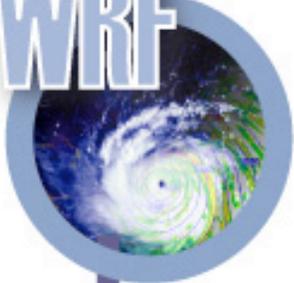


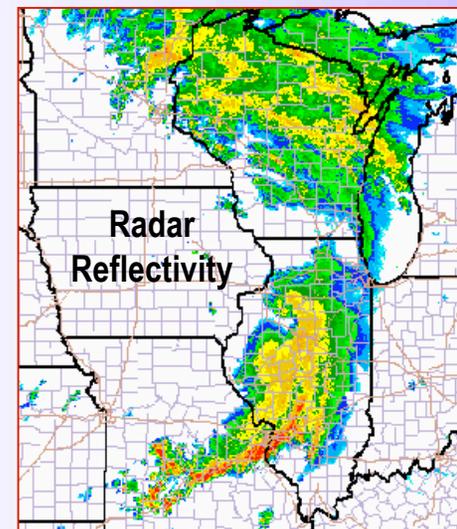
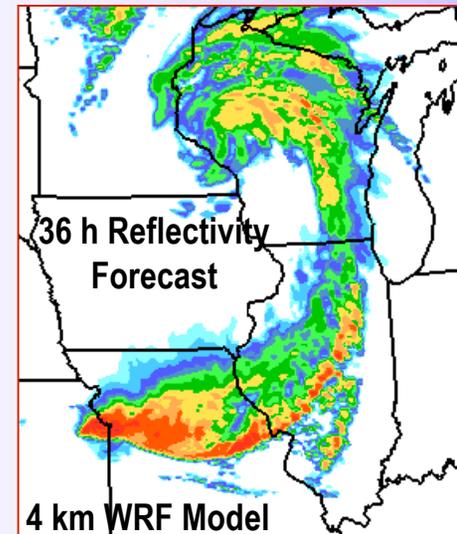
WRF



Convection-Resolving Forecasting with the WRF Model

Joseph B. Klemp

National Center for Atmospheric Research
Boulder, Colorado



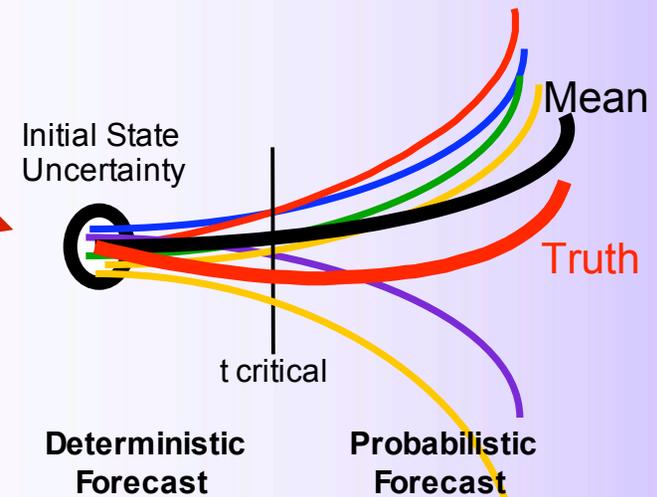
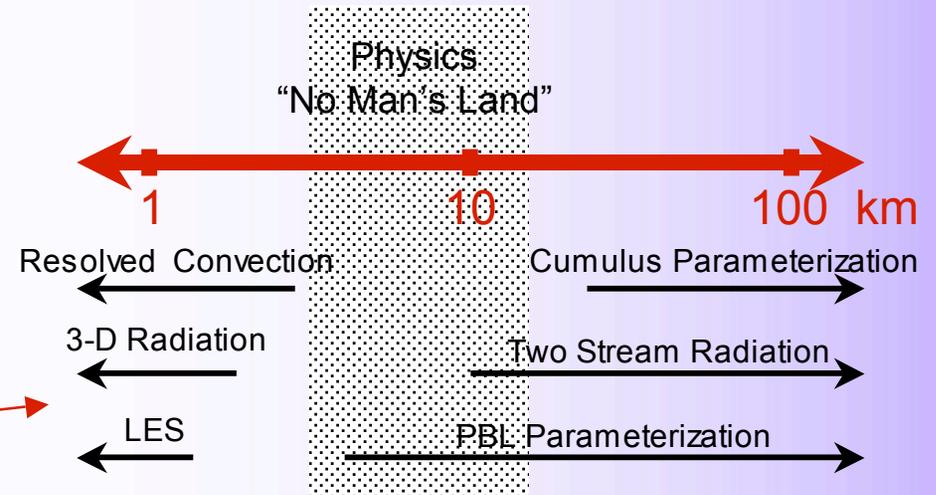
10 June 2003 12Z

WRF

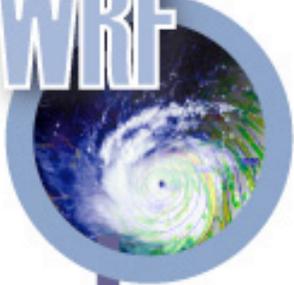


Challenges in High-Resolution NWP

- Small-scale observations
- Data assimilation
- Model resolution/numerics
- Model physics
- Predictability
- Ensemble forecasting
- Forecast verification



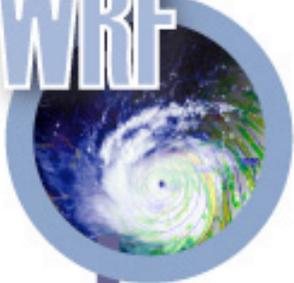
WRF



Advanced Research WRF Core

- Nonhydrostatic, compressible flux-form equations
- Terrain-following hydrostatic pressure vertical coordinate
- Arakawa C-grid, two-way interacting moving nested grids
- 3rd order Runge-Kutta split-explicit time differencing
- Conserves mass, momentum, dry entropy, and scalars using flux form prognostic equations
- 5th order upwind or 6th order centered differencing for advection
- Multiple physics combinations (many converted from MM5)

WRF

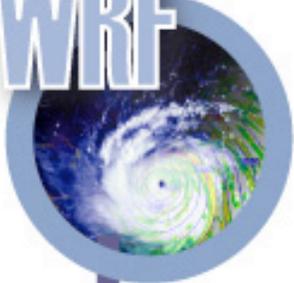


Physics Options Implemented in WRF

- Microphysics: Kessler-type (no-ice), Reisner, Lin et al. (graupel included), WSM3, WSM5, **WSM6**, Ferrier
- Cumulus Convection: New Kain-Fritsch, Grell Ensemble, Betts-Miller-Janjic
- Shortwave Radiation: **Dudhia** (MM5), Goddard, GFDL, CAM*
- Longwave Radiation: **RRTM**, GFDL, CAM*
- Turbulence: Prognostic TKE, Smagorinsky, constant diffusion
- PBL: MRF, MYJ, **YSU**
- Surface Layer: **Similarity theory**, MYJ
- Land-Surface: 5-layer soil model, RUC LSM
Noah unified LSM, CLM*

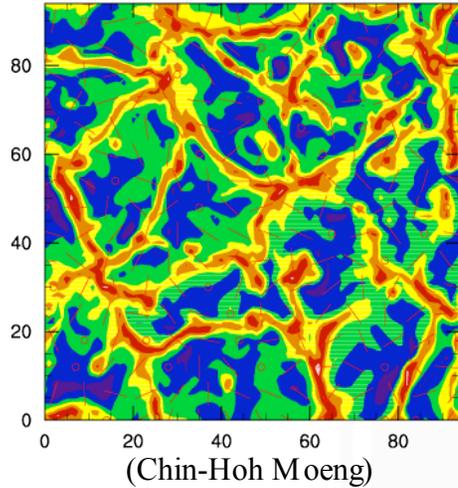
* In progress

WRF

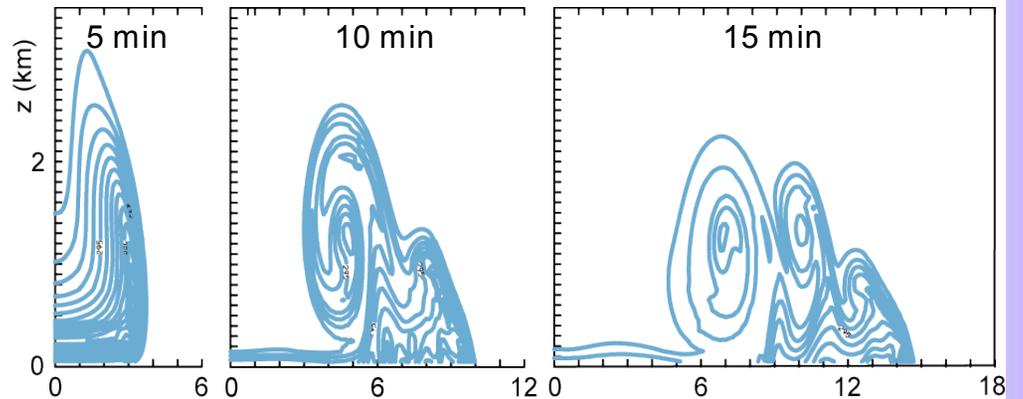


WRF Model Testing and Verification

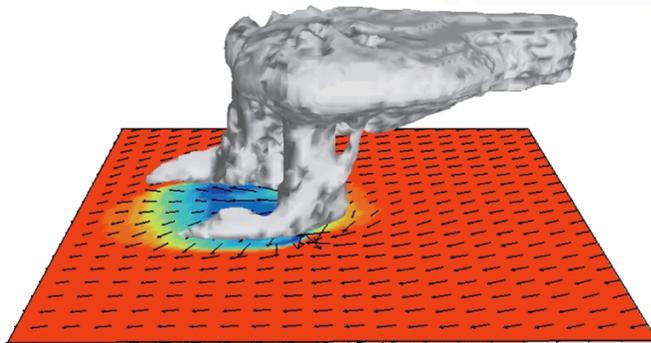
PBL LES, $\Delta x = 50$ m



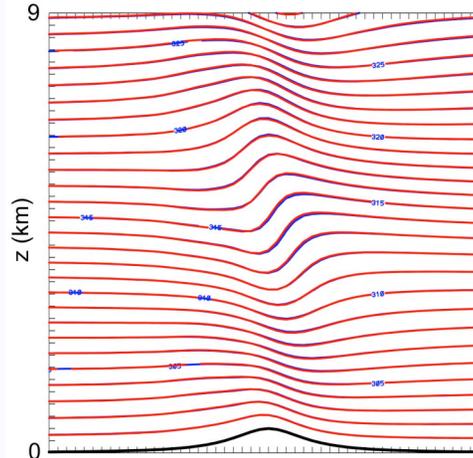
Density current, $\Delta x = 100$ m



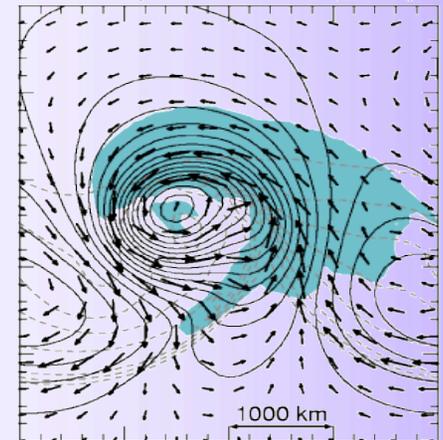
Supercell thunderstorm,
 $\Delta x = 1$ km



Mountain wave,
 $\Delta x = 20$ km



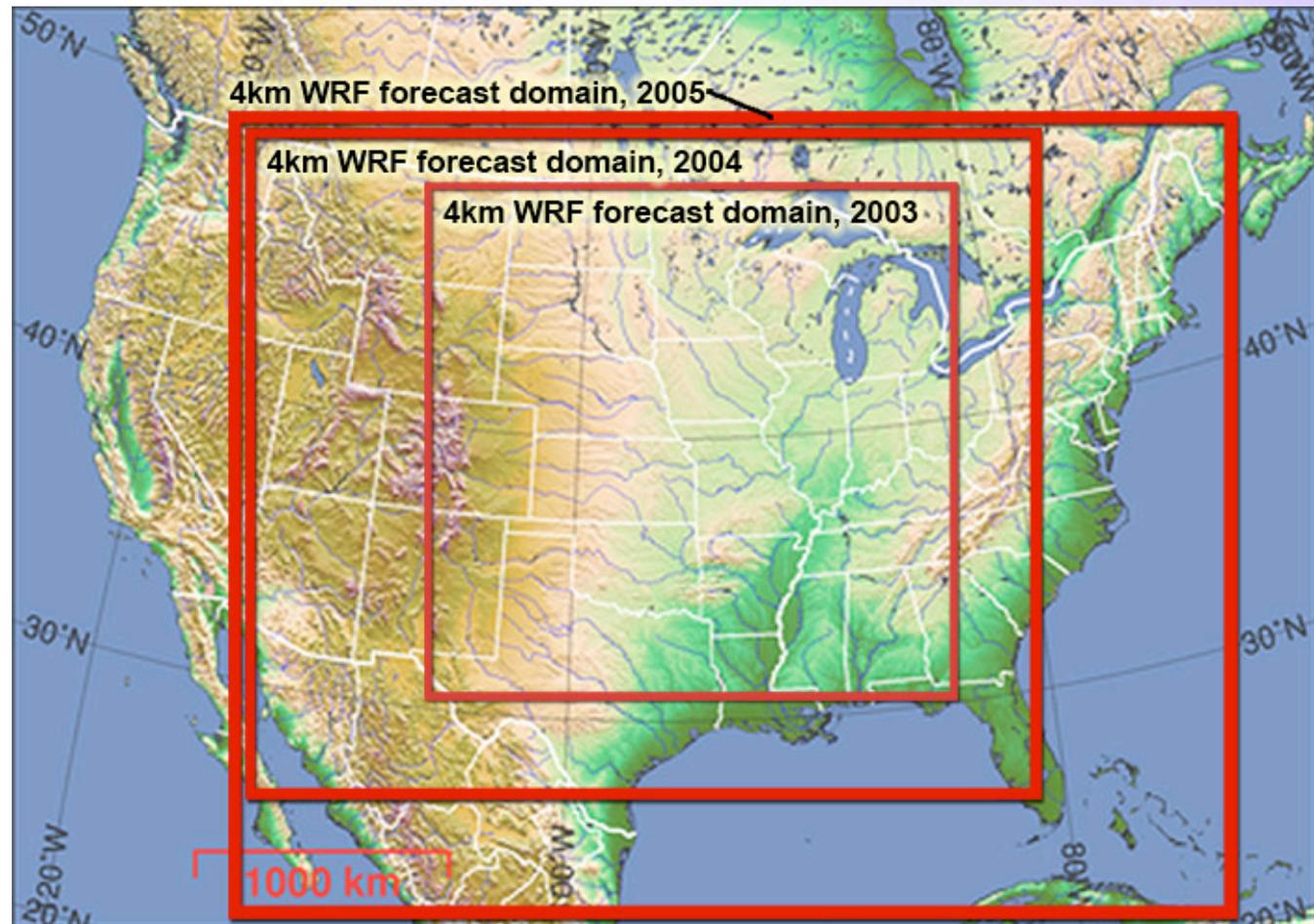
Baroclinic wave,
 $\Delta x = 100$ km



WRF



WRF 4 km Realtime Convective Forecasts



May 15 – July 6 2003 supporting BAMEX

May – July 2004, 2005 In collaboration with SPC, NWS, CAPS

Mesoscale & Microscale Meteorology Division

NCAR

WRF



WRF Real-time Forecasts: 2004, 2005

- 4-km from 0000 UTC - 36 h
- Version 1.3 (2.0.3.1)
- Eta initial and boundary conditions (40 km)
- Physics:
 - Lin et al. microphysics (WSM6)
 - YSU PBL (first-order closure)
 - Noah LSM (HRLDAS)
- 2000 km X 2000 km domain / 2800 km X 2600 km domain
- 5.0h (6.5h) on 128 (192) IBM Power-4 processors

