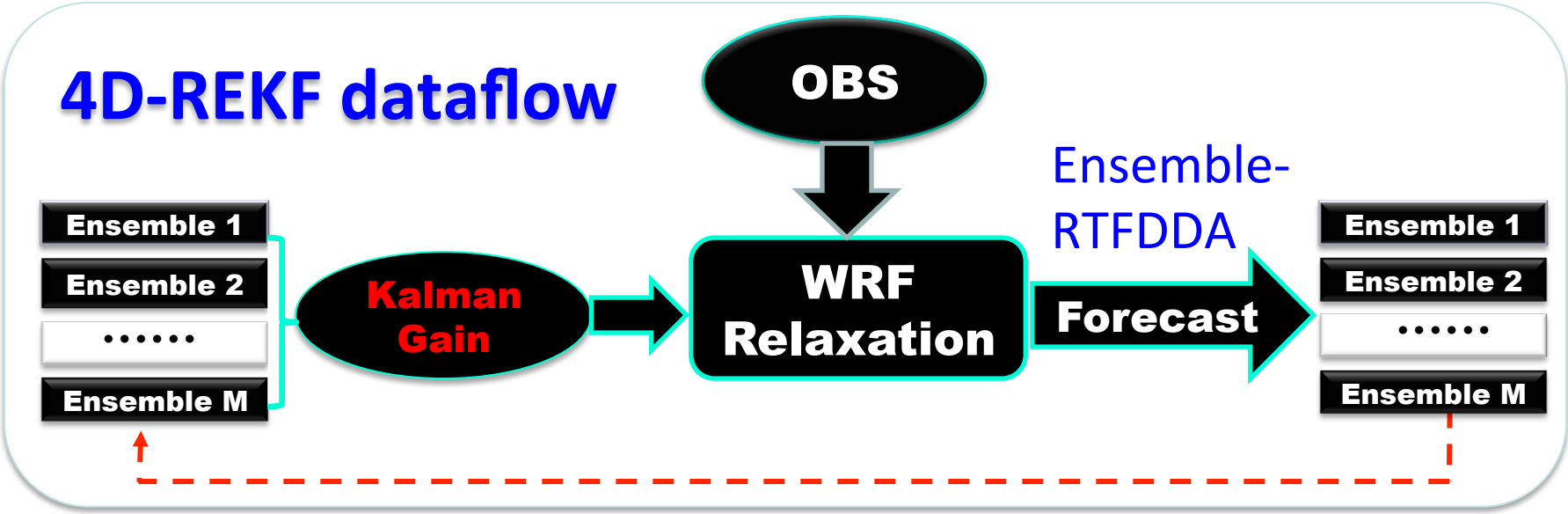
NCAR

3DDA		4DDA
OA: Simple empirical isotropic (distance) function	Nudging WRF or MM5	RTFDDA
3DVAR: Historical daily(24h-12h forecast) isotropic weight function	Constraint WRF	4D-Var
ENKF: Ensemble flow-dependent anisotropic weight function	Nudging WRF	4D-REKF

4D-REKF: 4-Dimensional Relaxation Ensemble Kalman Filter (FDDA and forecasting)

4D-REKF: Advanced FDDA Engine

NCAR



Ensemble Kalman Gain

$$W_{xy,j} = K_e = P^f H^T (HP^f H^T + O)^{-1}$$

WRF

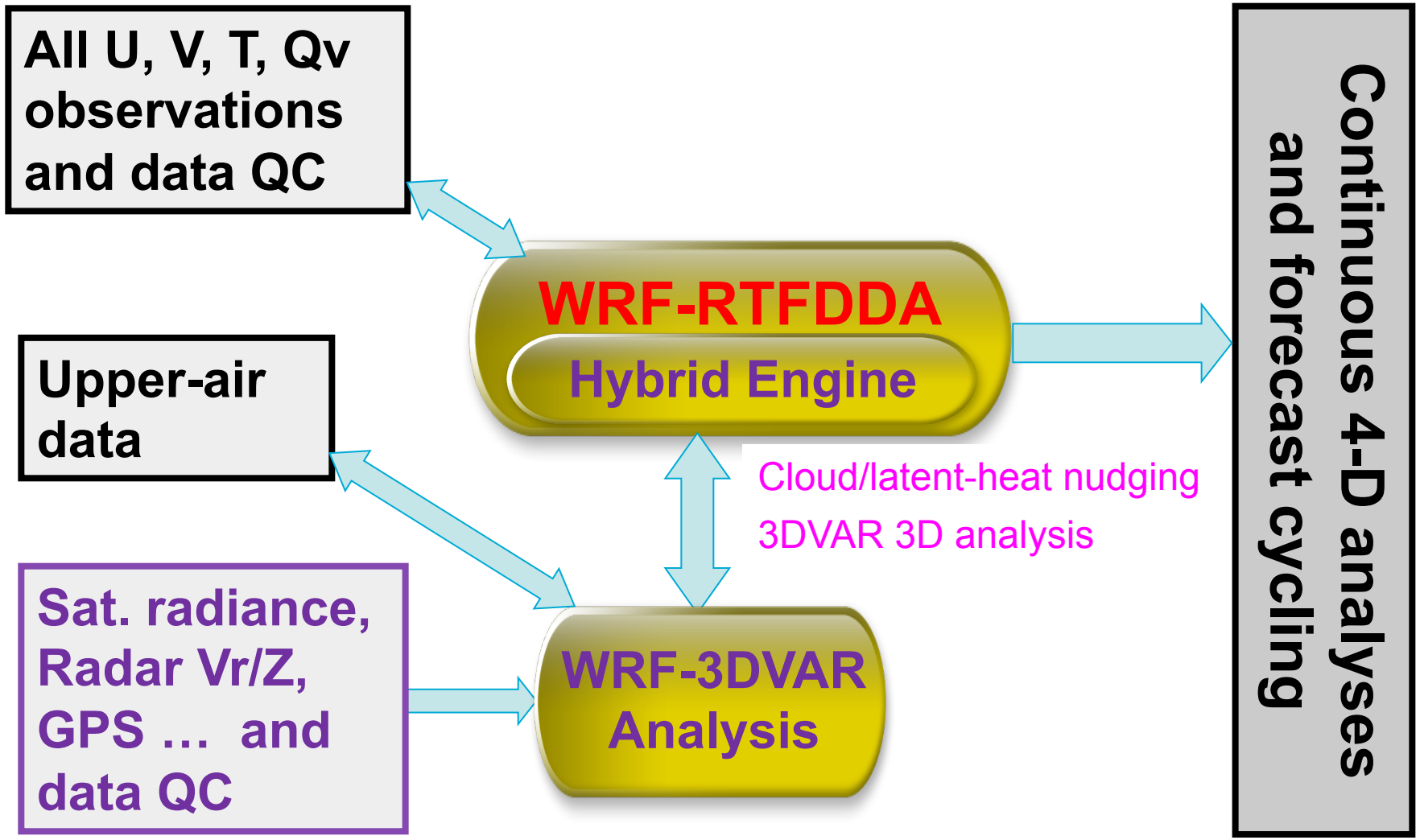
Relaxation coefficient

$$\frac{\partial X}{\partial t} = F(X,x,y,\sigma,t) + G_\alpha \frac{\sum_{i=1}^{N} W_{xy,i} W_{\sigma,i}^2 W_{t,i}^2 W_{qc,i}^2 \cdot (y_i^{obs} - HX)}{\sum_{i=1}^{N} W_{\sigma,i} W_{t,i} W_{qc,i}}$$

4D-REKF Combines EDA and EPS technologies

Hybrid Approach for Satellite and Radar Data Assimilation

NCAR



Unique Advantages of (E-)RTFDDA

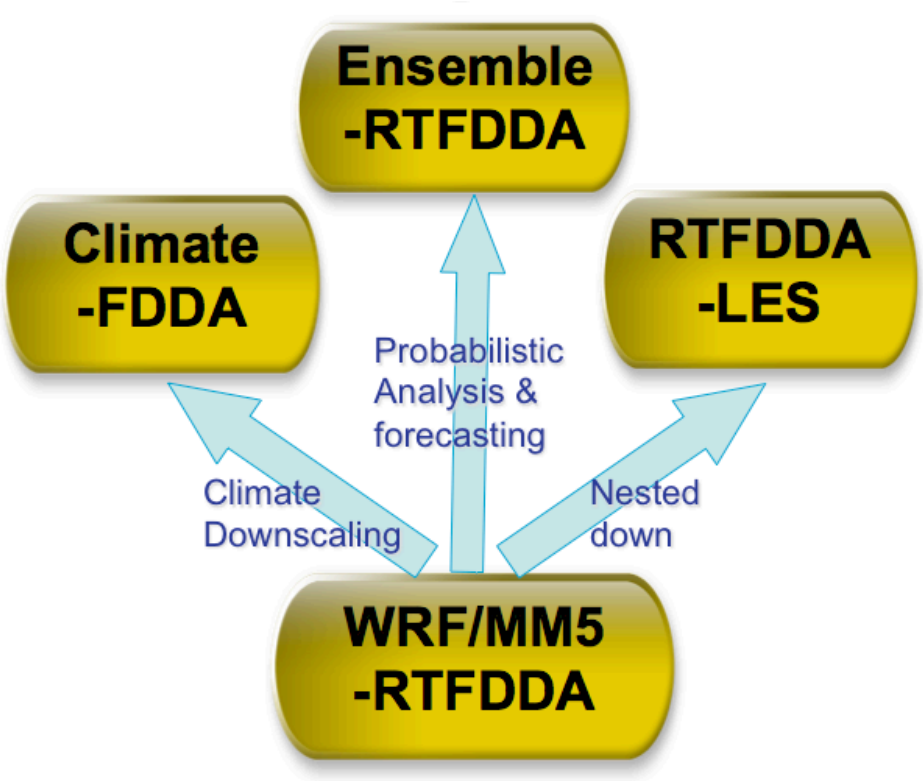
NCAR

- It assimilates all observations into the WRF model equations along with the model forward integration ("forecasts"); and thus
- it produces 4D continuous dynamically-balanced, physically-consistent, and cloud "spun-up" analysis and forecasts of full weather variables on high-resolution grids.

