Improvement of Convective/Severe Weather Prediction through an Integrative Analysis of WRF simulations and NEXRAD/GOES Observations over the CONUS

PI: Dr. Xiquan Dong, University of North Dakota

Co-Is: Drs. Aaron Kennedy and Matt Gilmore

Graduate Students: Ronald Stenz, David Goines,
Joshua Markel

NOAA Collaborator: Adam Clark, NSSL

Motivation

- Flash floods are often triggered by frontal squall lines in spring and mesoscale convective systems in summer. They occur often over the CONUS, rank first among the weather-related causes of property damage. In 2013, they accounted for 8 of the 9 weather related billion dollar losses.

- NOAA forecasters are responsible for making the public aware of these phenomena in advance, and this requires accurate simulations of the thunderstorms responsible for these threats.

- To improve forecasts and translate research quickly to operational meteorology, HWT was developed. Utilizing the latest in forecasting techniques, NSSL and NCEP have run deterministic convection-permitting WRF simulations to aid in forecasting hazardous weather.

- Preliminary research by the UND group and others suggests that the simulated convective properties are dramatically affected by the microphysics scheme. However, it is not understood which microphysics schemes may perform best over long periods of time and how performance may vary by synoptic regime.

Proposed Objectives

To better guide present operational forecasts of hazardous weather using convection-permitting models and future ensemble practices, we propose to perform detailed evaluations of both deterministic and ensemble suites of convection-permitting simulations in the following two objectives.

Objective 1: Evaluation of WRF simulated convective systems and precipitation

Objective 2: Develop and determine best practices for a microphysics based WRF ensemble

Objective 1:
Evaluation of WRF simulated convective systems and precipitation

The primary goal is to understand how well convective systems and associated precipitation are simulated and how this performance varies with the large-scale atmospheric state (synoptic regime) through the application of Self Organizing Maps (SOMs, Kennedy 2011).

The second goal is to study the formation-dissipation processes of convective complexes, such as initiation regions, duration, and intensity; and investigate the estimated precipitation over the classified convective and stratiform regions of DCS (Feng et al. 2011) through an integrative analysis of WRF simulations and NEXRAD/GOES observations.