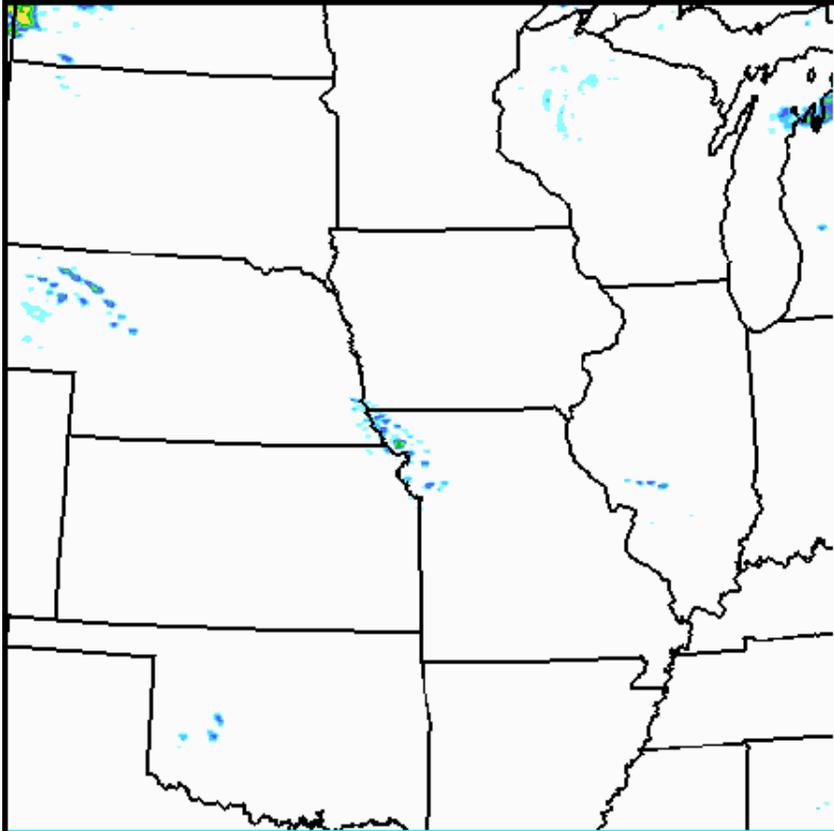
WRF



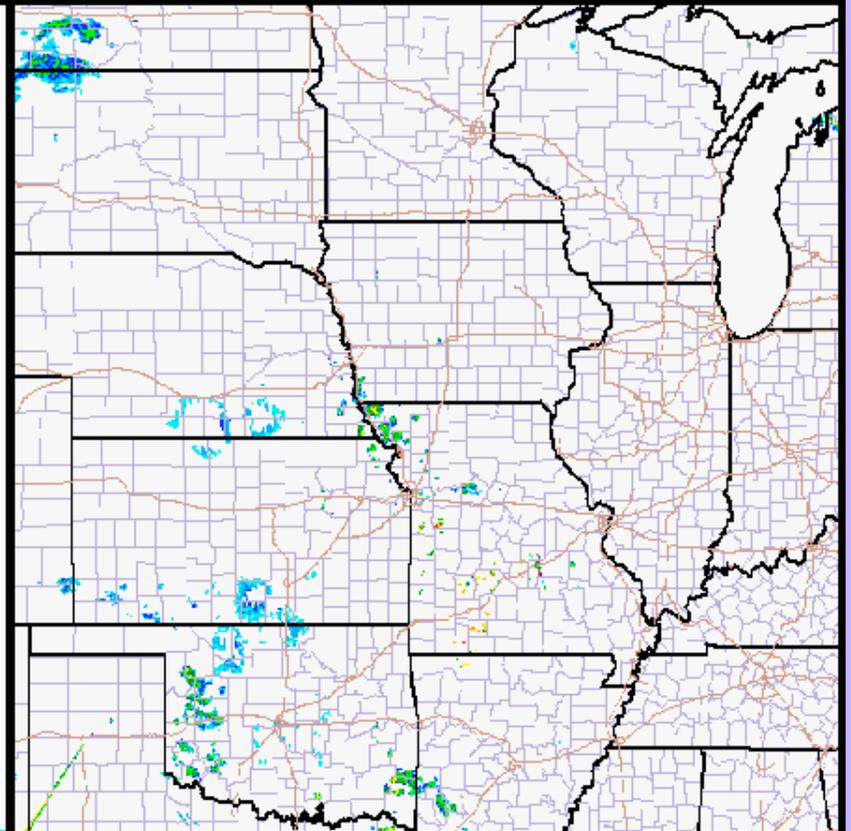
Real-time WRF 4 km BAMEX Forecast

Initialized 00 UTC 9 June 03

12 h forecast 12 UTC 9 June 03



Reflectivity forecast



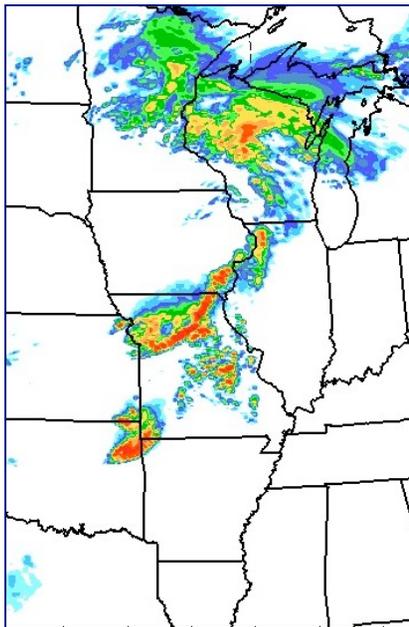
Composite NEXRAD Radar

WRF



Real-time 12 h WRF Reflectivity Forecast

Valid 6/10/03 12Z



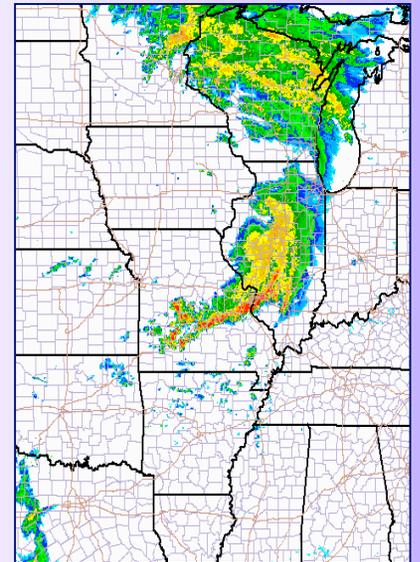
**4 km BAMEX
forecast**



**10 km BAMEX
forecast**

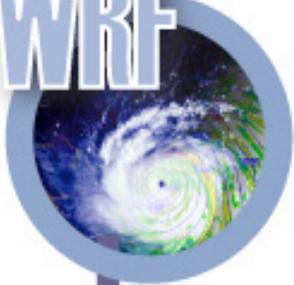


**22 km CONUS
forecast**



**Composite
NEXRAD Radar**

WRF

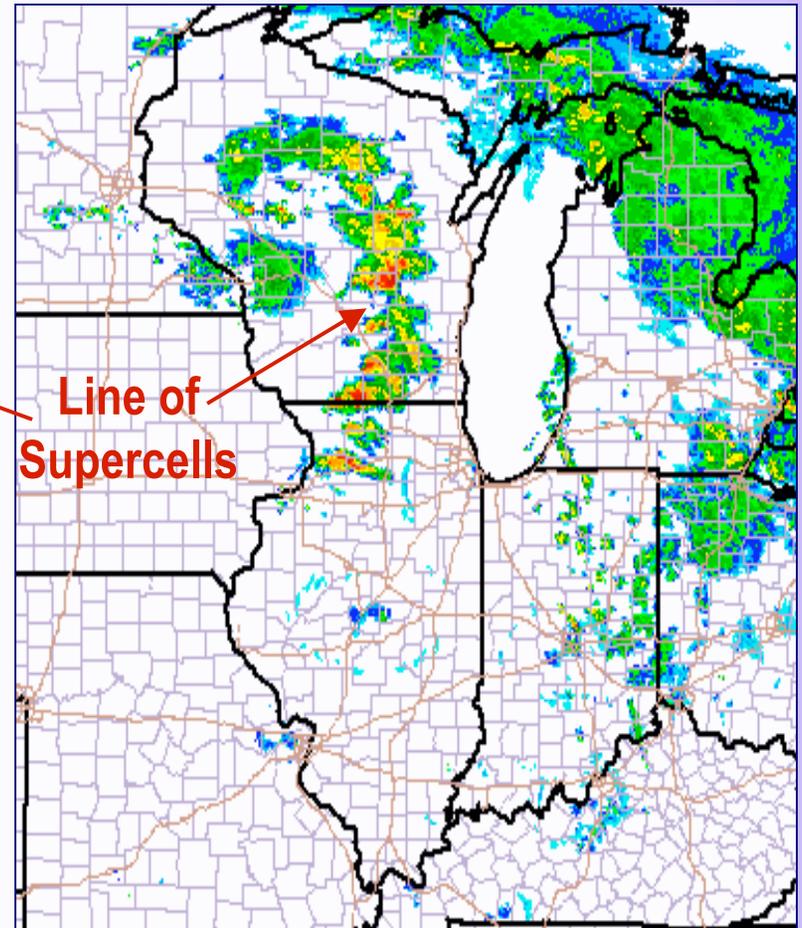
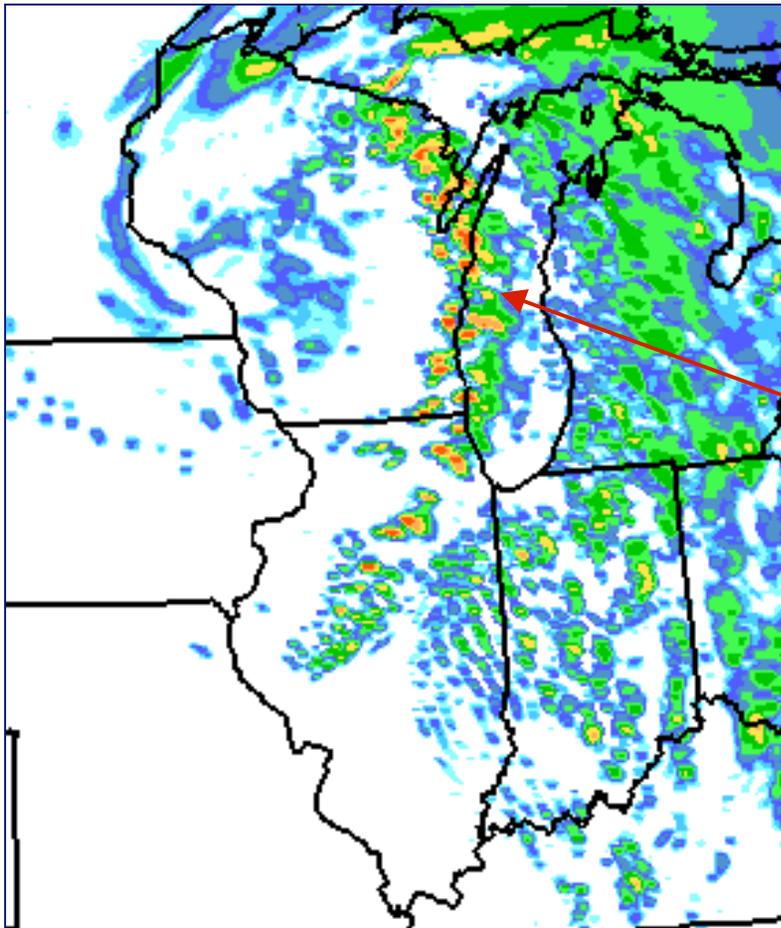