The "X-FDDA Suite"

NCAR

X-FDDA: a suite of WRF based multi-scale continuous data assimilation and forecasting tools for supporting user/mission-oriented weather applications.



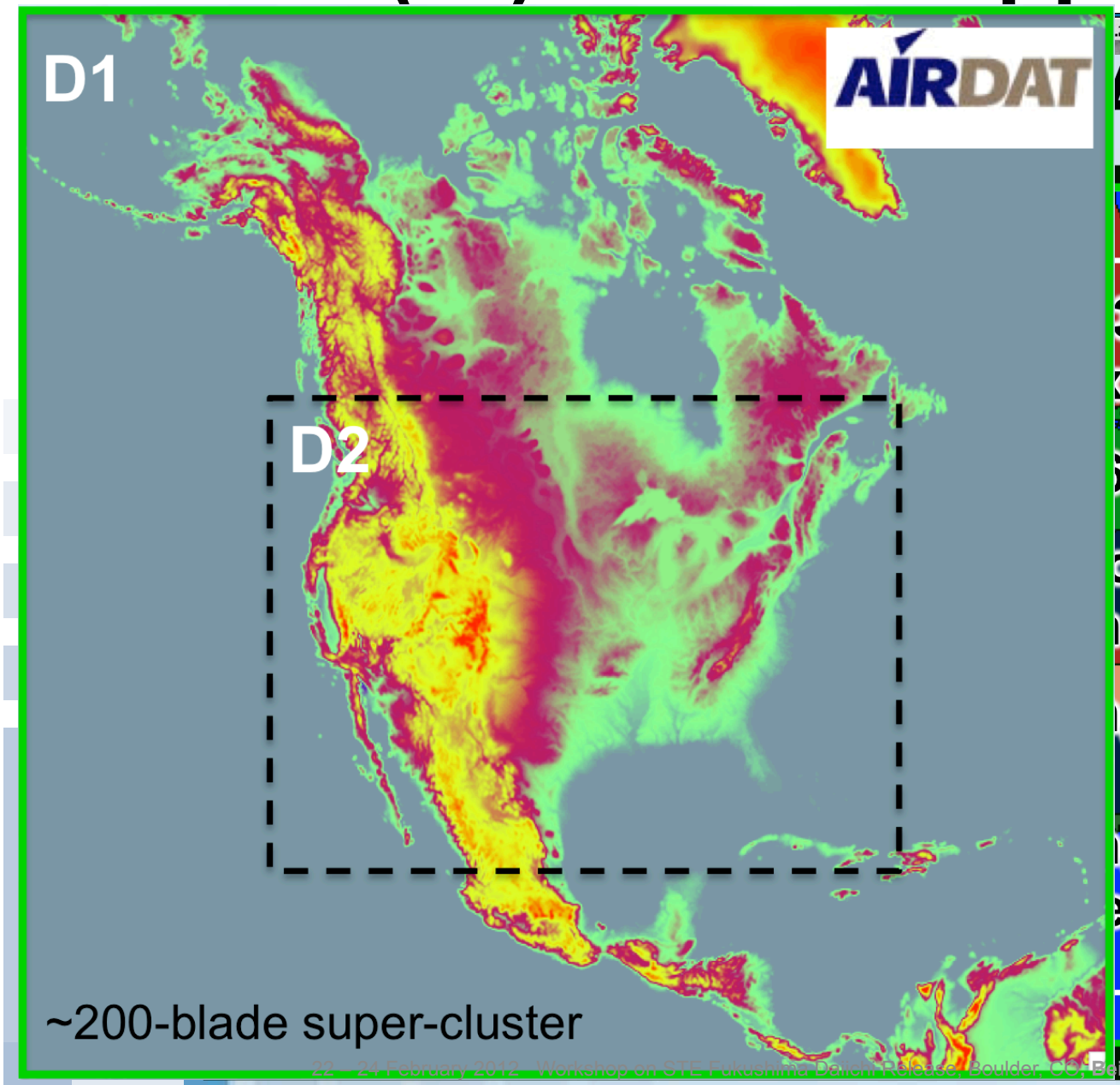
Mesoscale deterministic FDDA and forecasting

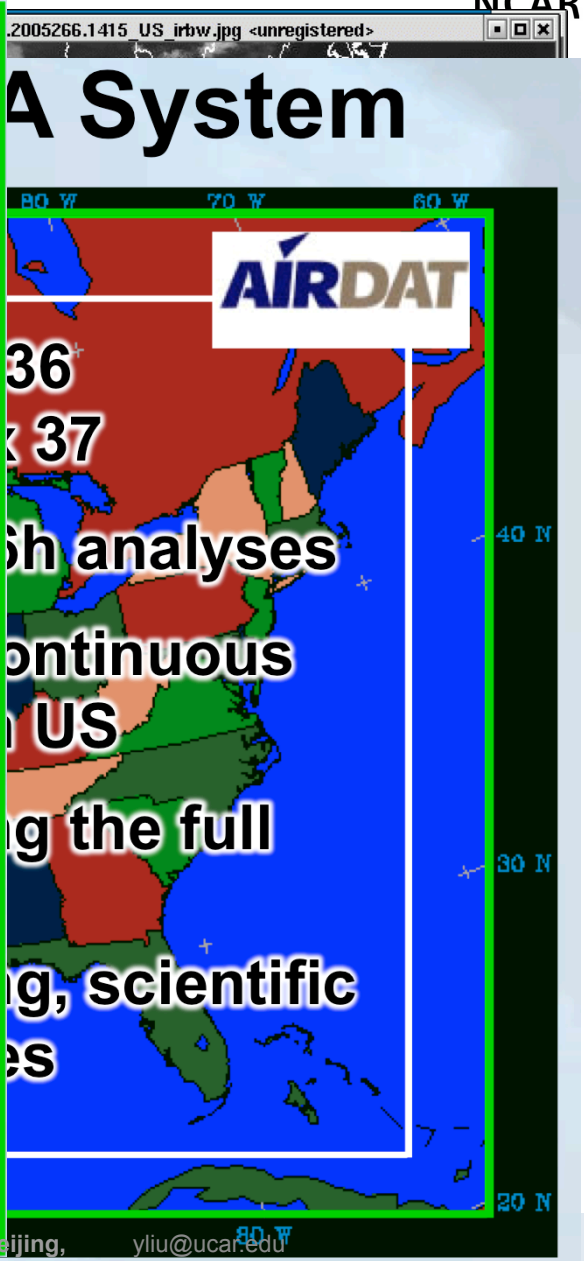
Mesoscale ensemble FDDA and forecasting

Microscale FDDA and forecasting

Production of regional and/or global micro-climatology

NCAR (E-)RTFDDA Applications





An Example of the Operational (E-)RTFDDA Forecasting Systems

RTFDDA

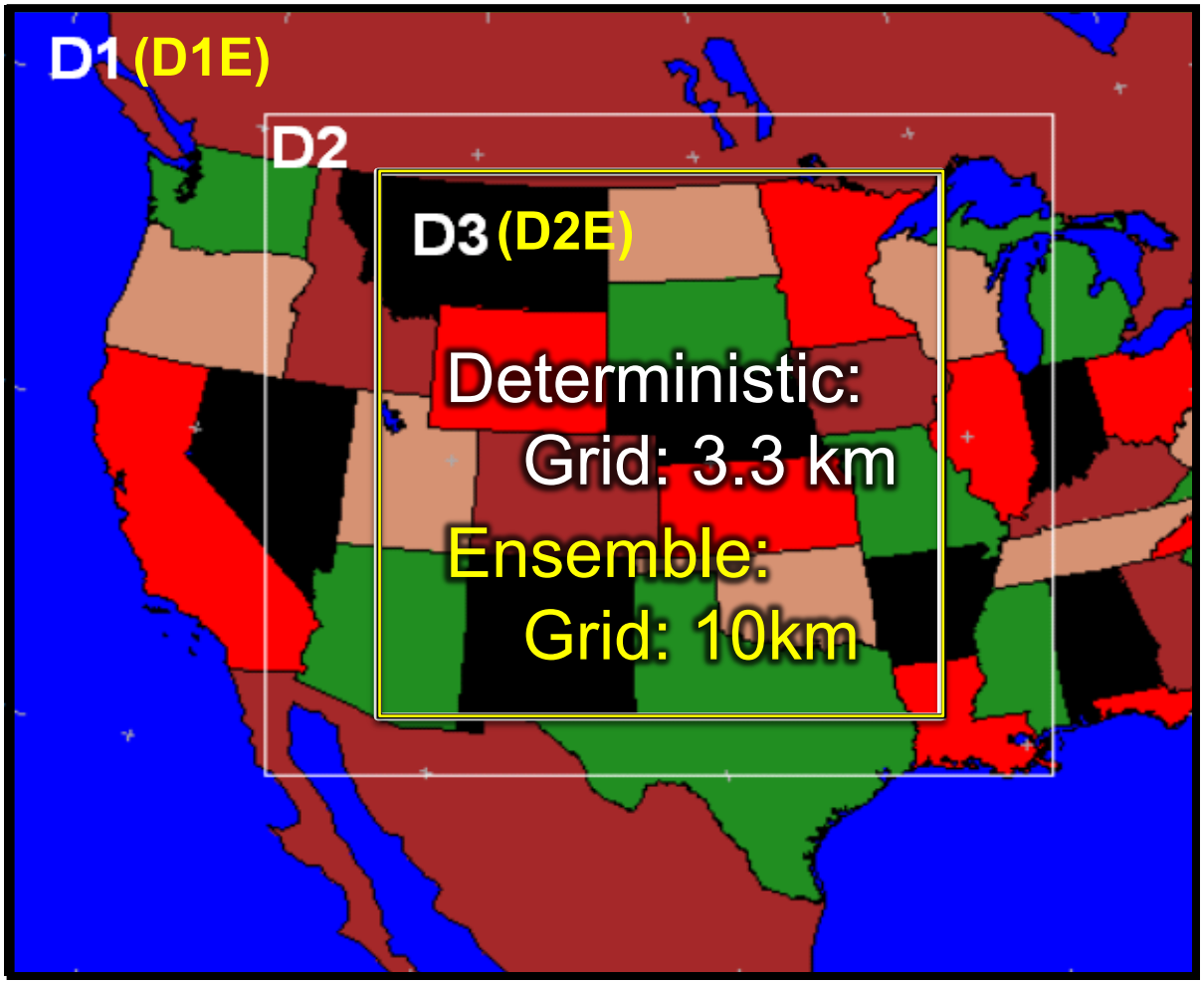
High-resolution deterministic prediction