Data sets

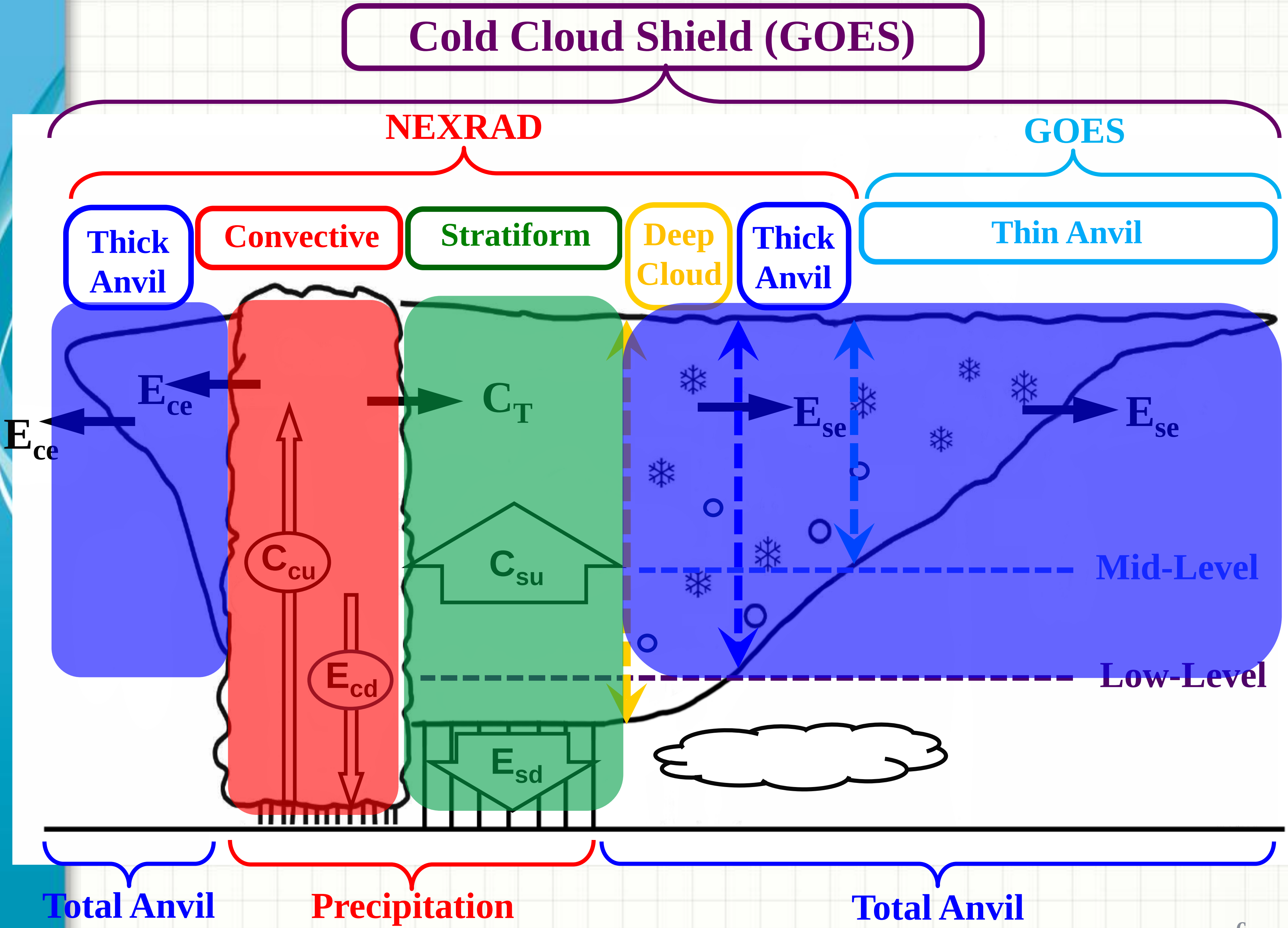
The NEXRAD radar observations from the NSSL National Mosaic and MultiSensor QPE Q2 (NMQ) project will be the primary dataset for evaluating the WRF simulations.

UND Hybrid Classification Product (2010-2013):

Feng et al. (2011) developed a merged/hybrid dataset of NEXRAD and GOES satellite data to produce a 3-D product of convective structure and to classify a deep convective system (DCS) into three components: Convective Core (CC), Stratiform Region (SR) and Anvil Region (AC). Feng et al. (2011) further used these results to study the coverages and associated precipitation over these three regions.