Real-time WRF 4 km BAMEX Forecast

Valid 5/30/03 23Z

23 h Reflectivity Forecast

Composite NEXRAD Radar



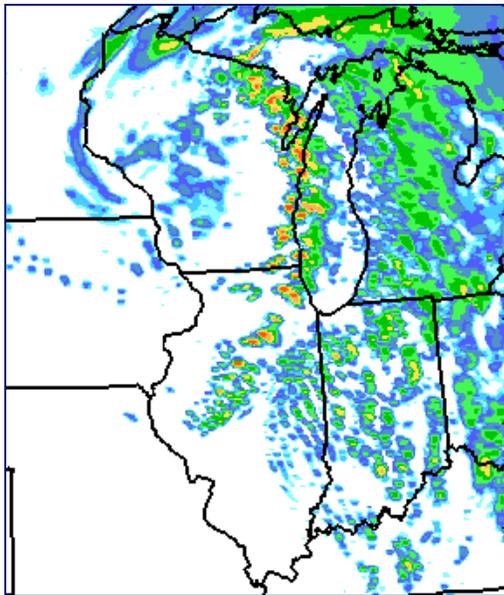
Line of
Supercells

WRF

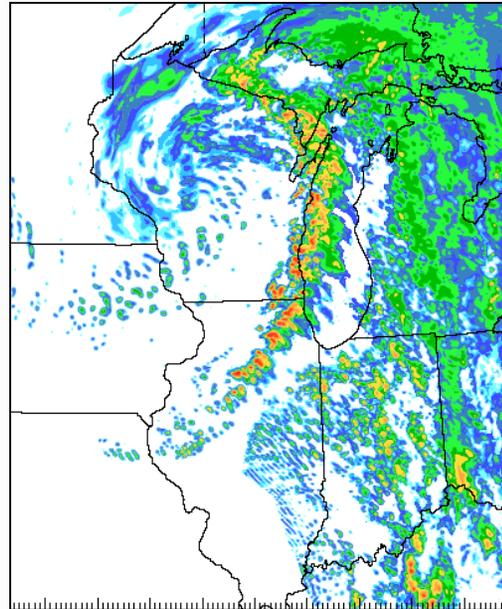
Real-time WRF BAMEX Forecast

Valid 5/30/03 23Z

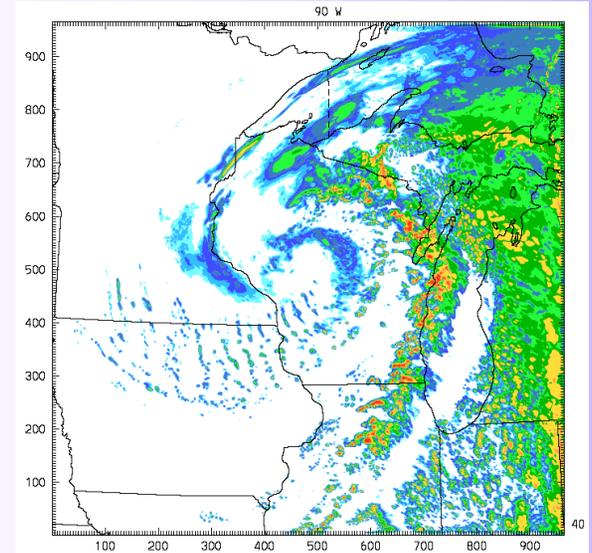
4 km



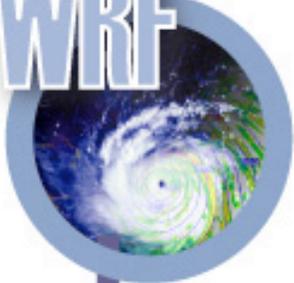
2 km



1 km



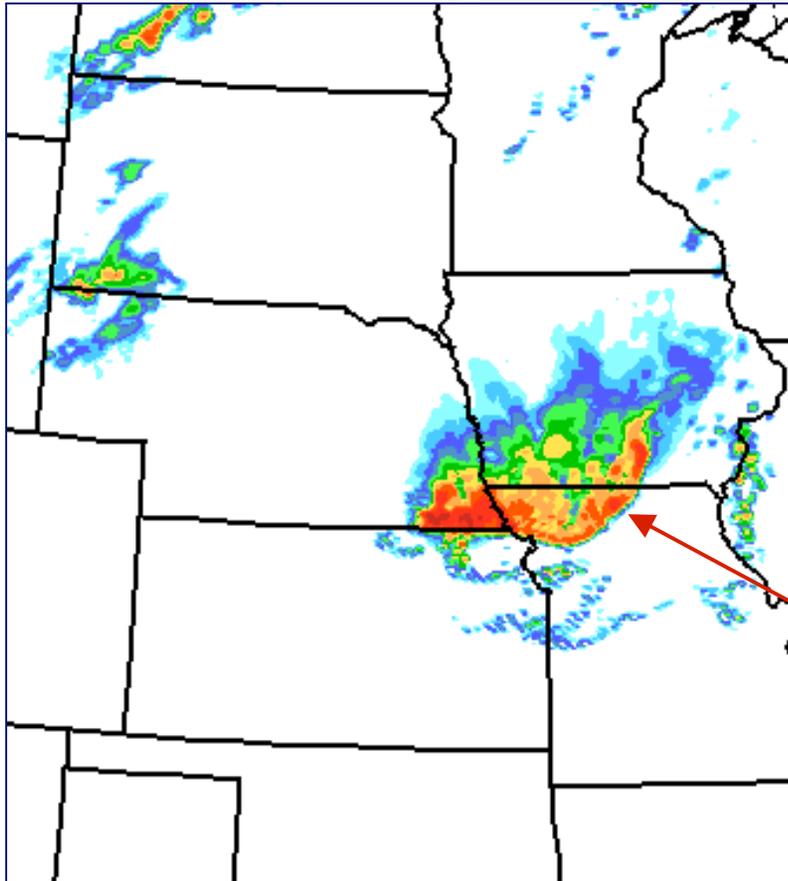
WRF



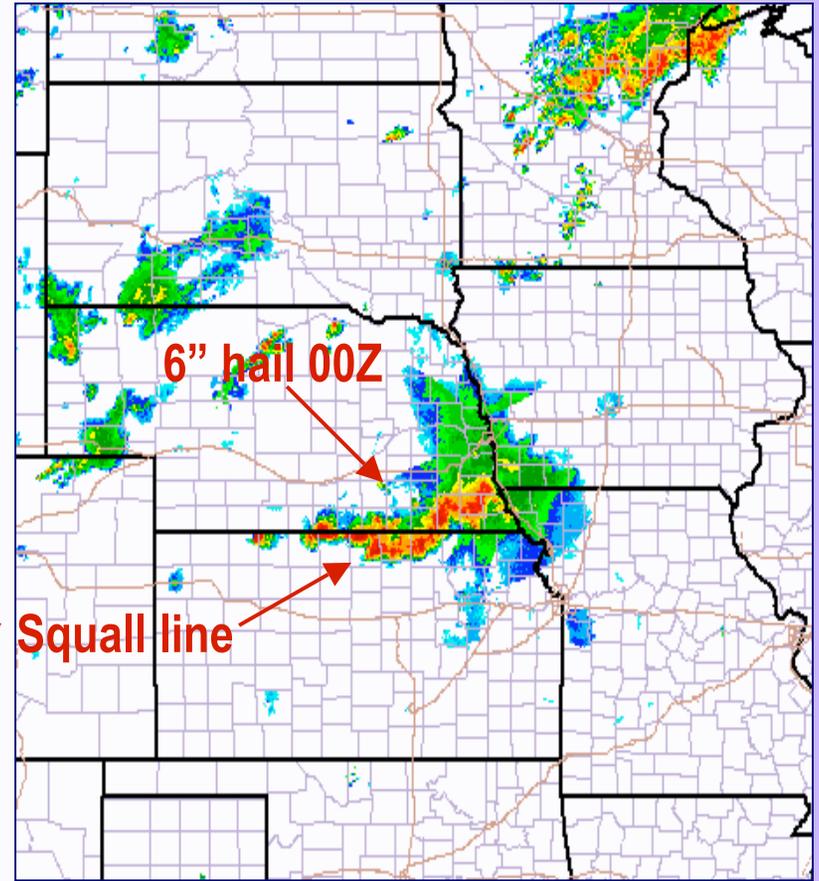
Realtime WRF 4 km BAMEX Forecast

Valid 6/23/03 06Z

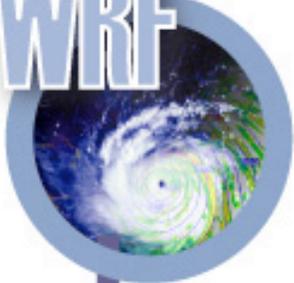
30 h Reflectivity Forecast



Composite NEXRAD Radar



WRF



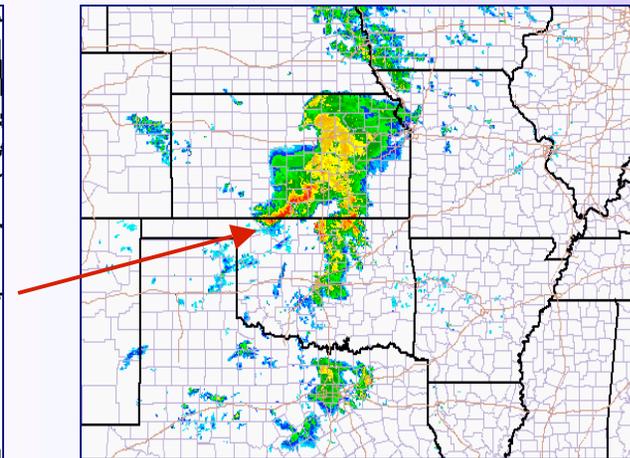
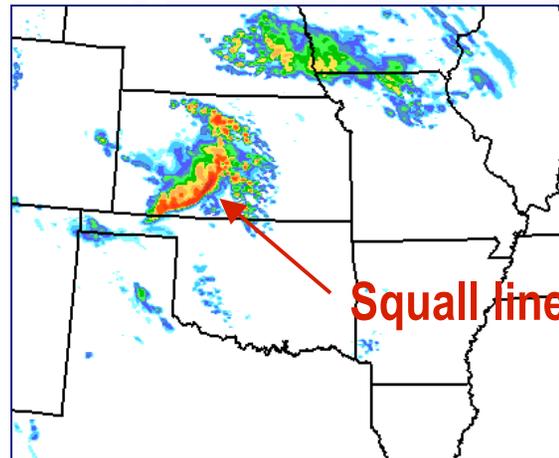
Realtime WRF 4 km BAMEX Forecast

Initialized 5/24/03 00Z

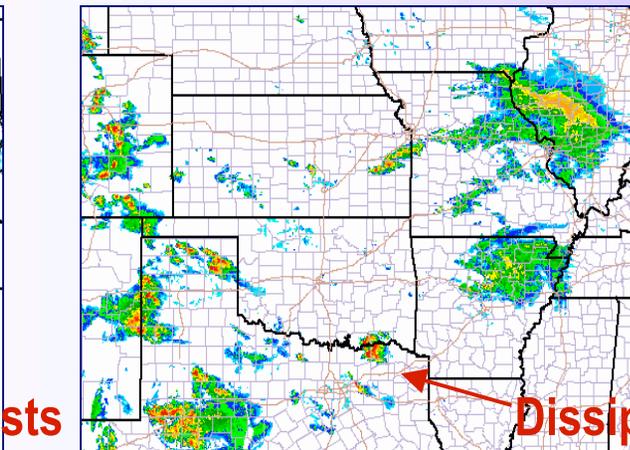
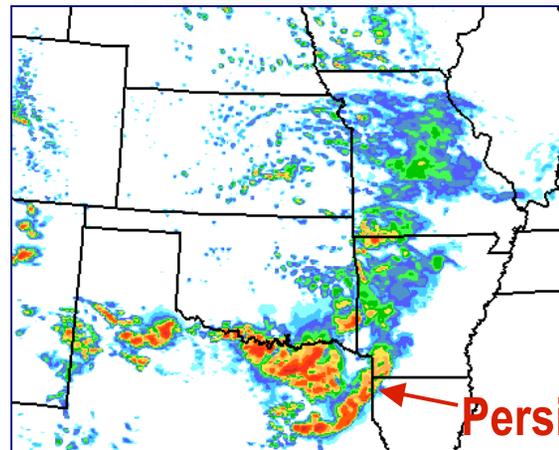
Reflectivity Forecast

Composite NEXRAD Radar

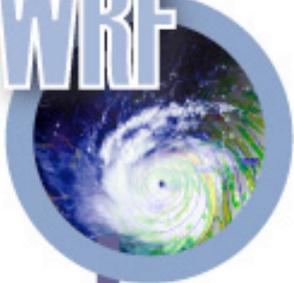
12 h



24 h

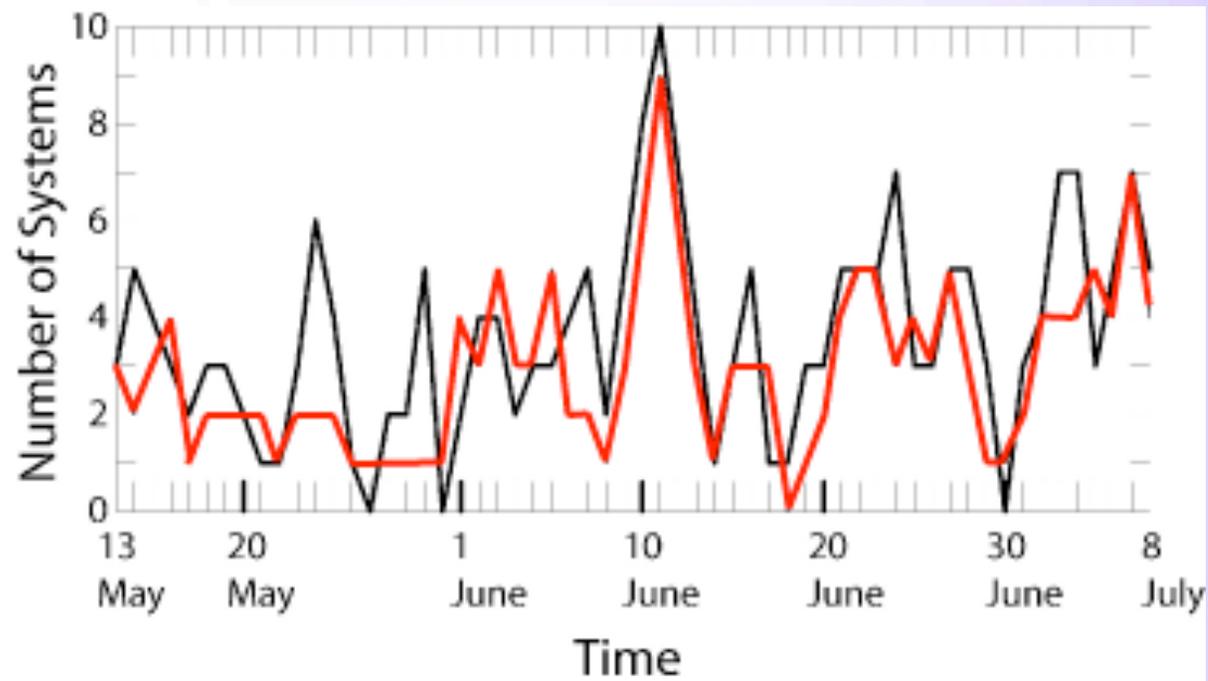


WRF



Preliminary BAMEX Forecast Verification

Number of MCSs for each 36 h forecast initialized at 00 UTC.