- 3h update cycles
- 24-72h forecasts
- 15min to 1h outputs

E-RTFDDA

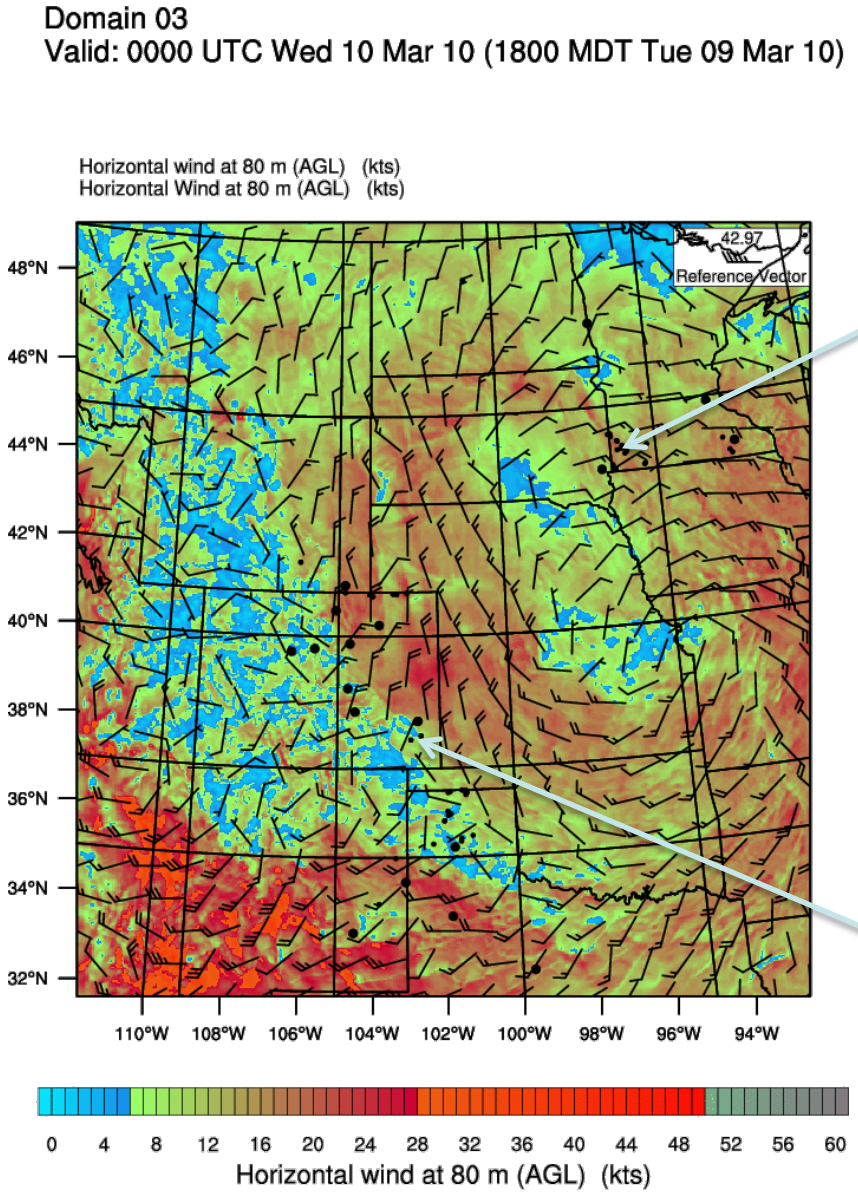
Probabilistic prediction

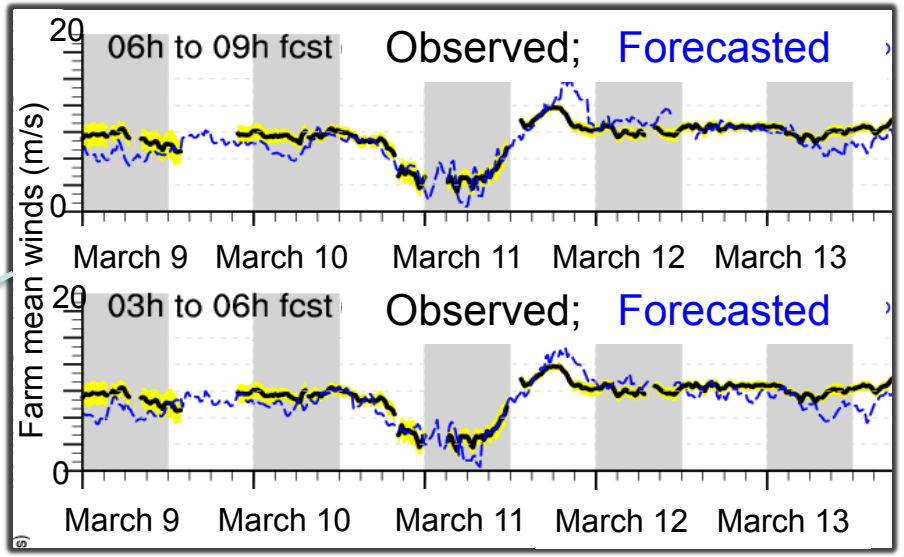
- 6h update cycles
- 72h forecasts
- 1h outputs

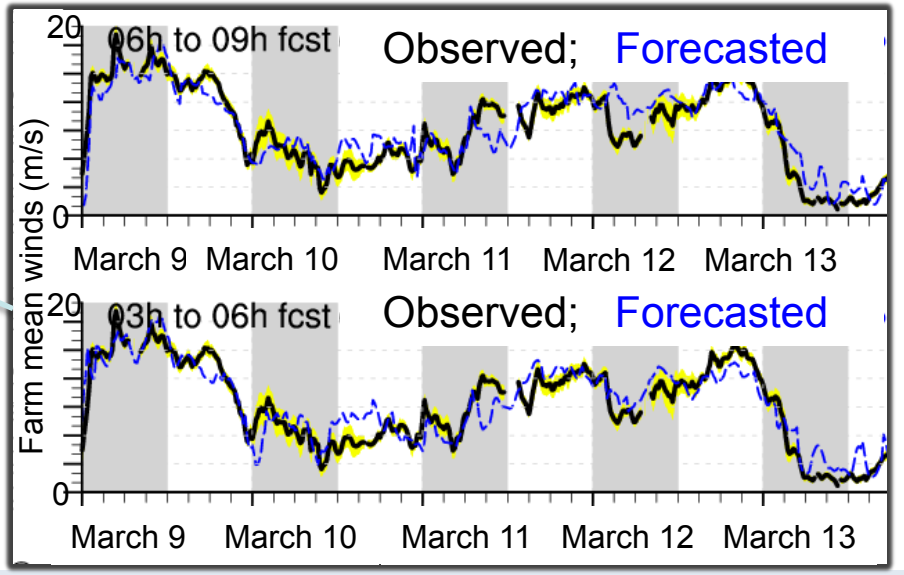


3.3-km Grid WRF-RTFDDA Forecast of 80m-AGL Winds

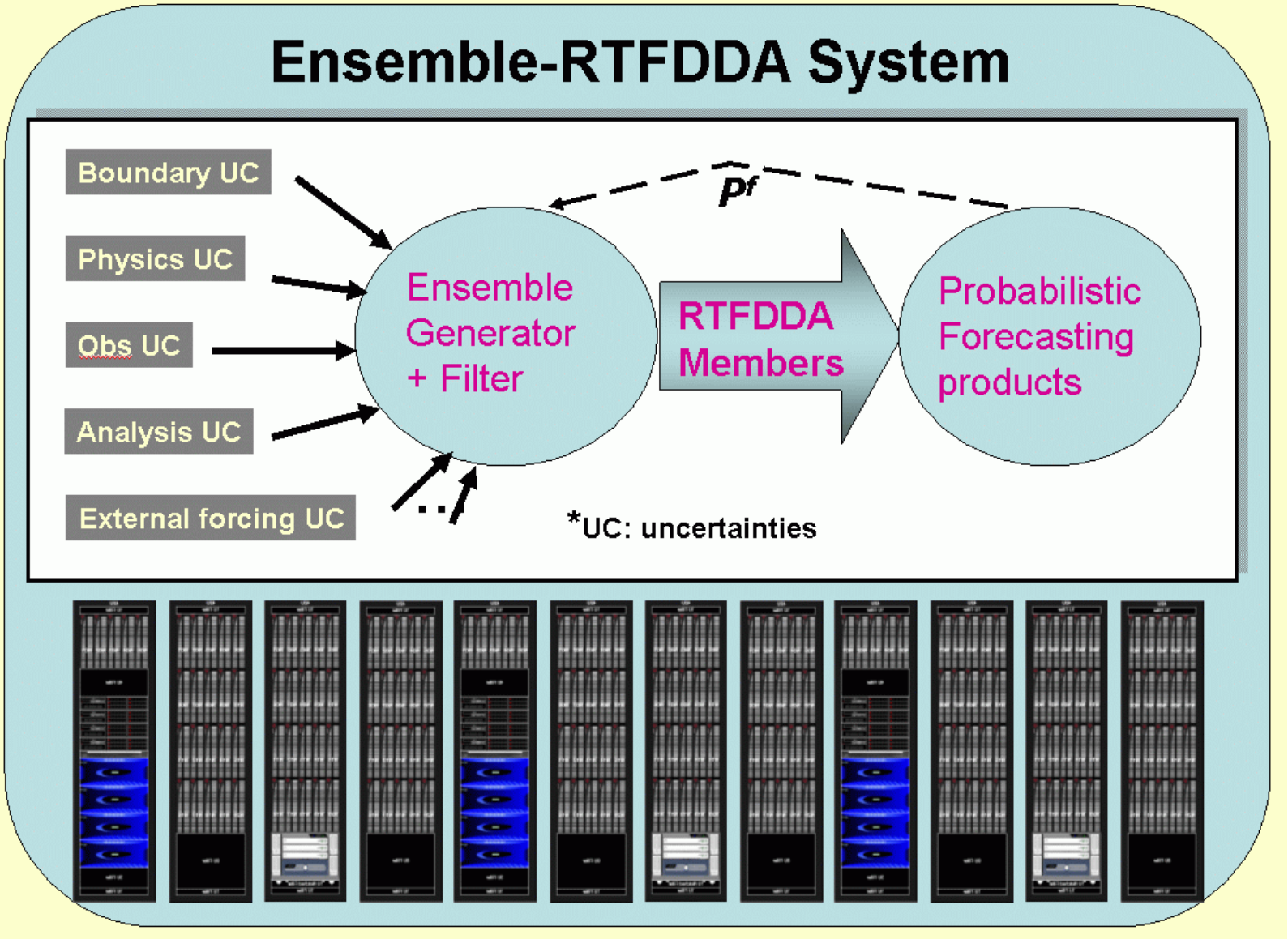
NCAR





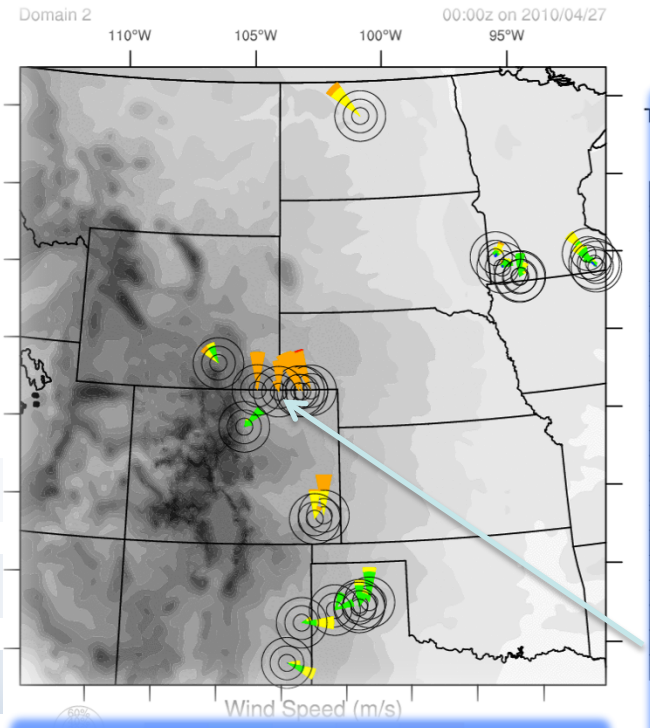


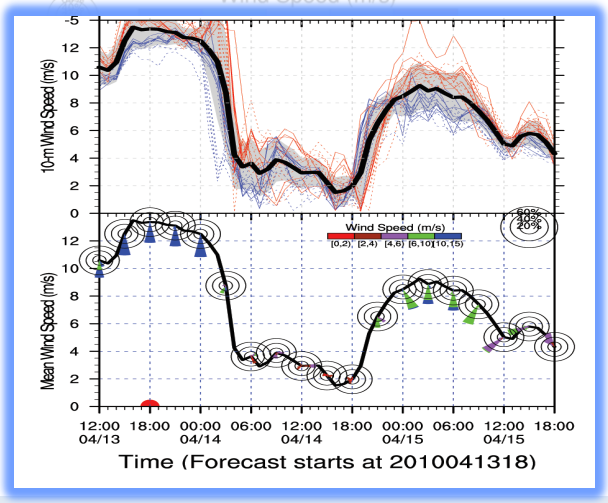
NCAR Ensemble-RTFDDA

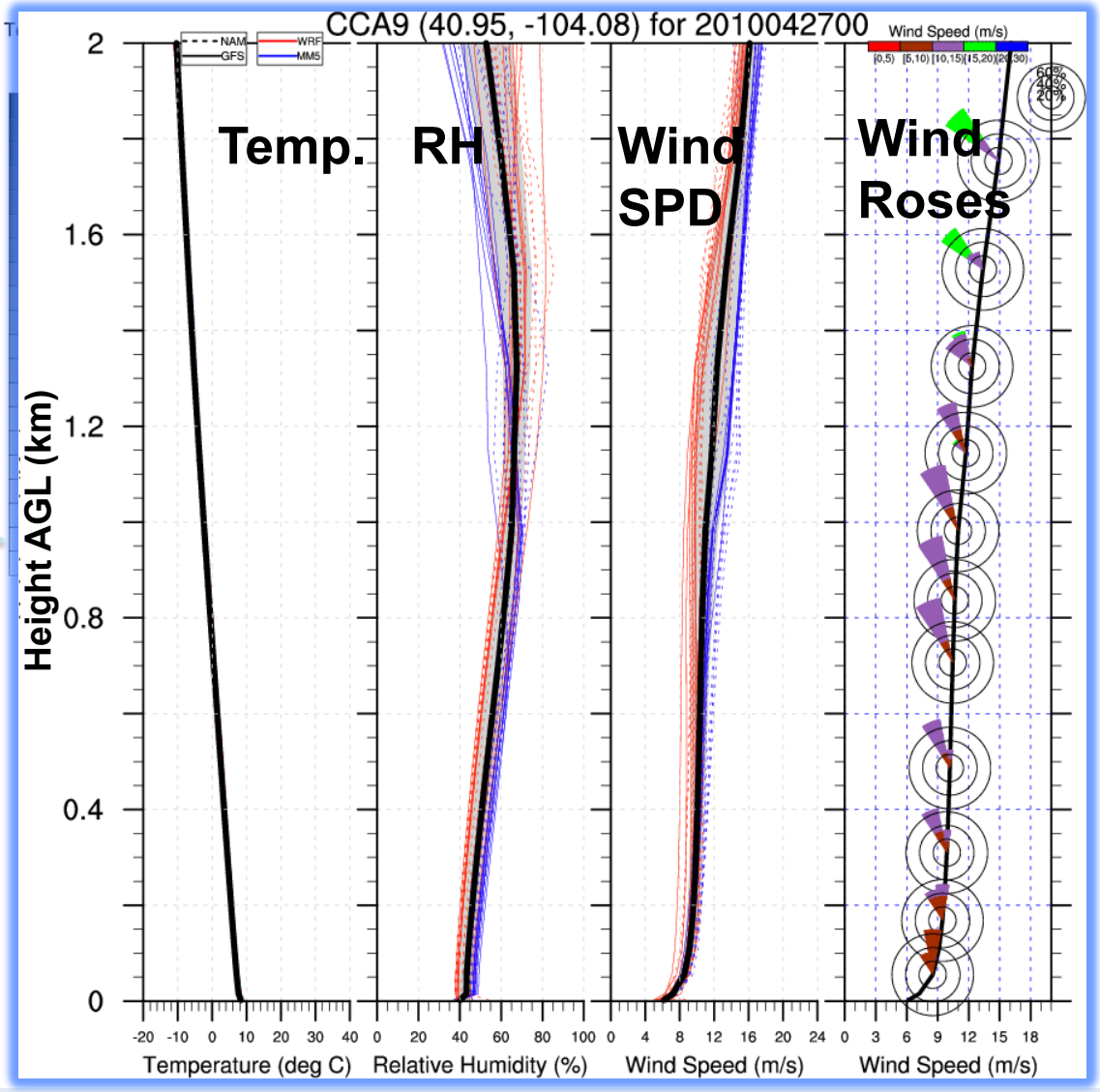


NCAR 30-member E-RTFDDA FCST Example

NCAR



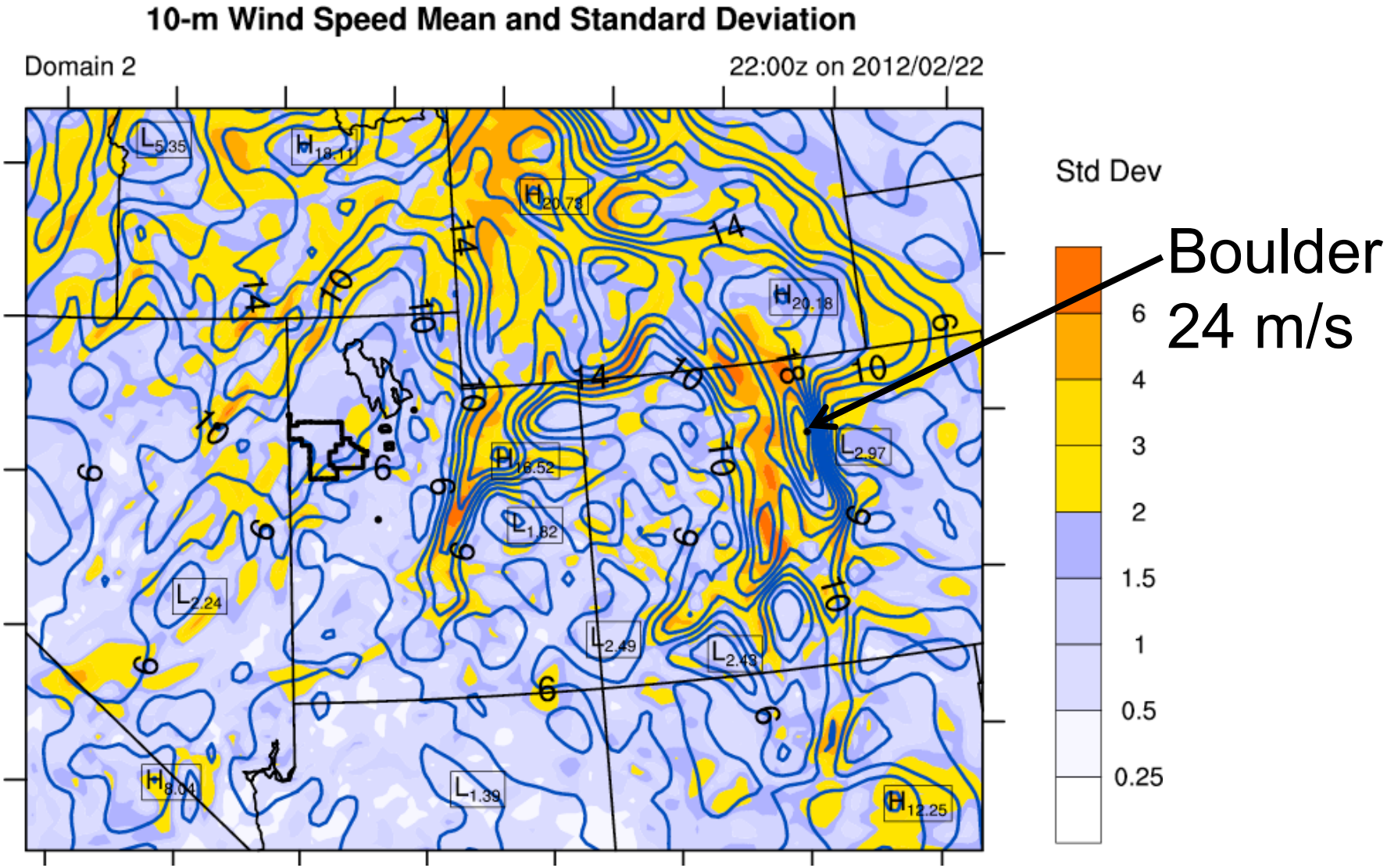




NCAR 30-member E-RTFDDA FCST Example