— Observed — Forecast

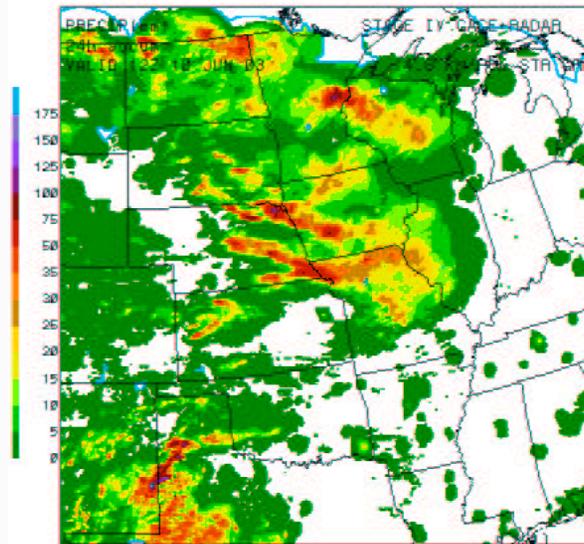
(Done, Davis, and Weisman)

WRF



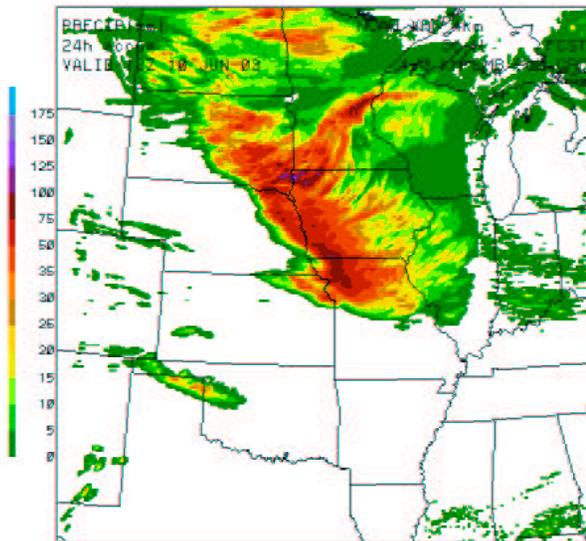
24 hr precipitation verification

OBS

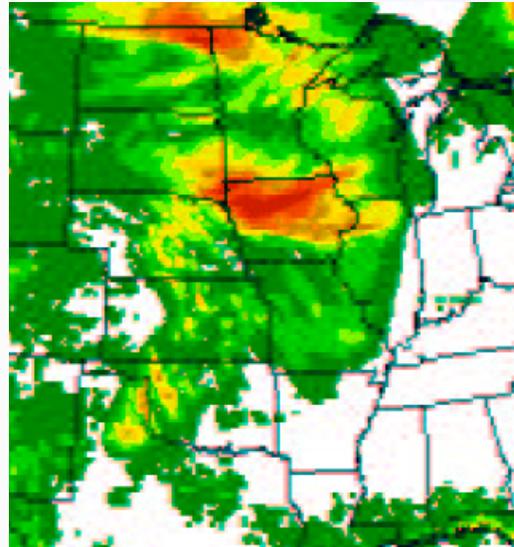


Valid 6/10/03
12 UTC

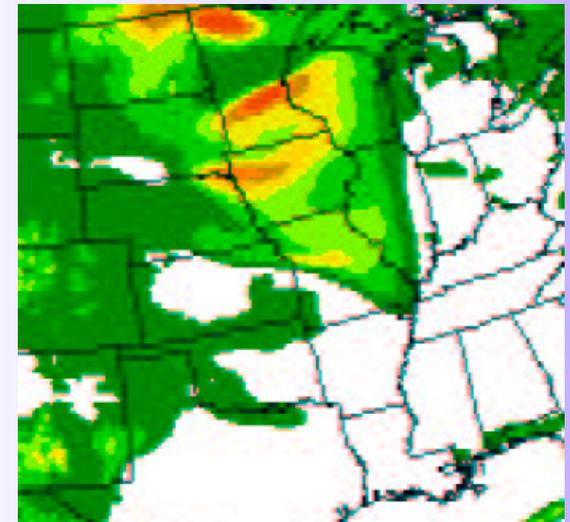
4 km WRF



10 km WRF

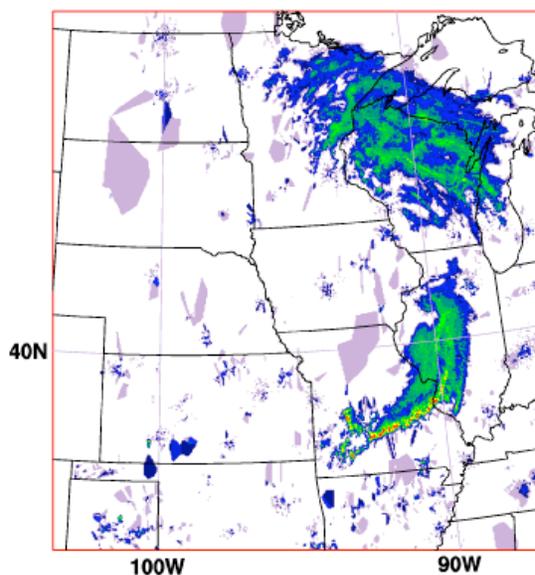


12 km ETA



4 km WRF 12 h Reflectivity Forecast

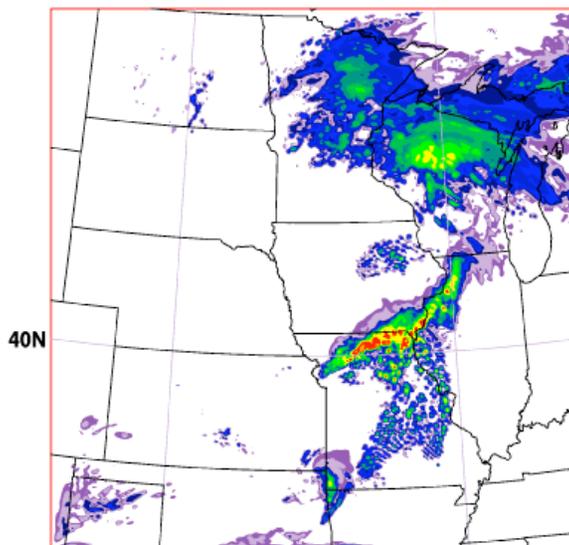
Valid 10 June 2003 12 Z



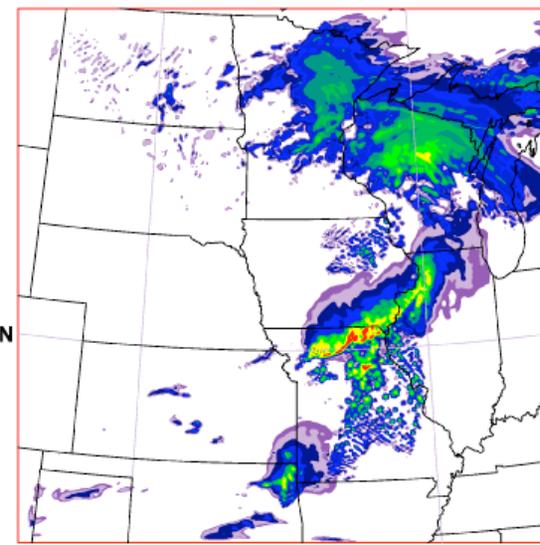
NEXRAD Composite



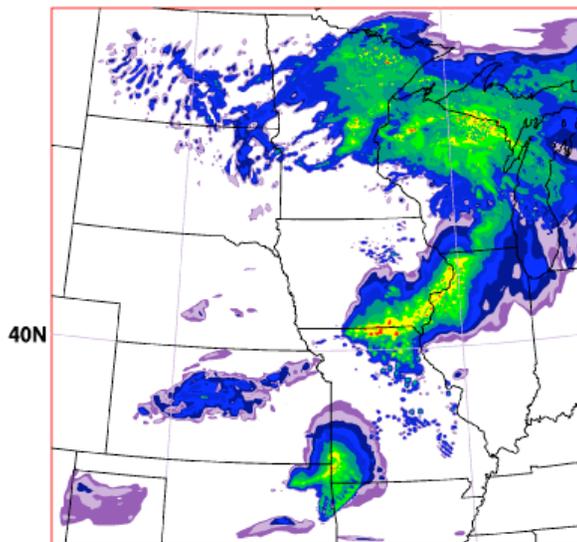
(Axel Seifert, 2004)



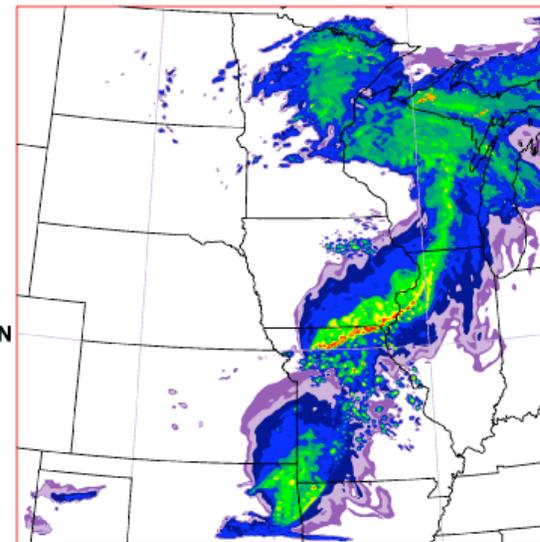
Lin, et al. Scheme



WSM-6 Scheme



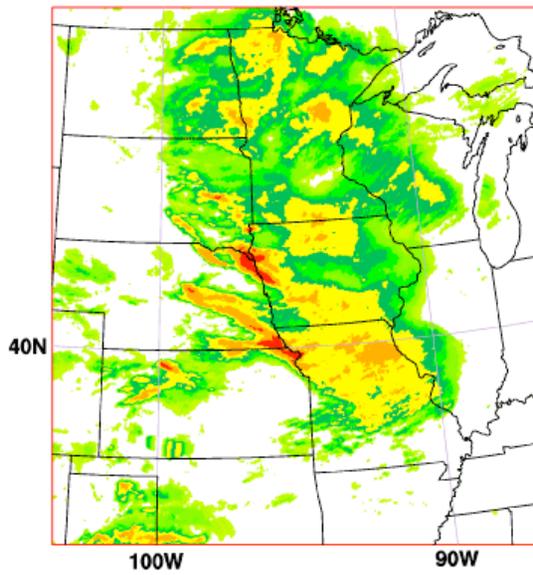
Reisner Scheme



SB2004 Scheme

4 km WRF 12 h Precipitation Forecast

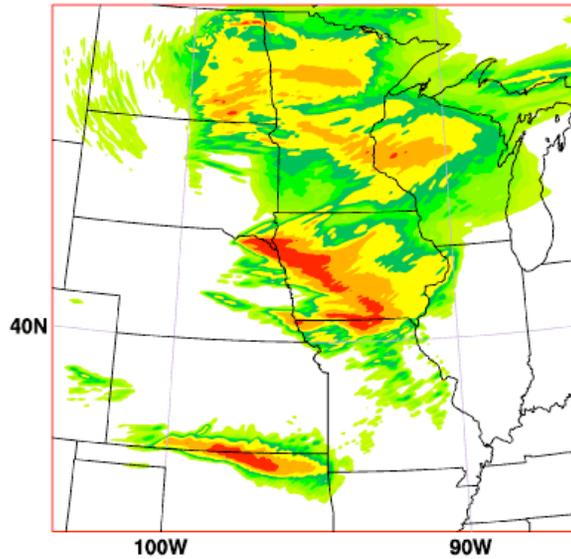
Valid 10 June 2003 12 Z



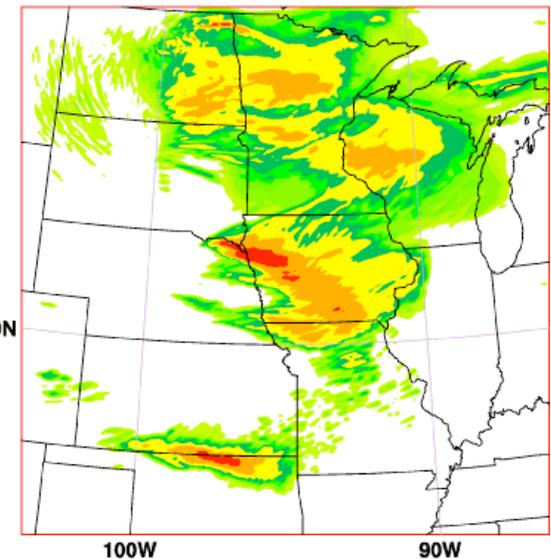
NCEP Stage 4 Data



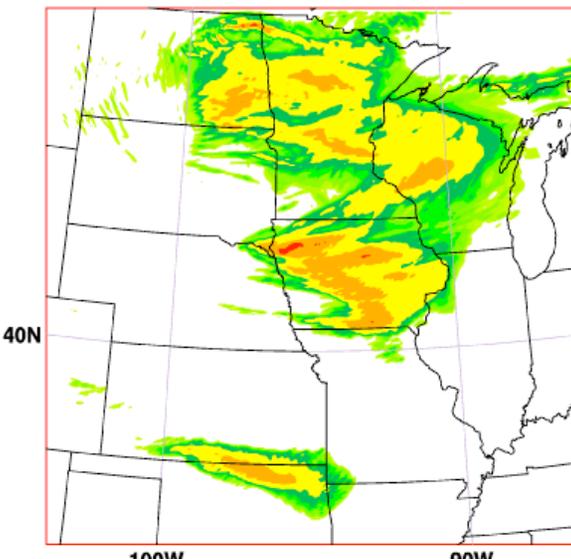
(Axel Seifert, 2004)



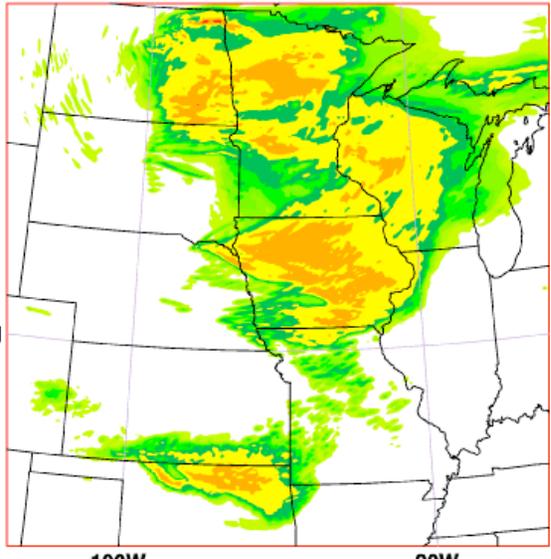
Lin, et al. Scheme



WSM-6 Scheme

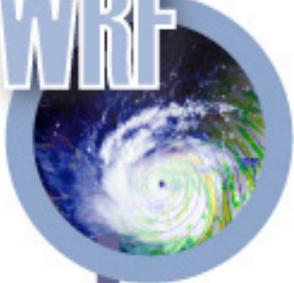


Reisner Scheme



SB2004 Scheme

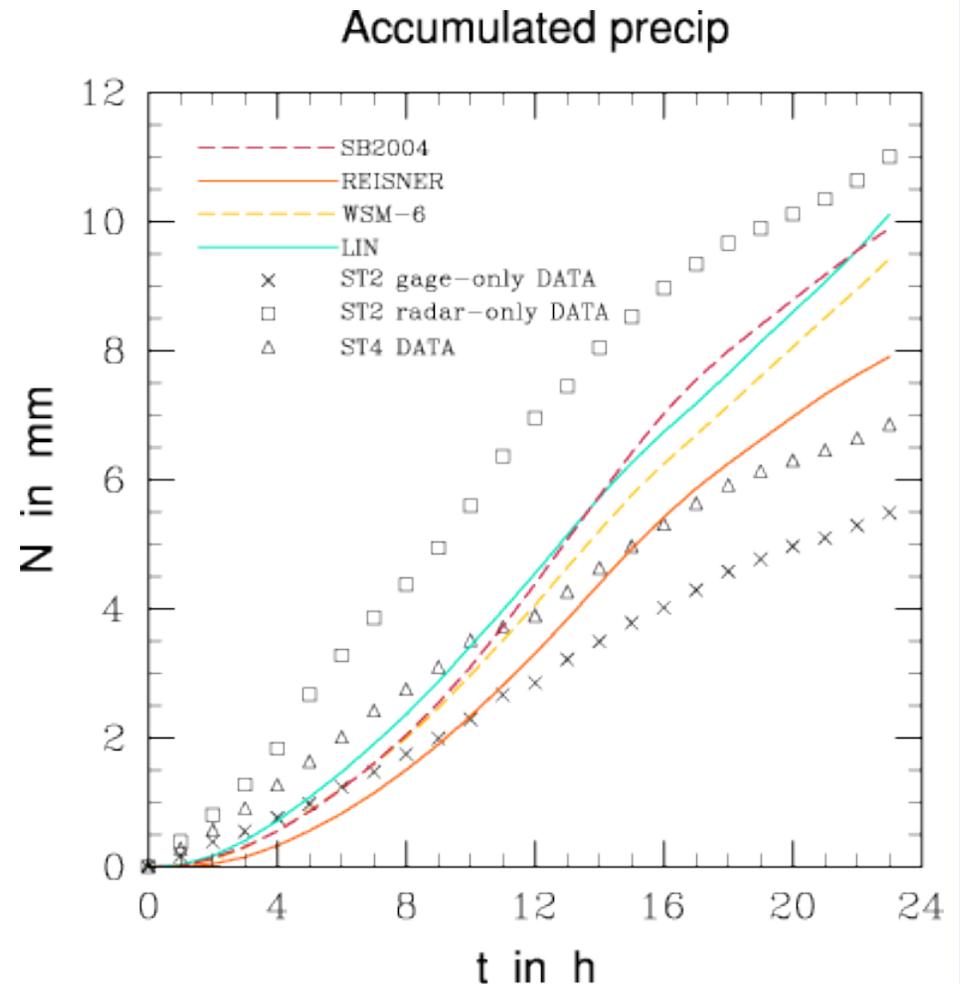
WRF



4 km WRF Accumulated Precipitation Forecast

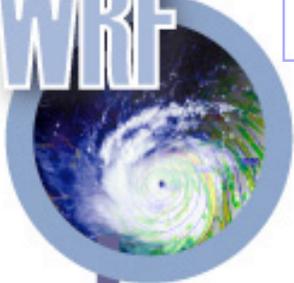
Beginning 10 June 2003 00 Z

- Precipitation characteristics are relatively insensitive to the specific microphysical scheme
- Uncertainties in observed precipitation may be larger than model sensitivity to microphysics



(Axel Seifert, 2004)

WRF



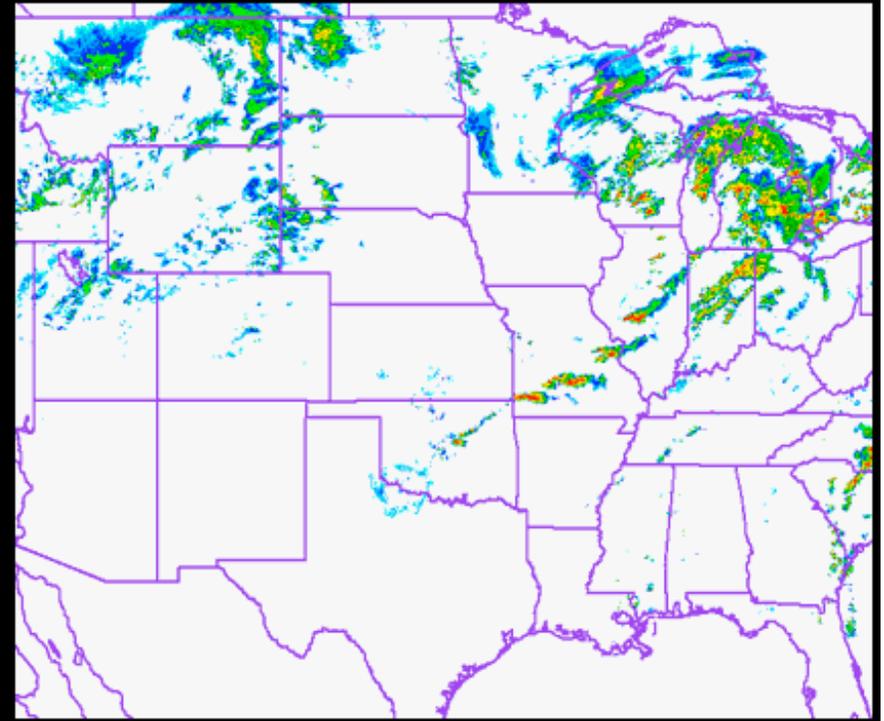
Real-time WRF 4 km Spring 2004 Forecast

Initialized 00 UTC 24 May 04

Reflectivity forecast

Composite NEXRAD Radar

00h forecast 00 UTC 24 May 2004



Severe squall line forecast at ~28 h in northern Missouri and Illinois (high winds, tornados observed)

Mesoscale & Microscale Meteorology Division

NCAR

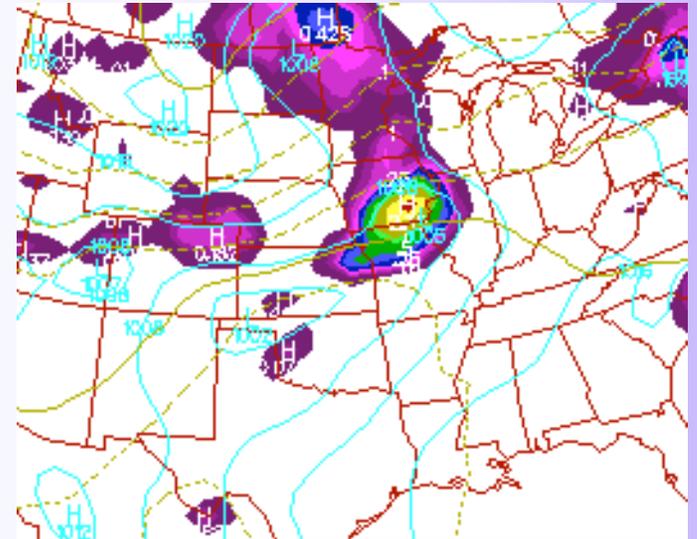
WRF



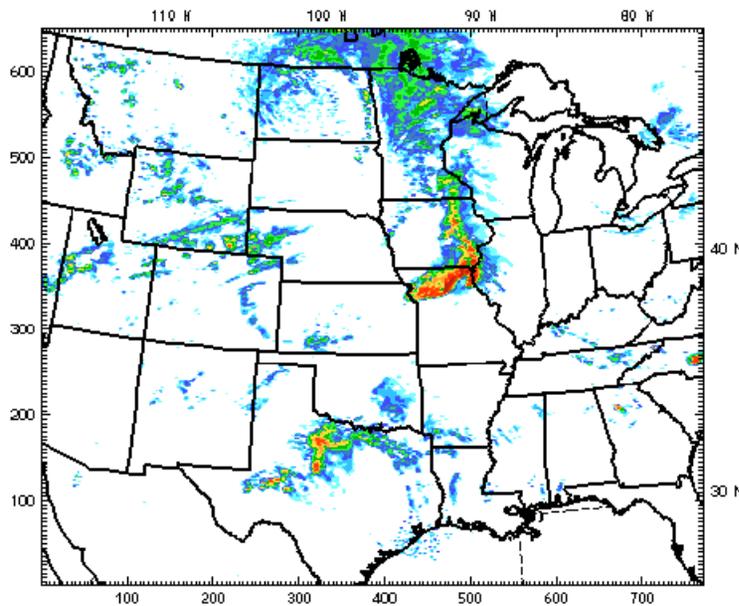
Comparison with Operational Model Guidance