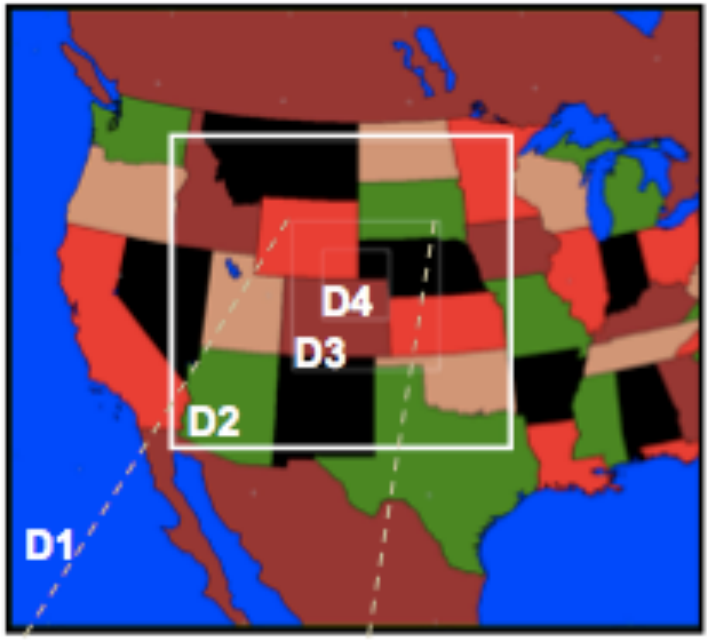
NCAR

Vaild: 23Z, Feb. 22, 2012 (Yesterday, 4pm)

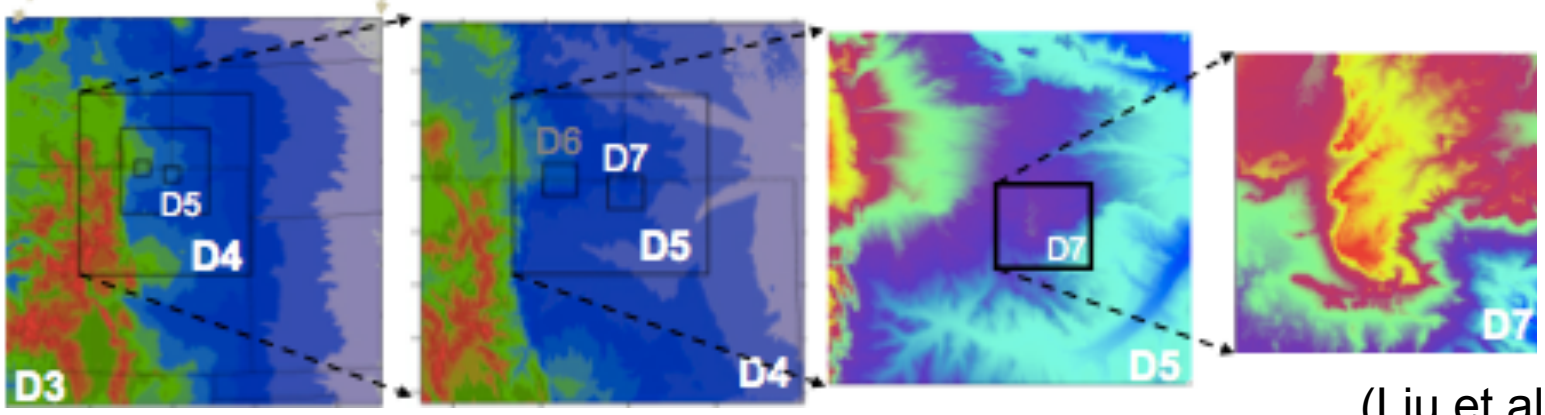


RTFDDA-LES Simultaneous Nested-Down from Synoptic Scale to LES scales

NCAR



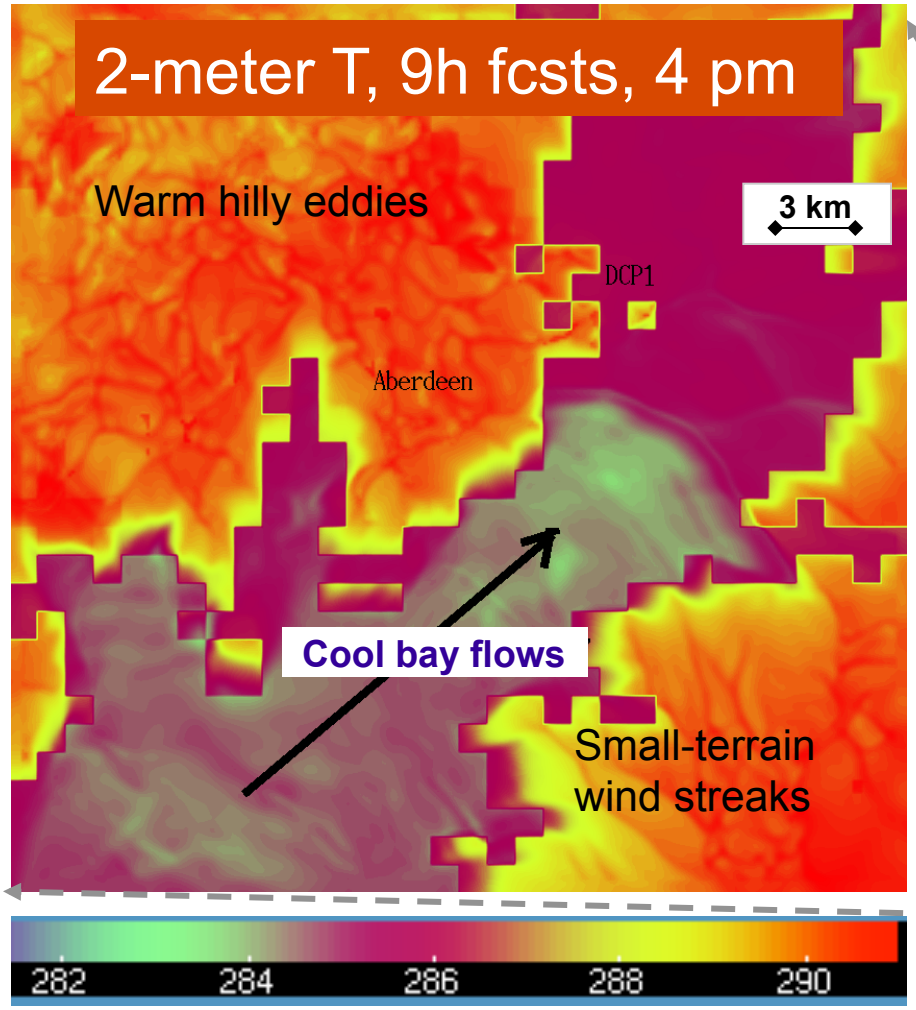
D1: 30000m 128x114
D2: 10000m 184x169
D3: 3333m 244x247
D4: 1111m 331x346
D5: 370m 505x490
D6: 123m 262x268
D7: 123m 280x271



(Liu et al. 2011)

Complex Coastal Flows

NCAR



6 nested grids

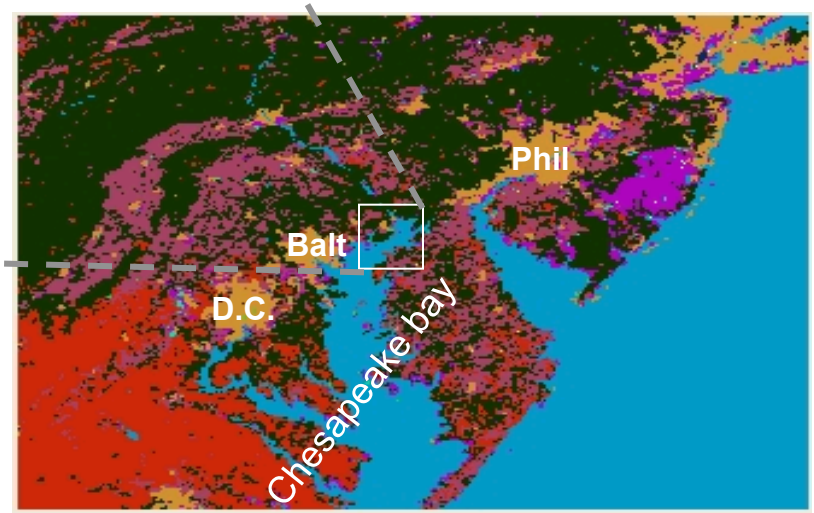
DX= 30/10/3.3/1.1/0.370 /0.123 km

30” terrain and land use

37 sigma levels

24h forecasts:

12Z 16 Apr – 12Z 17 Apr 2008



RTFDDA Complex Terrain Flows

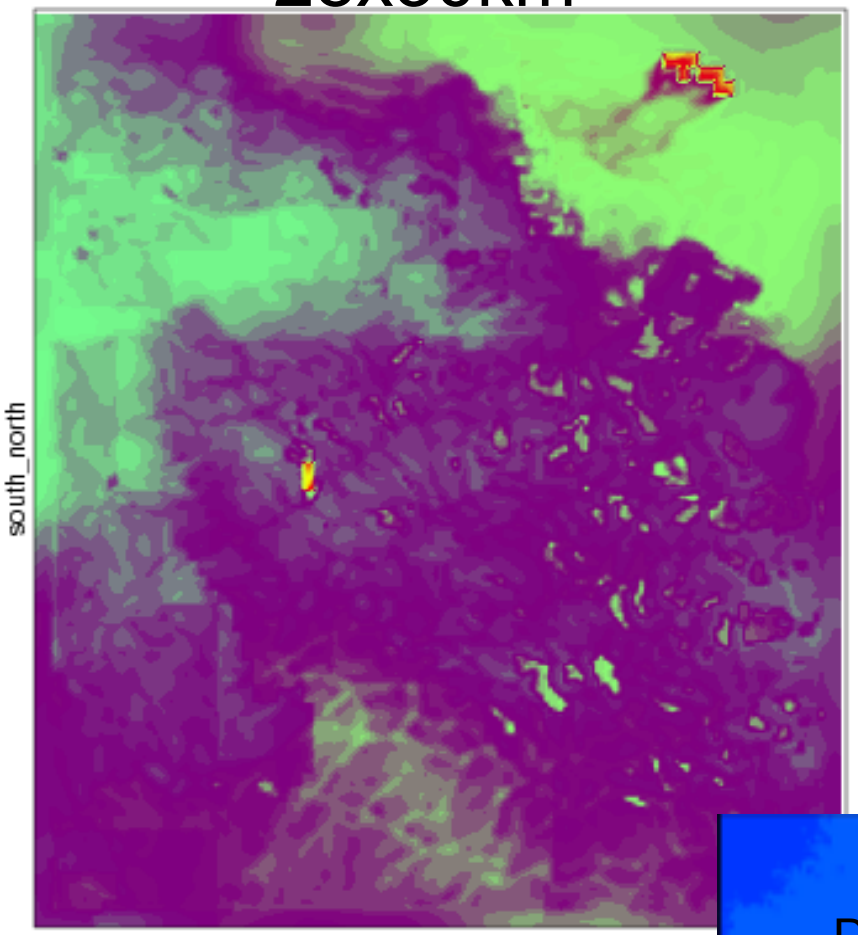
300m Grid
Qv-2m (kg/kg)

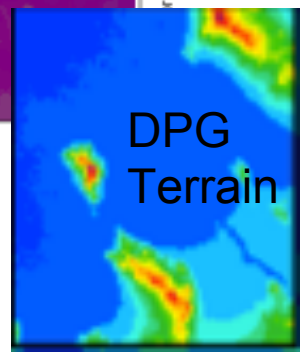
Every 15 minutes from
00Z 15 July to 00Z 16 July
2010

What We See?

- ✓ **Blocking/gap flows**
- ✓ **Boundary Rolls (am)**
- ✓ **Thermals (Popcorn; pm)**
- ✓ **Lake evaporations**
- ✓ **Inflow moisture from the Great Salt Lake**