May 25, 2004

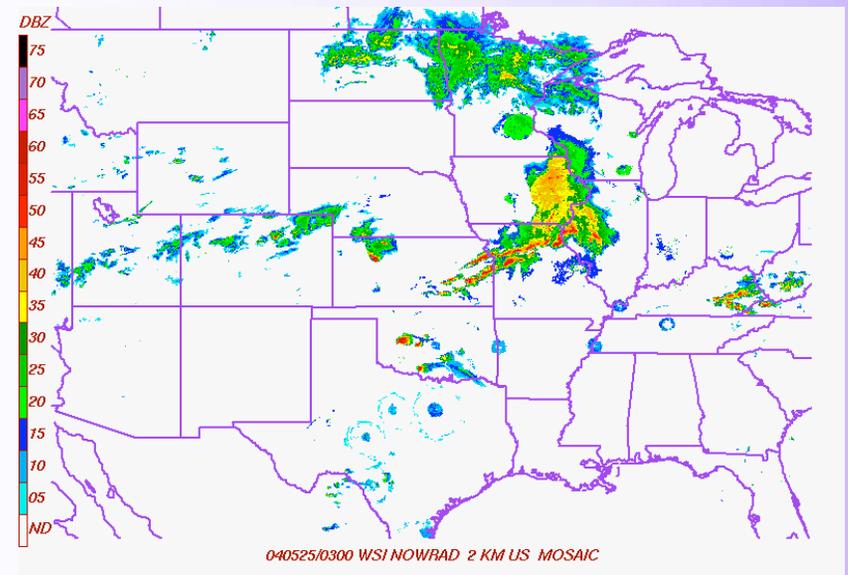
ETA 06 GMT precip - 3 hr



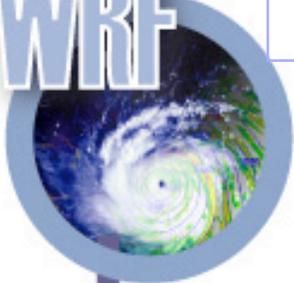
WRF 03 GMT - 27 hr



Radar 03 GMT



WRF

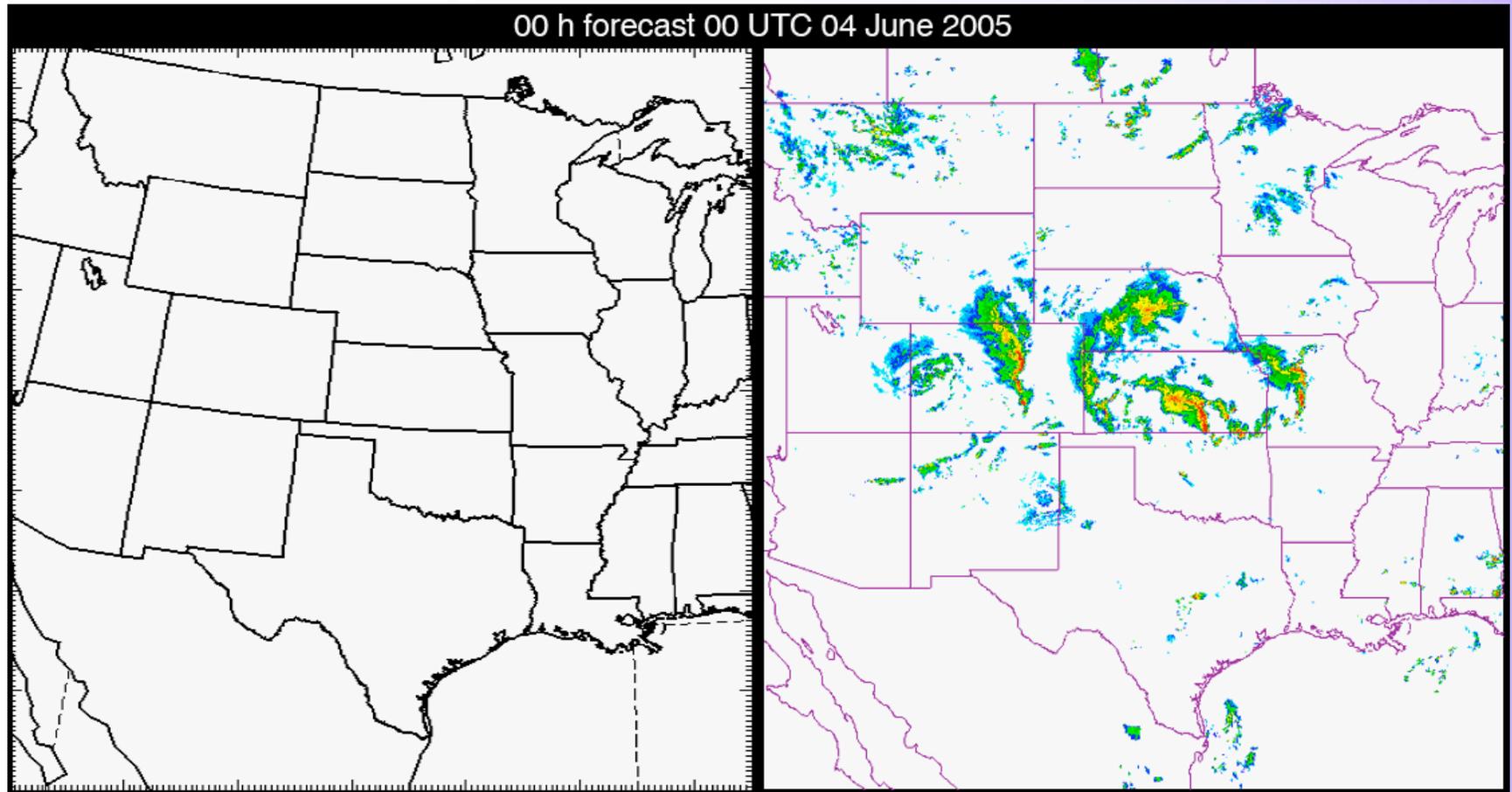


Real-time WRF 4 km Spring 2005 Forecast

Initialized 00 UTC 4 June 05

Reflectivity forecast

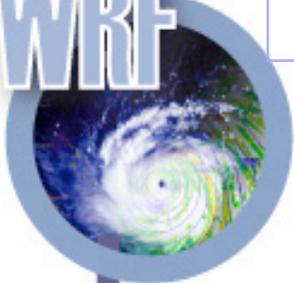
Composite NEXRAD Radar



Mesoscale & Microscale Meteorology Division

NCAR

WRF

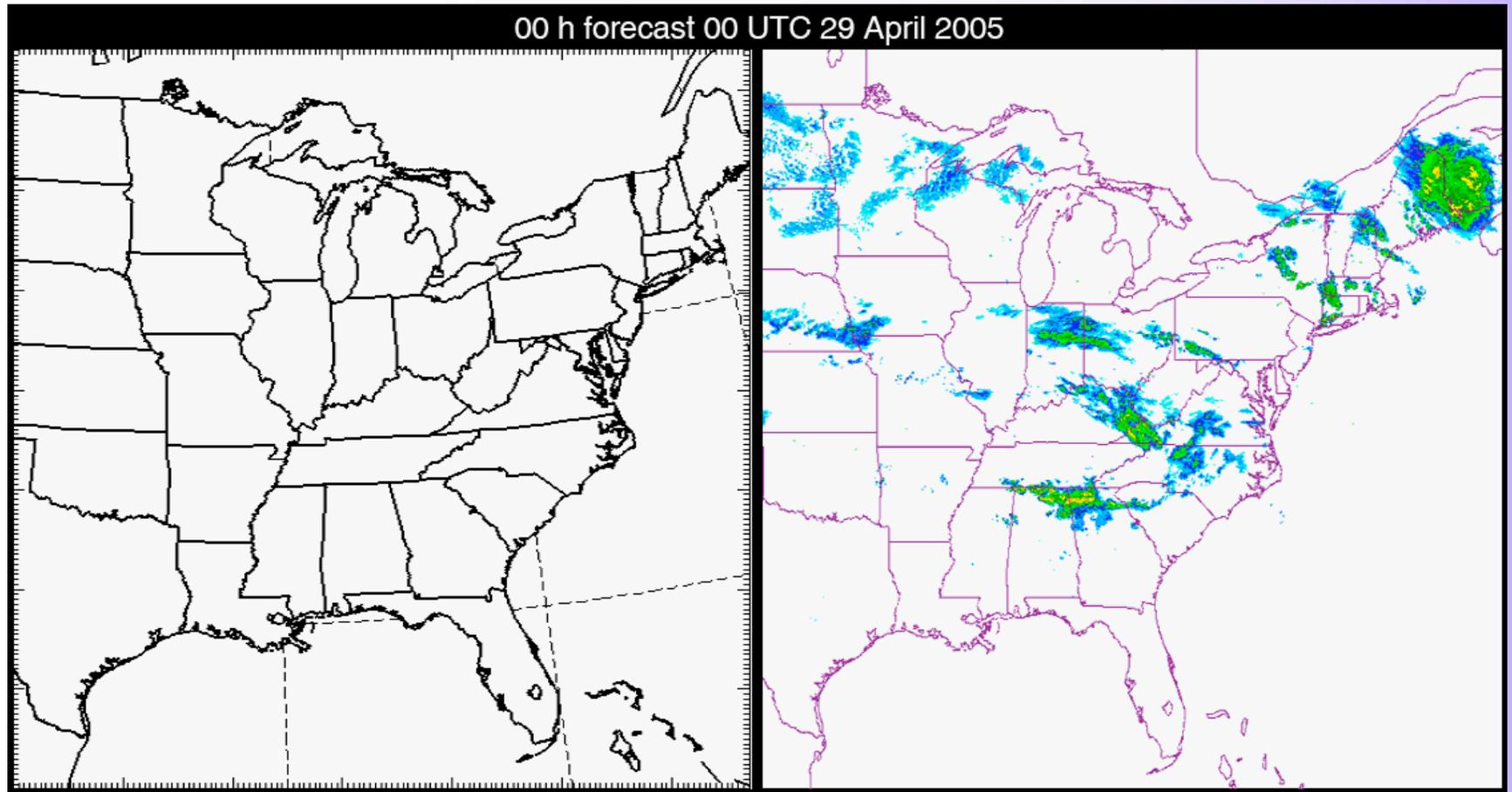


Real-time WRF 4 km Spring 2005 Forecast

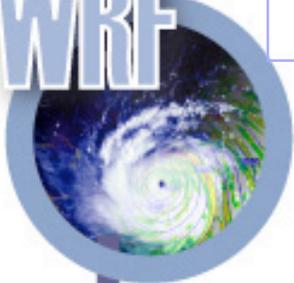
Initialized 00 UTC 29 May 05

Reflectivity forecast

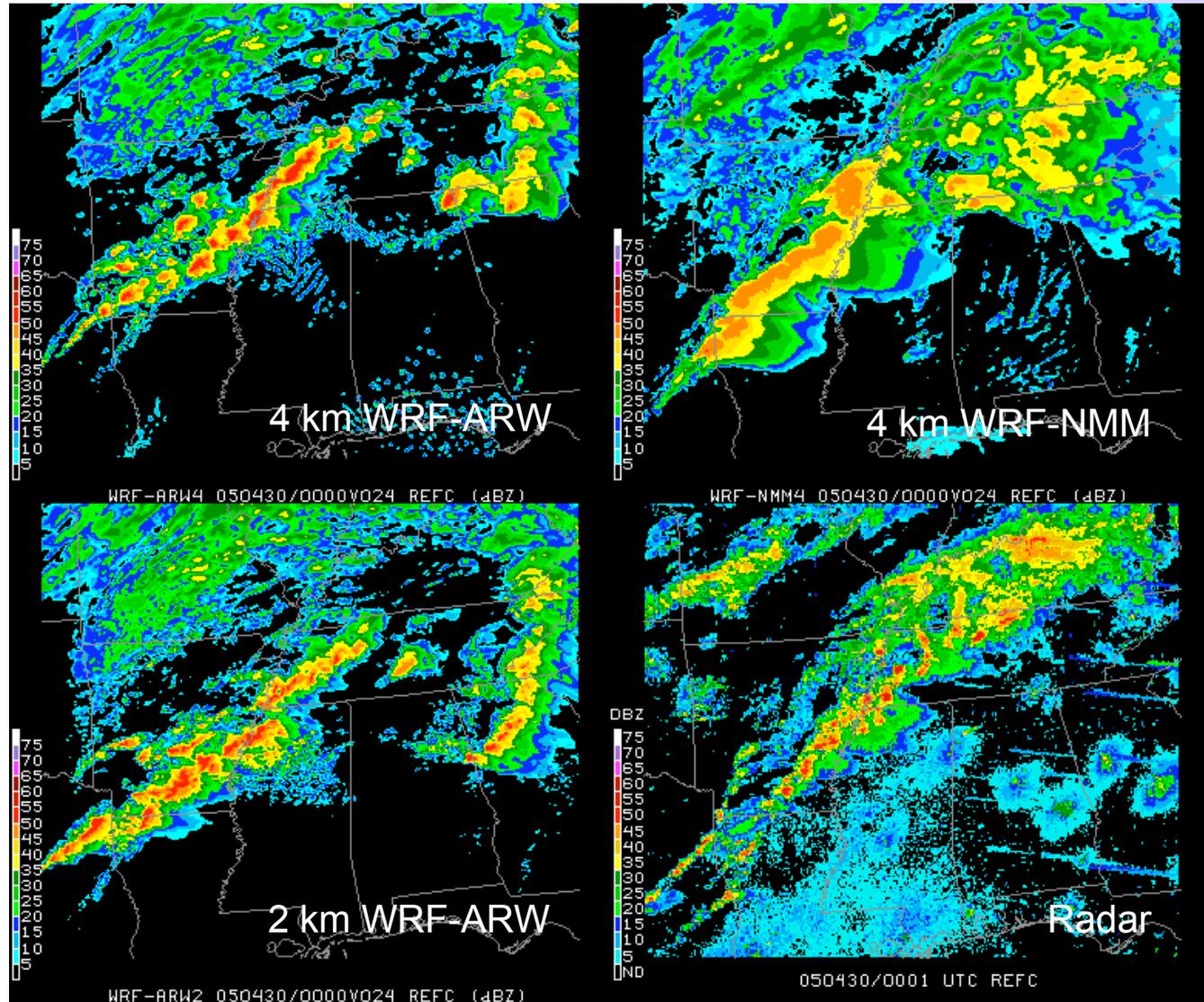
Composite NEXRAD Radar



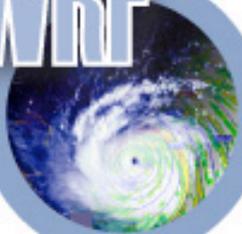
WRF



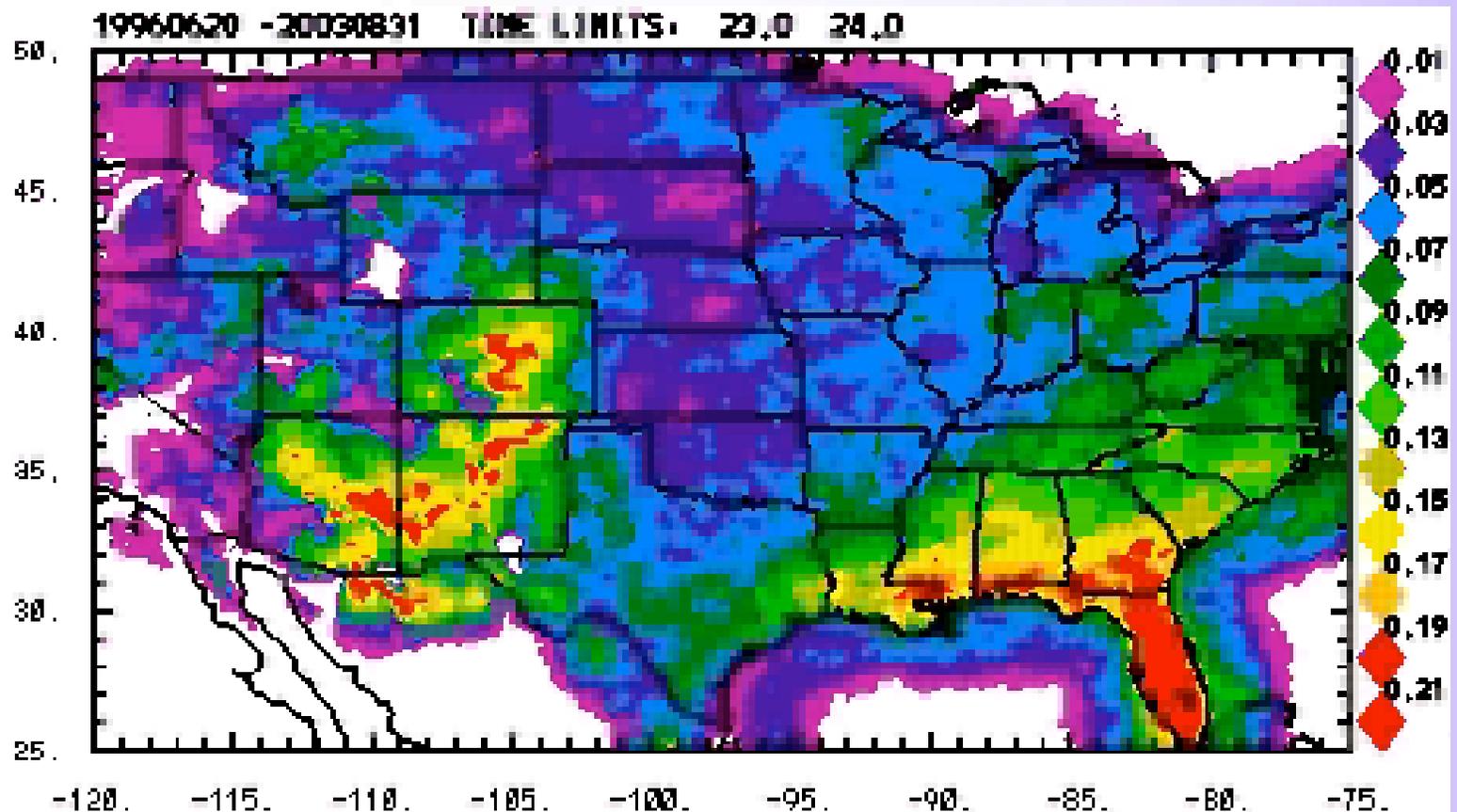
24 h Reflectivity Forecast valid 5-30-05 00Z



WRF



Diurnal Precipitation Frequency: 1996-2003





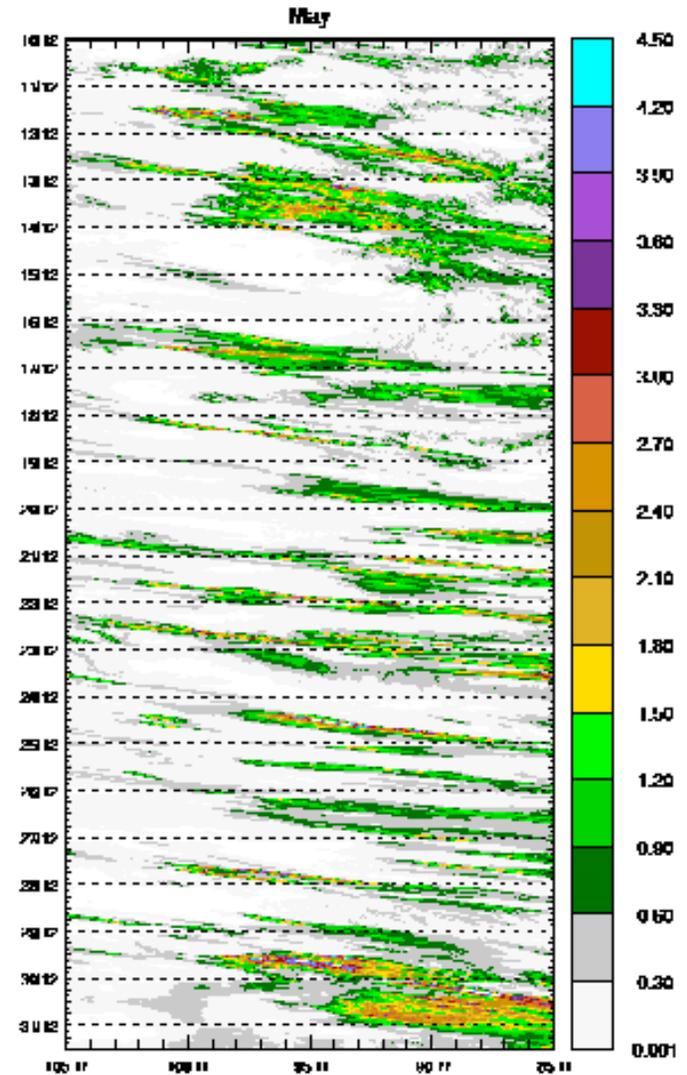
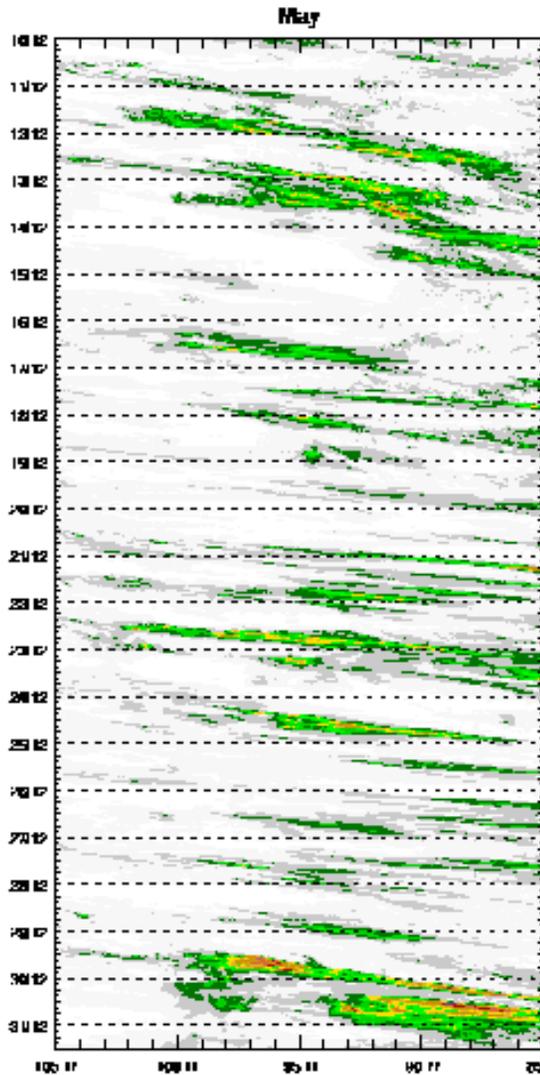
Hovmoller Depiction of Hourly Precip