28x30km^2

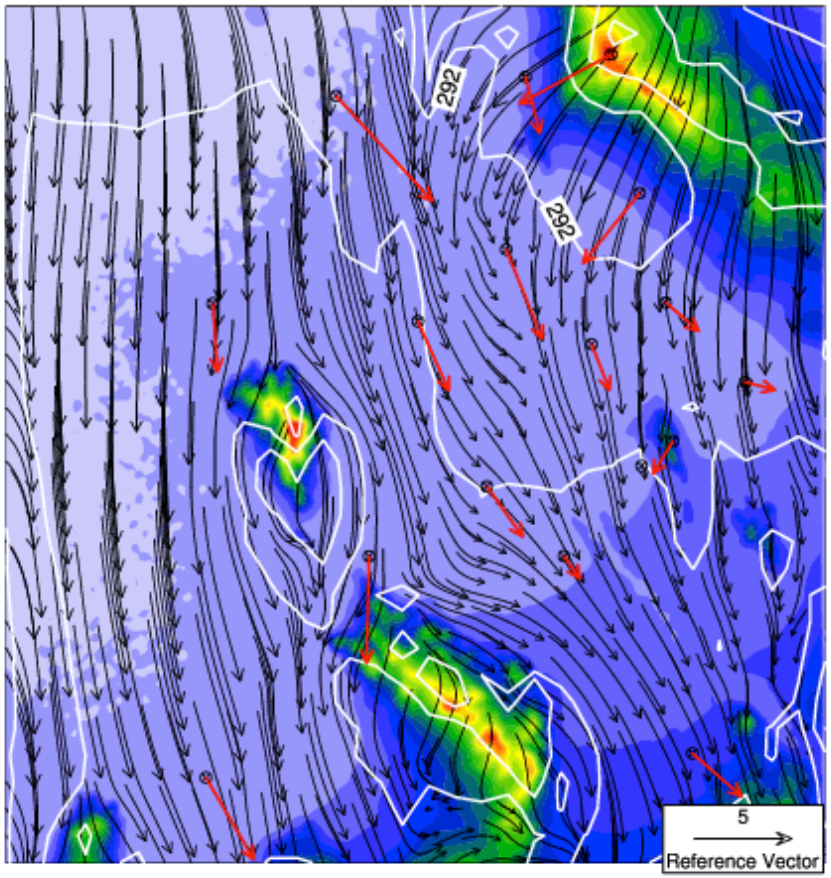




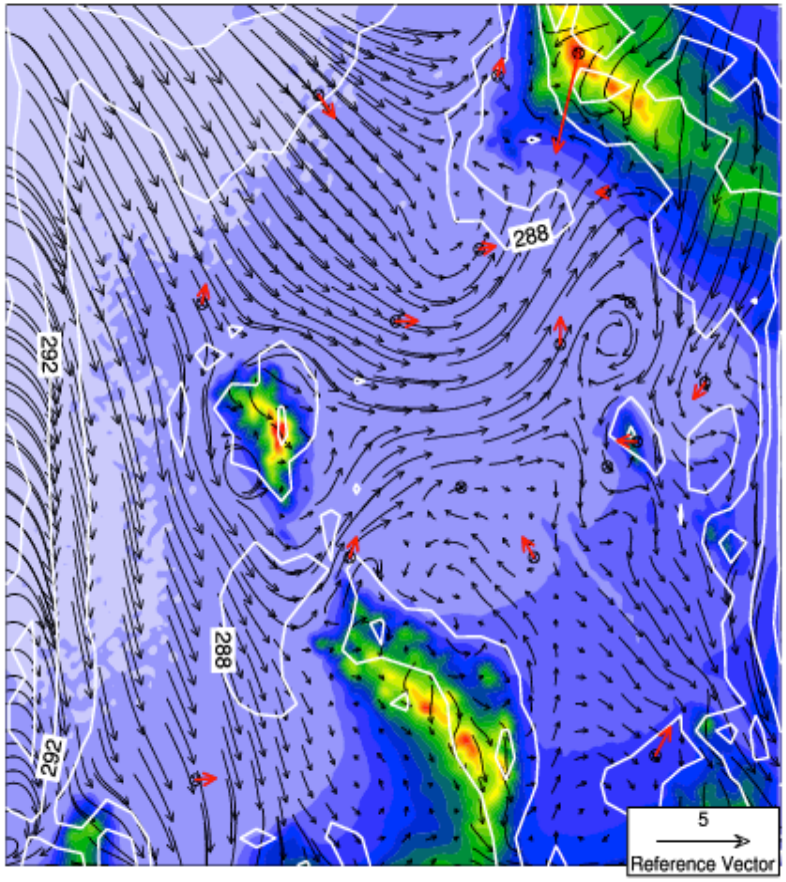
Surface Wind Verification

NCAR

07/14/2010 12 UTC

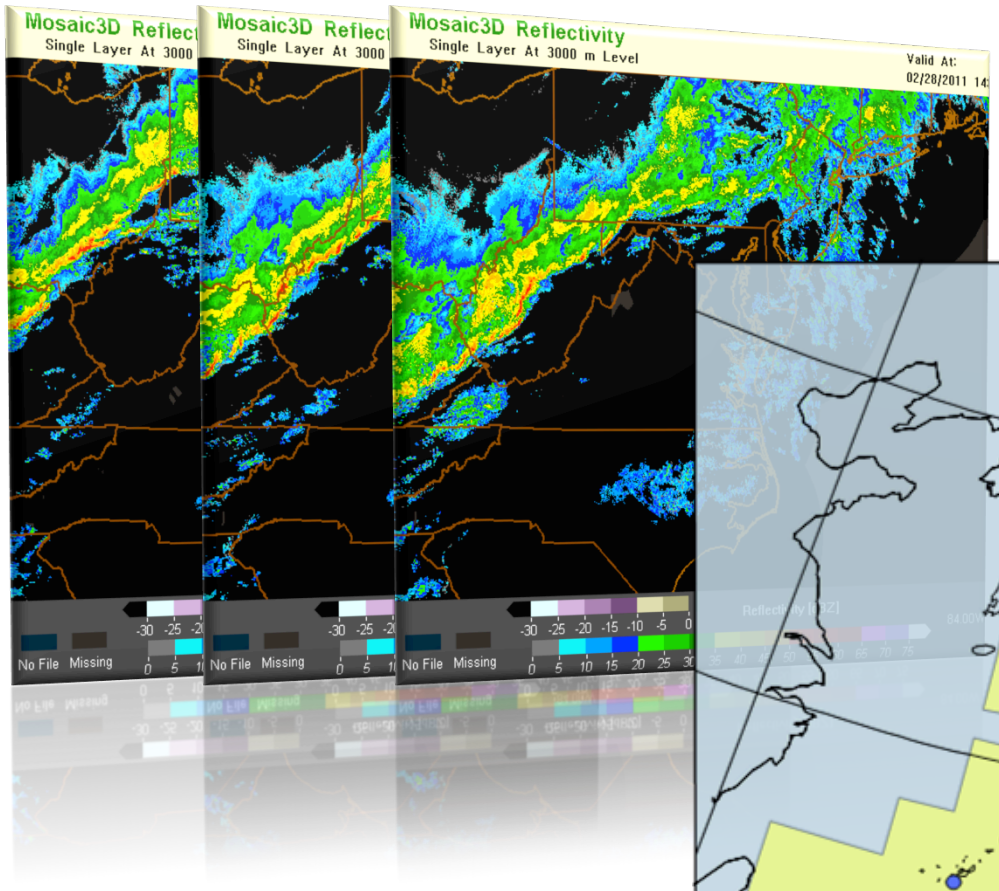


07/15/2010 12 UTC

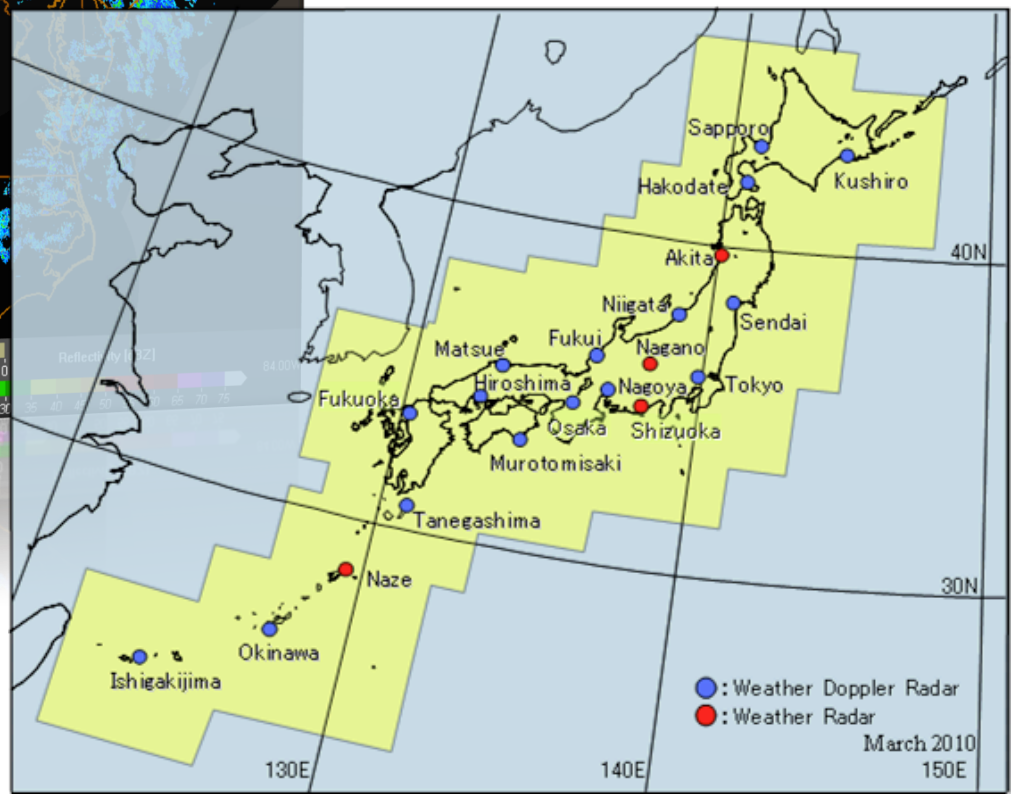


Radar Data Assimilation

NCAR



20 C-band radars



Impact of radar data LHN on cyc200906 1206

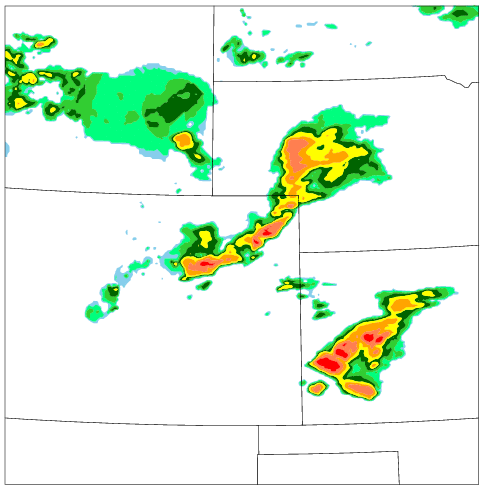
NCAR

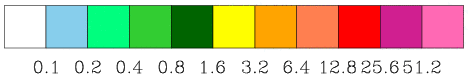
analysis

Restart from 00 UTC

Stage4 Rainfall (mm/hr)

Validated at 2009061206

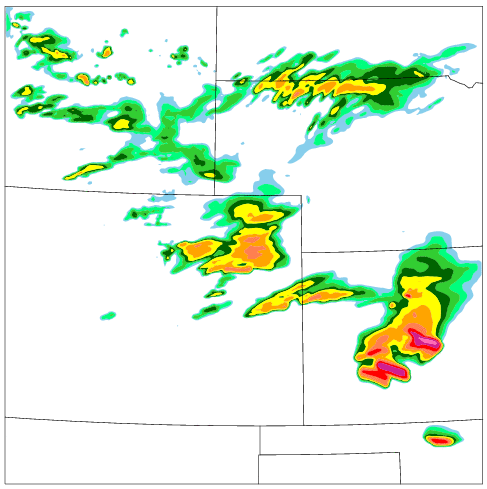


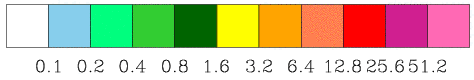


Observation

1 Hour Precipitation (mm)

Validated at 2009061206

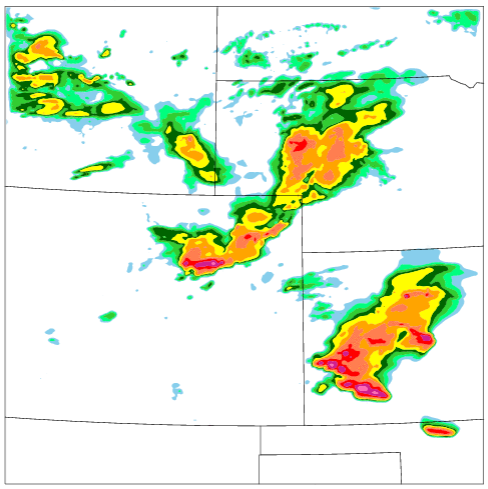


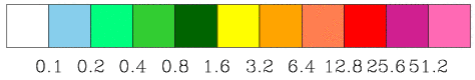


RTFDDA - no radar

1 Hour Precipitation (mm)

Validated at 2009061206





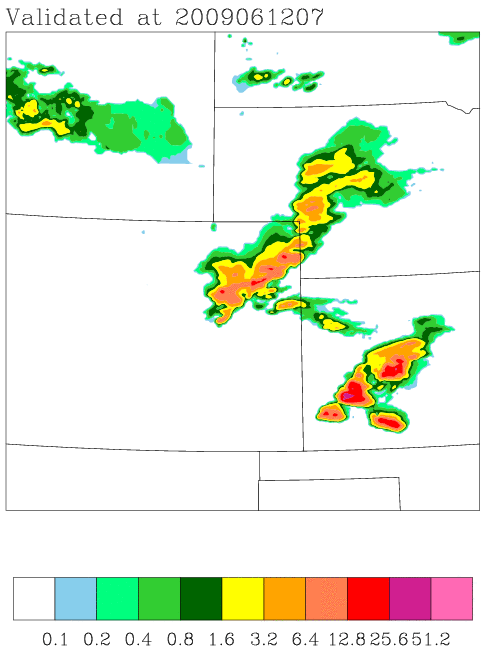
RTFDDA with radar LHN

Impact of radar data LHN on cyc200906 1206

NCAR

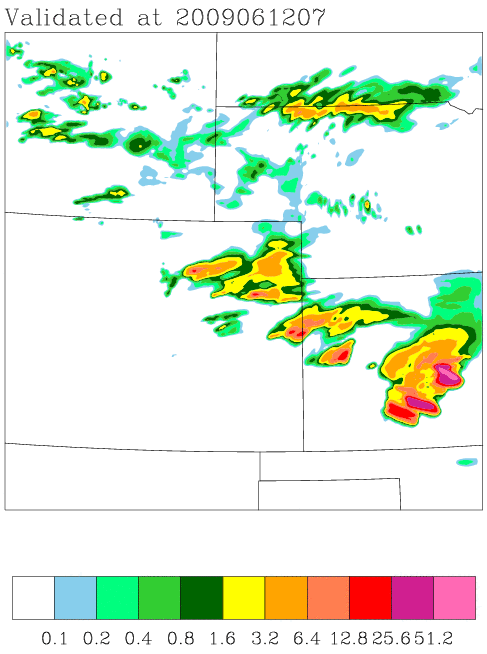
1 h forecast

Stage4 Rainfall (mm/hr)