Longitudinal 1 hr Precip. May 10-31, 2004

Stage IV

WRF

Precip averaged
in the latitudinal
direction



mm

WRF



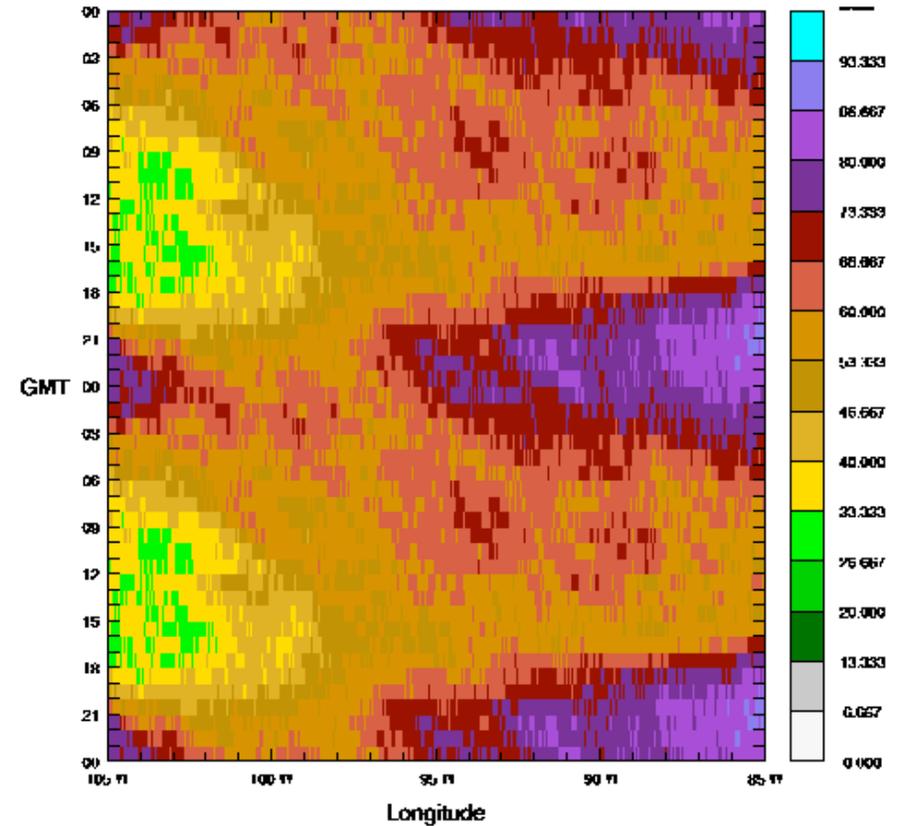
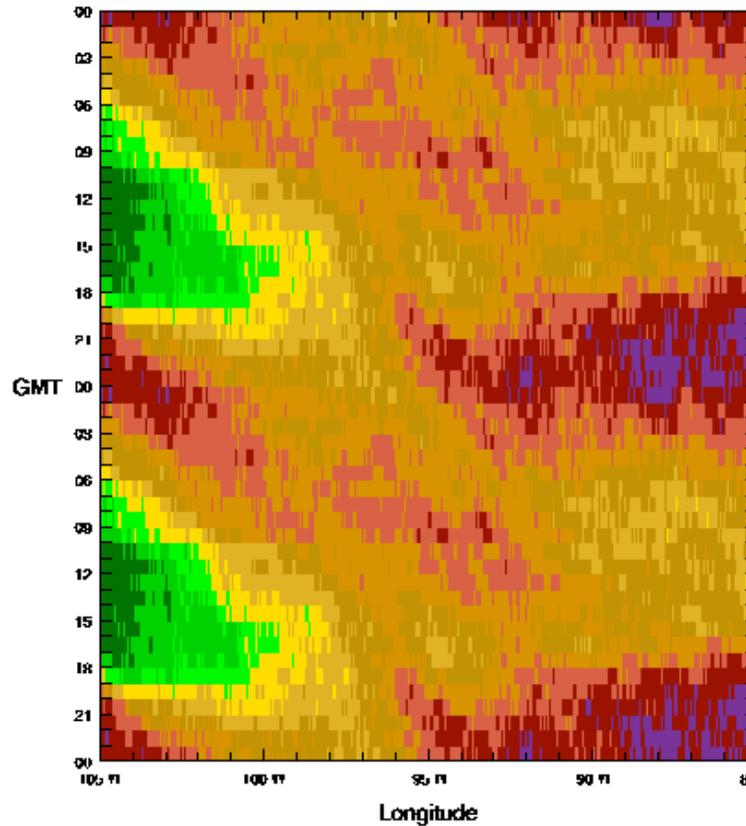
Diurnal Average Frequency: 2004

Stage IV

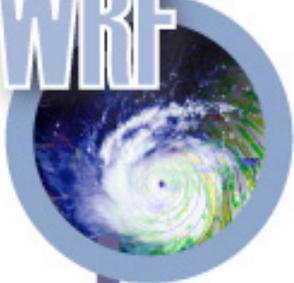
4 km WRF

Threshold - 0.02 mm

Threshold - 0.02 mm



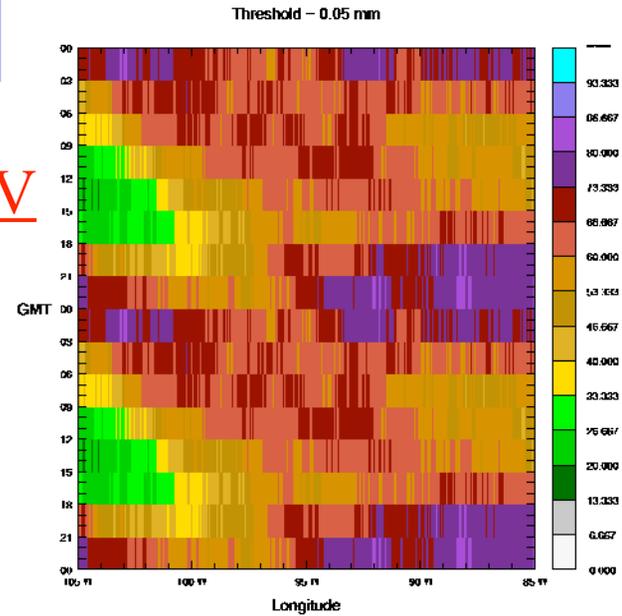
WRF



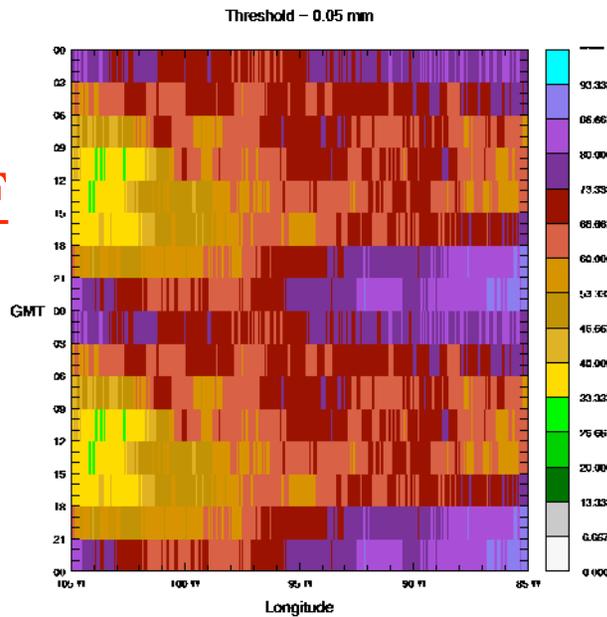
Diurnal Average Frequency

Stage IV

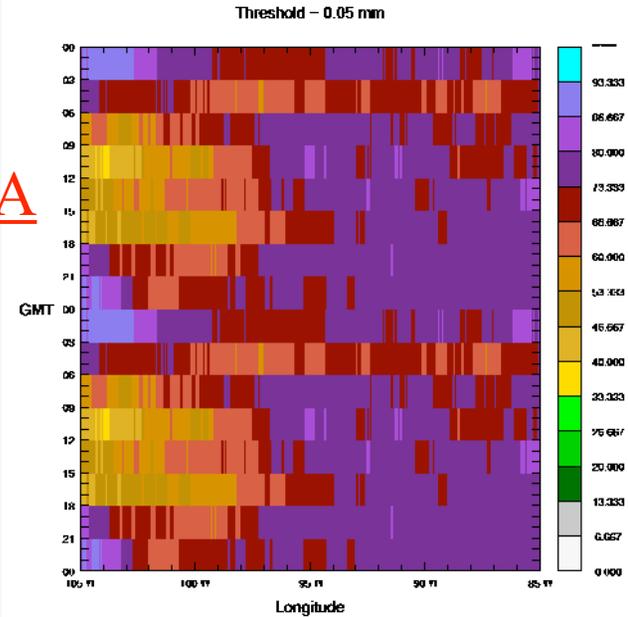
3 hr Precip.



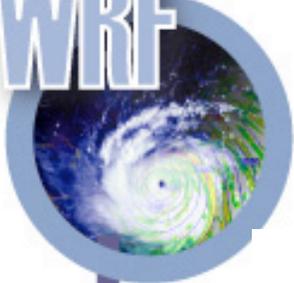
4 km WRF



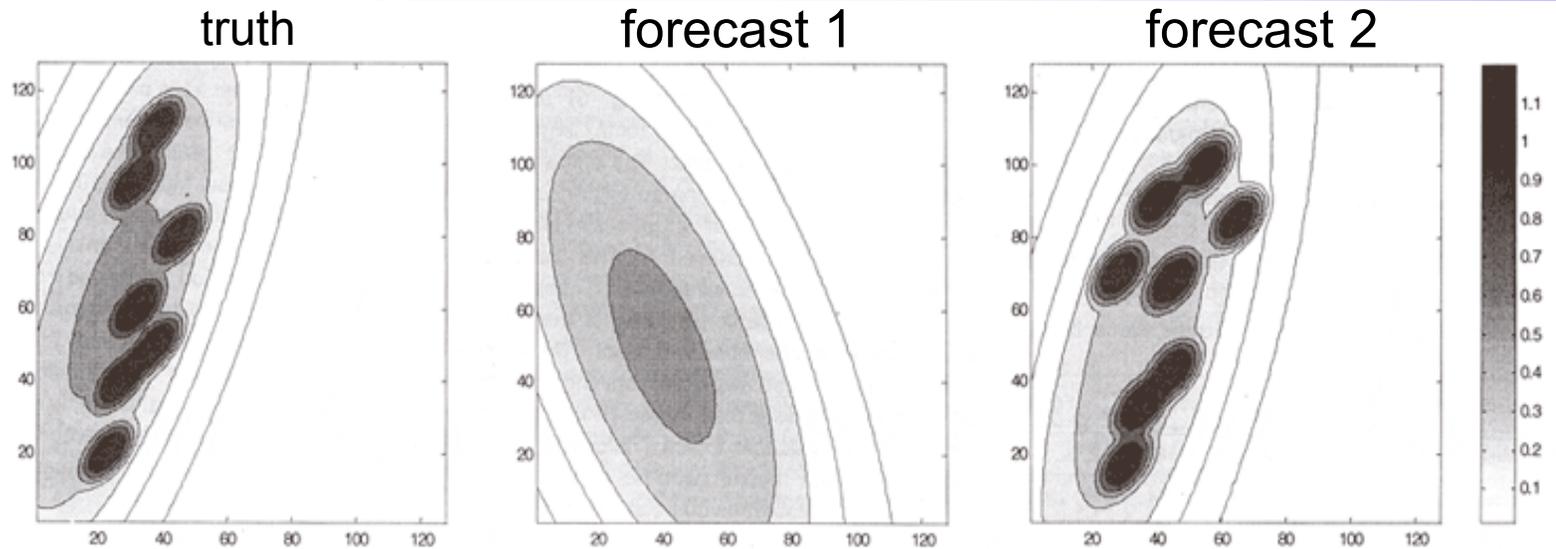
ETA



WRF



Problems with Traditional Verification Schemes

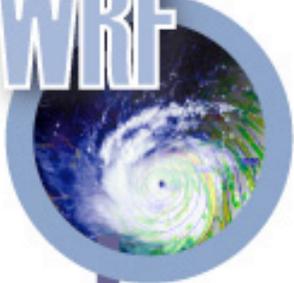


Verification measure	Forecast #1	Forecast #2
Mean absolute error	0.157	0.159
RMS error	0.254	0.309
Bias	0.98	0.98
Threat score	0.214	0.161
Equitable threat score	0.170	0.102

Issue: the obviously poorer forecast has better skill scores

From Mike Baldwin
NOAA/NSSL

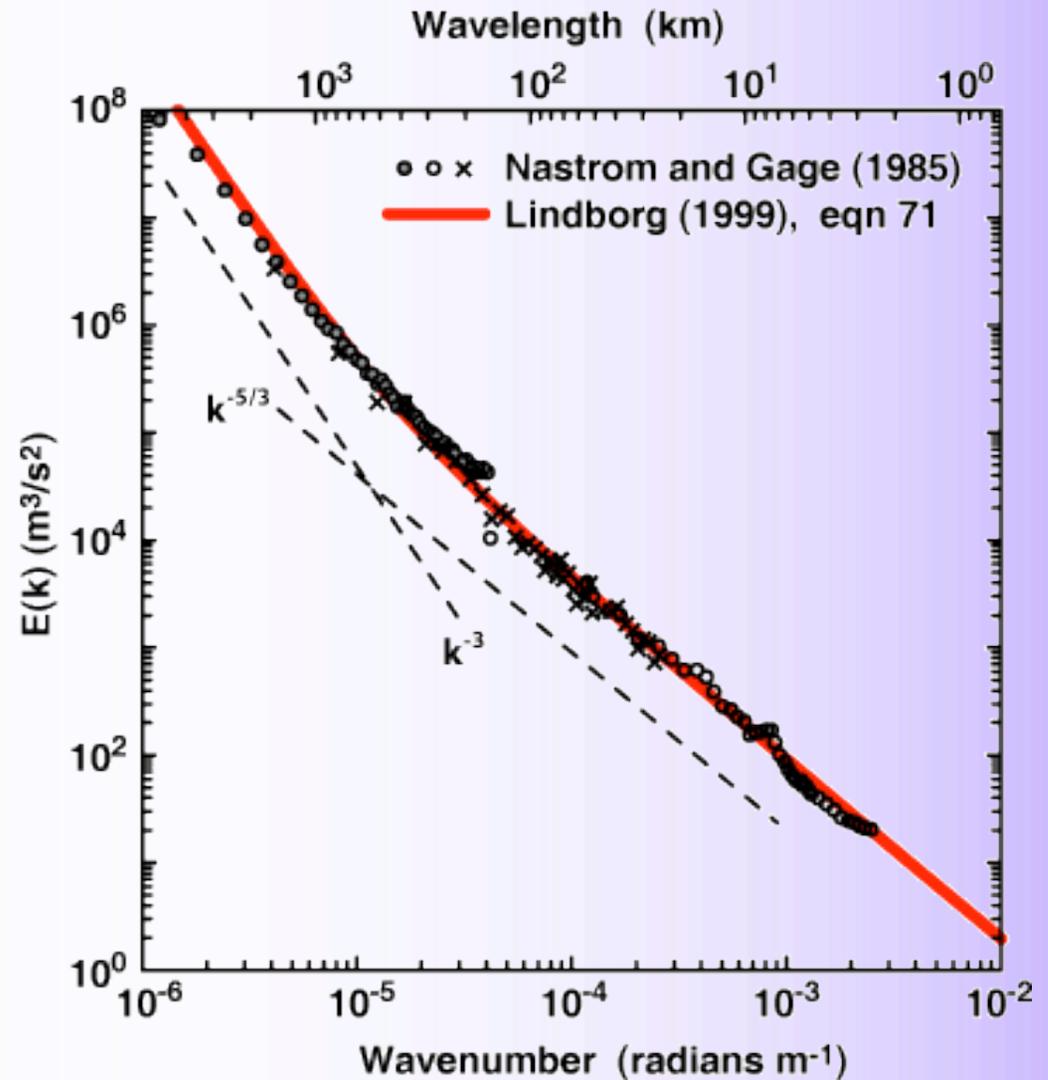
WRF



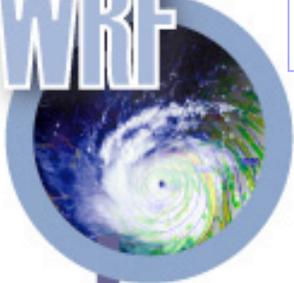
Kinetic Energy Spectra in NWP Models

Nastrom and Gage (1985)
Spectra computed from
GASP observations
(commercial aircraft)

Lindborg (1999) functional
fit from MOZAIC
observations (aircraft)



WRF



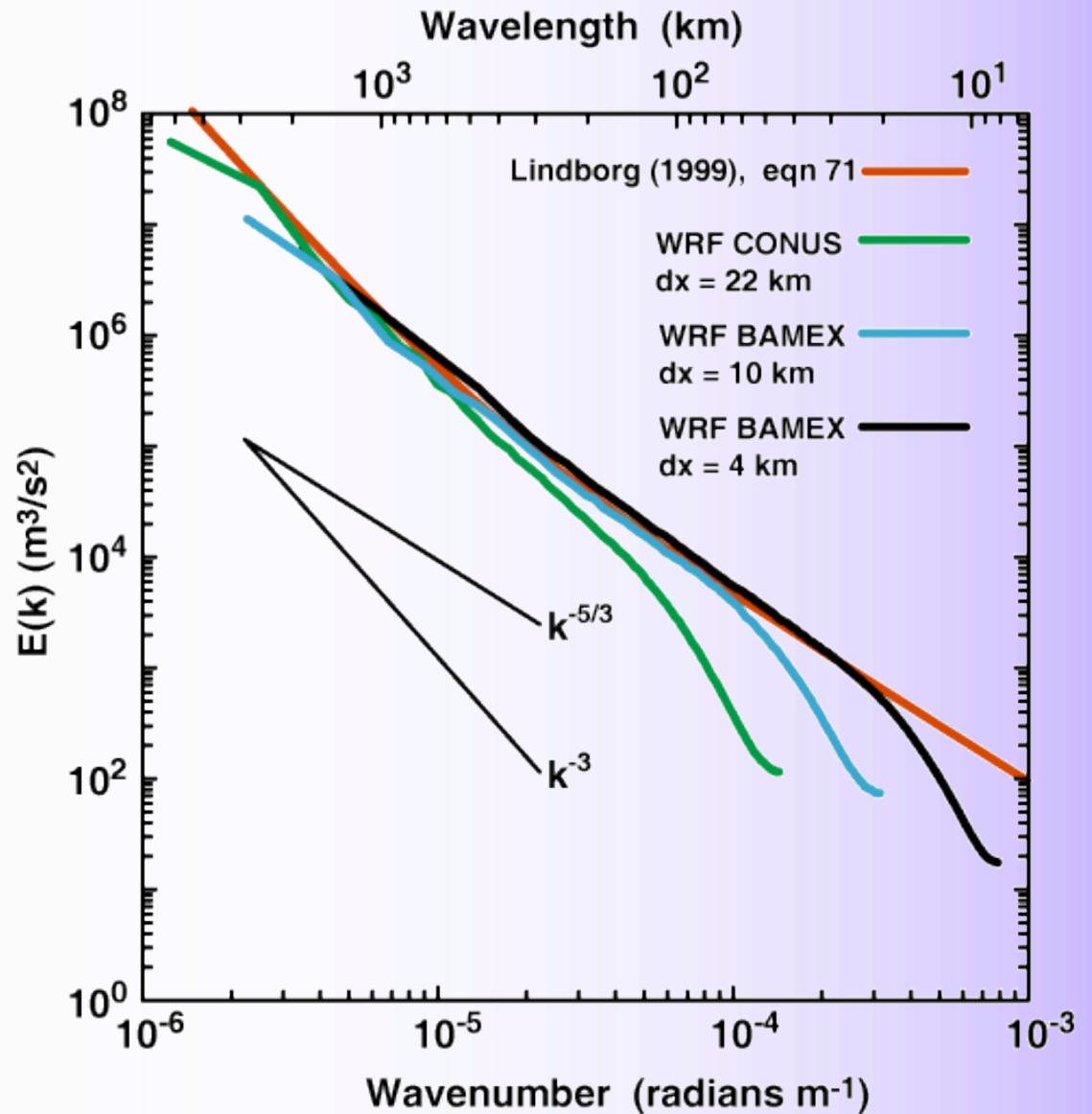
Spectra for WRF-ARW BAMEX Forecasts

1 June – 3 June 2003

Average over approx.
4 – 9 km height, on
model surfaces.

4, 10 and 22 km
WRF-ARW:
12 - 36 h forecast avg.

(Skamarock, 2004)



WRF



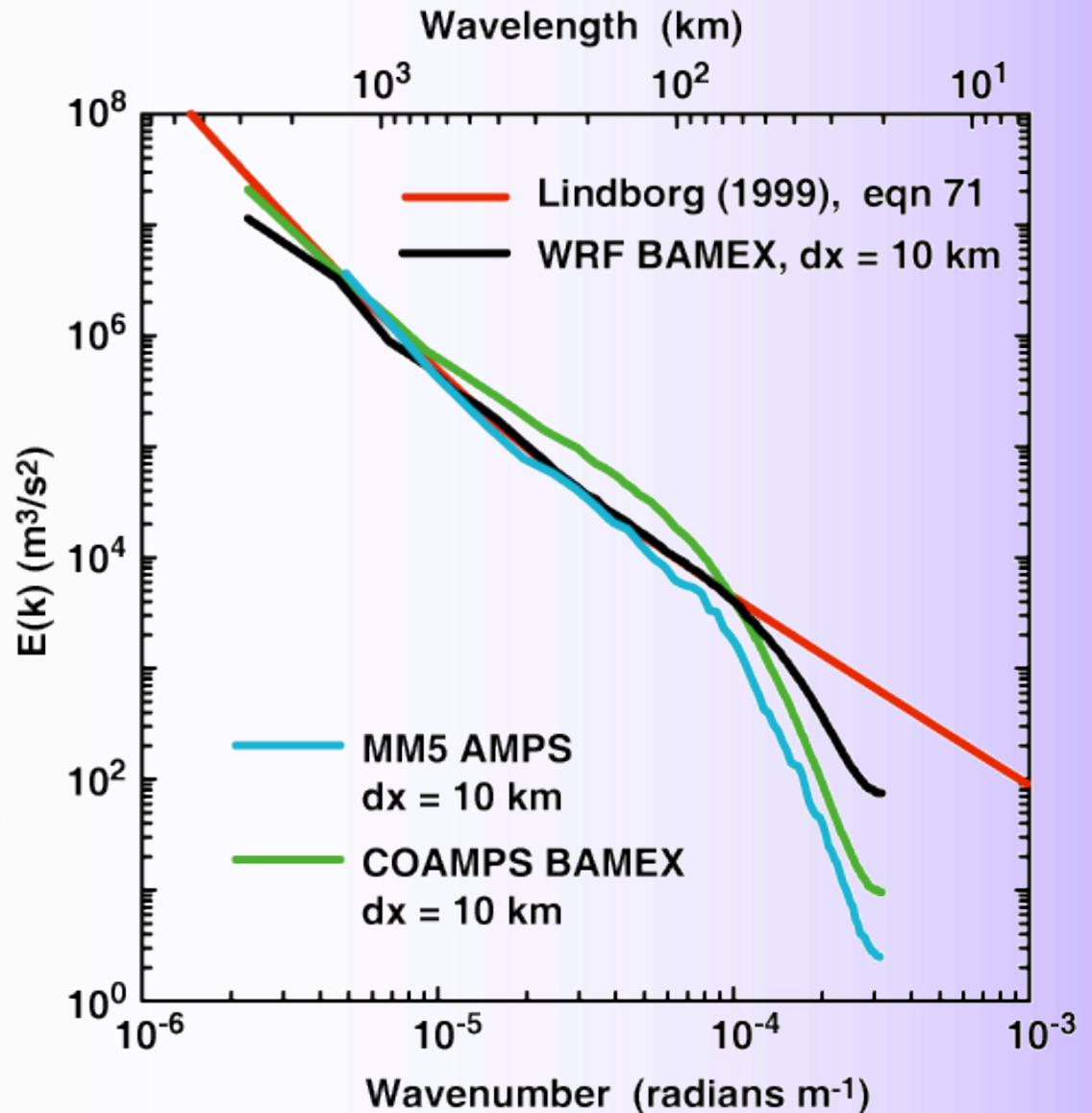
MM5, COAMPS and WRF-ARW Spectra

MM5 AMPS /Antarctica
20 Sept 2003, dx = 10 km

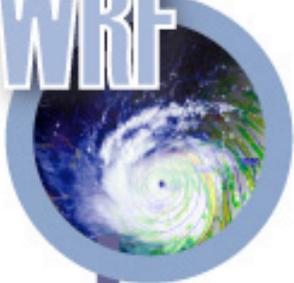
COAMPS BAMEX
2 June 2003, dx = 10 km

WRF-ARW BAMEX
1 – 3 June 2003, dx = 10 km

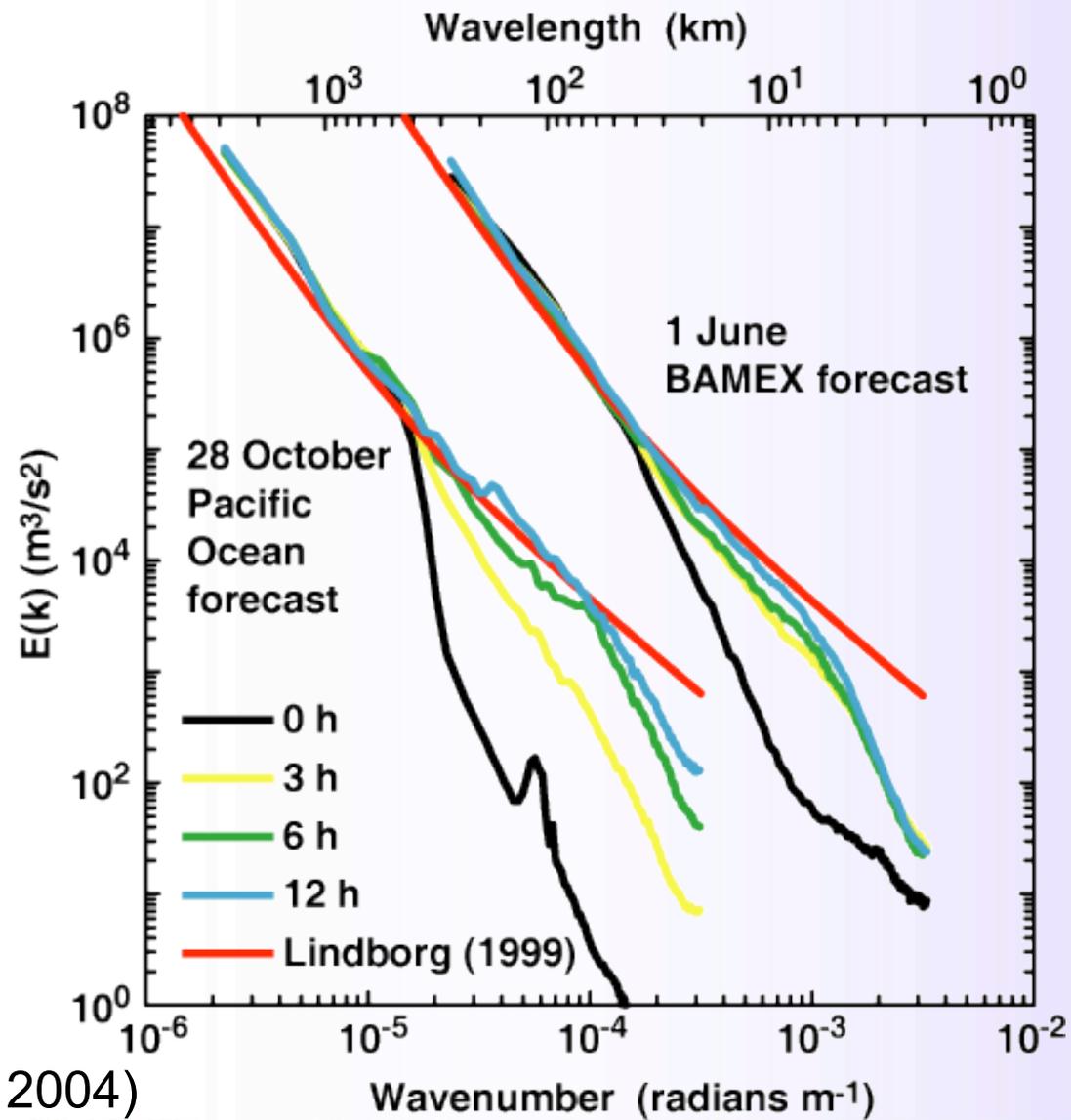
(Skamarock, 2004)



WRF

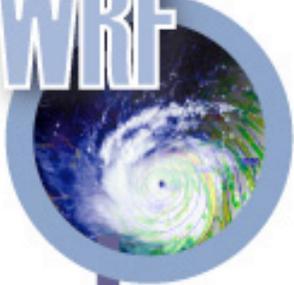


10 km Spectra Evolution (model spin-up)



(Skamarock, 2004)

WRF



Progress

4 km WRF simulations exhibit:

- A surprising ability to forecast mesoscale convective systems (MCS) out to 36 h
- A demonstrated skill at depicting MCS mode (bow echoes, mesoscale convective vortices, supercell lines)
- An ability to spin-up convective systems within 3-4 h from a cold start.
- Potential for significant improvement in forecast guidance over convective parameterization

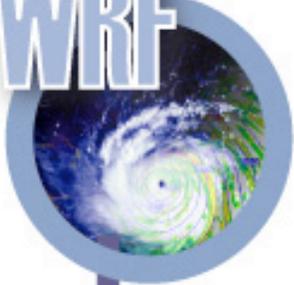
WRF



Challenges

- QPF problematic (too much convective precip)
- Stratiform regions appear too small
(microphysics?)
- Convective systems often fail to decay
(BL evolution?)
- Lack of detail in initialization

WRF



Advances needed for convective-scale forecasting

- Assimilation of small-scale structure (Doppler radar, etc.)
- New techniques for TKE/PBL for 1-5 km grids
- Shallow cumulus parameterization to improve convective initiation?
- More accurate treatment of ice/liquid species in cloud microphysics
- New verification techniques