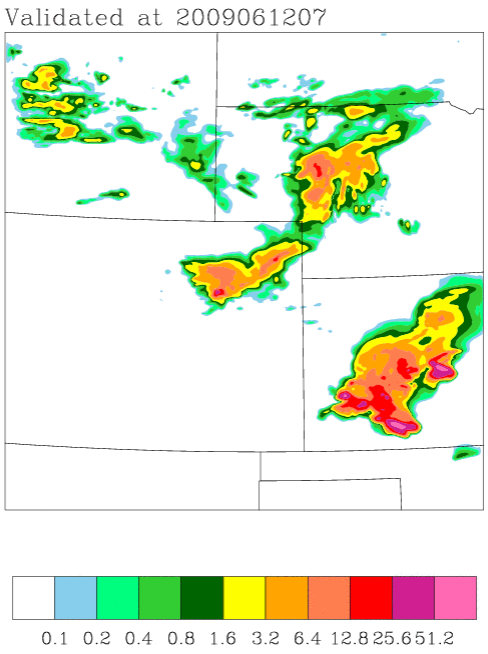
Observation

1 Hour Precipitation (mm)



RTFDDA - no radar

1 Hour Precipitation (mm)



RTFDDA with radar LHN

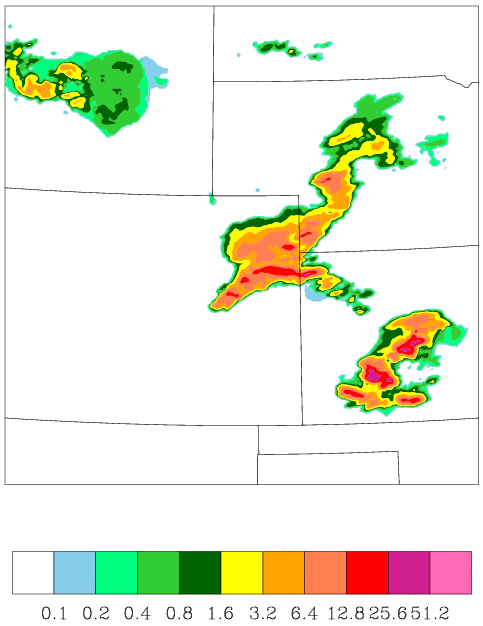
Impact of radar data LHN on cyc200906 1206

NCAR

2 h forecast

Stage4 Rainfall (mm/hr)

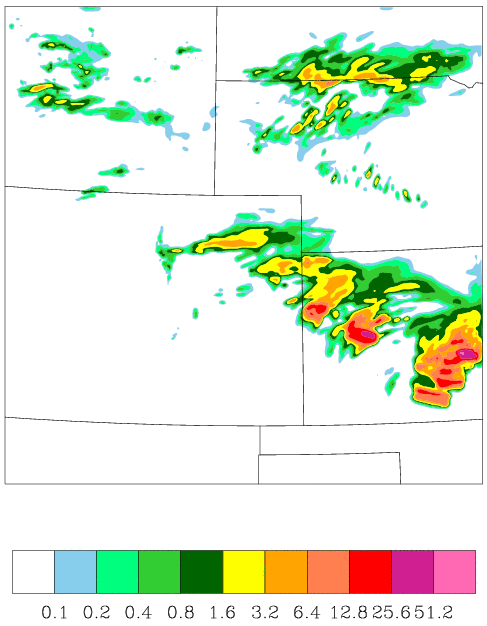
Validated at 2009061208



Observation

1 Hour Precipitation (mm)

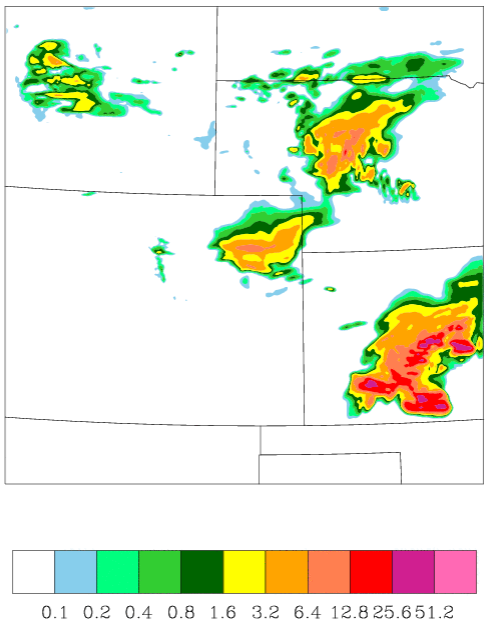
Validated at 2009061208



RTFDDA - no radar

1 Hour Precipitation (mm)

Validated at 2009061208



RTFDDA with radar LHN

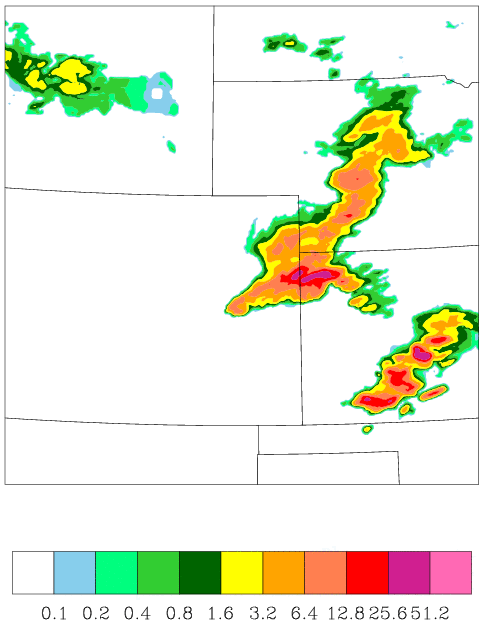
Impact of radar data LHN on cyc200906 1206

NCAR

3 h forecast

Stage4 Rainfall (mm/hr)

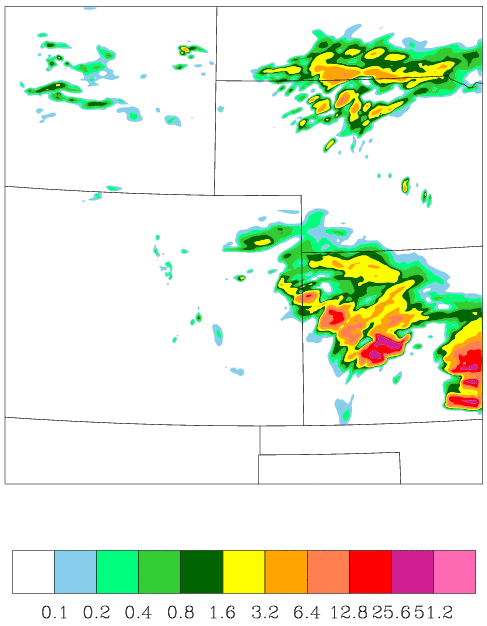
Validated at 2009061209



Observation

1 Hour Precipitation (mm)

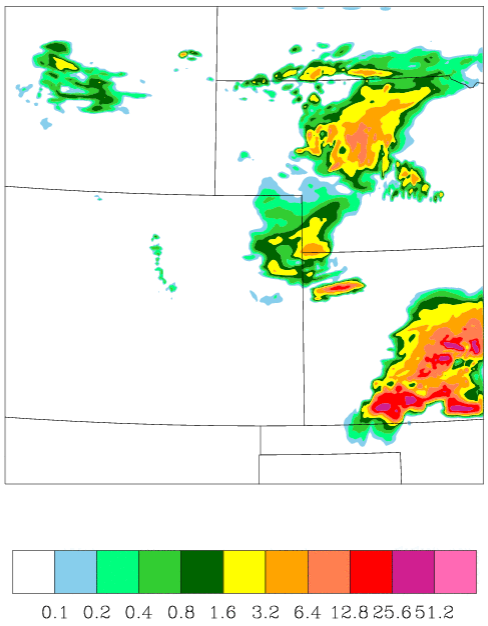
Validated at 2009061209



RTFDDA - no radar

1 Hour Precipitation (mm)

Validated at 2009061209



RTFDDA with radar LHN

In Summary …

1. NCAR (E-)RTFDDA, including high-res deterministic and ensemble NWP models, are built to support (special) weather-critical applications.
2. E-RTFDDA is built upon advanced ensemble data assimilation and probabilistic forecasting technologies, generating 4D multi-scale, synthetic, dynamically-balanced and physically-consistent, complete weather data, with information of uncertainty.
3. It is used to reconstruct precision weather environment for the past events, and for real-time DSS in emergence response as well.

Thank you!

Questions?