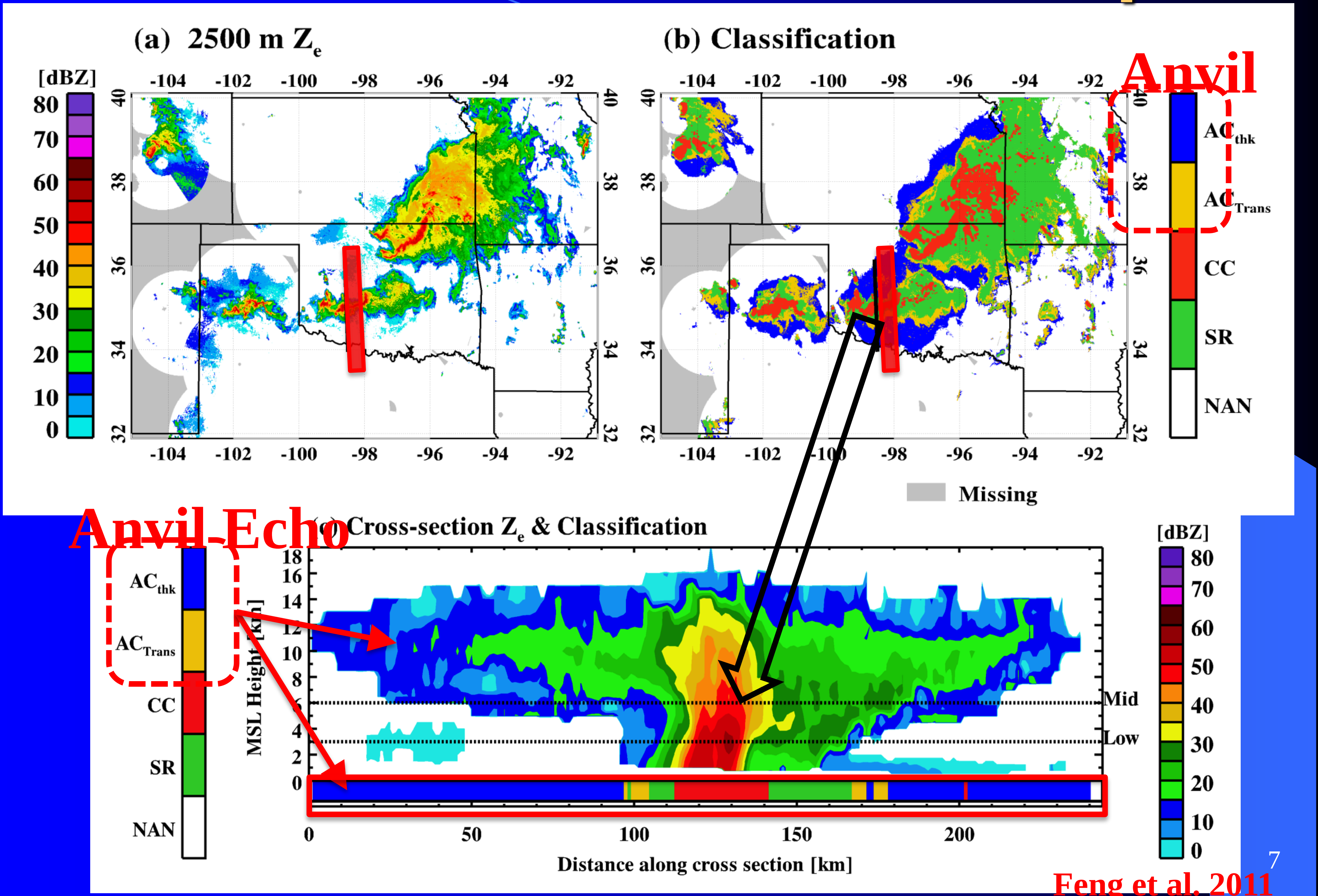
HWT Simulations (2010-2013):

The daily simulations have already been collected and processed by Aaron Kennedy for a previously-funded NSF post-doctoral fellowship. These simulations were generated using the Advanced Research WRF core (WRF-ARW) at NSSL, and WRF-NMM at NCEP.



Feng et al. (2011) JGR

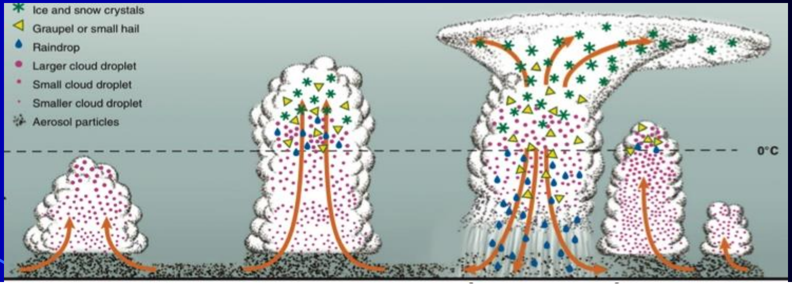
Radar Classification Example

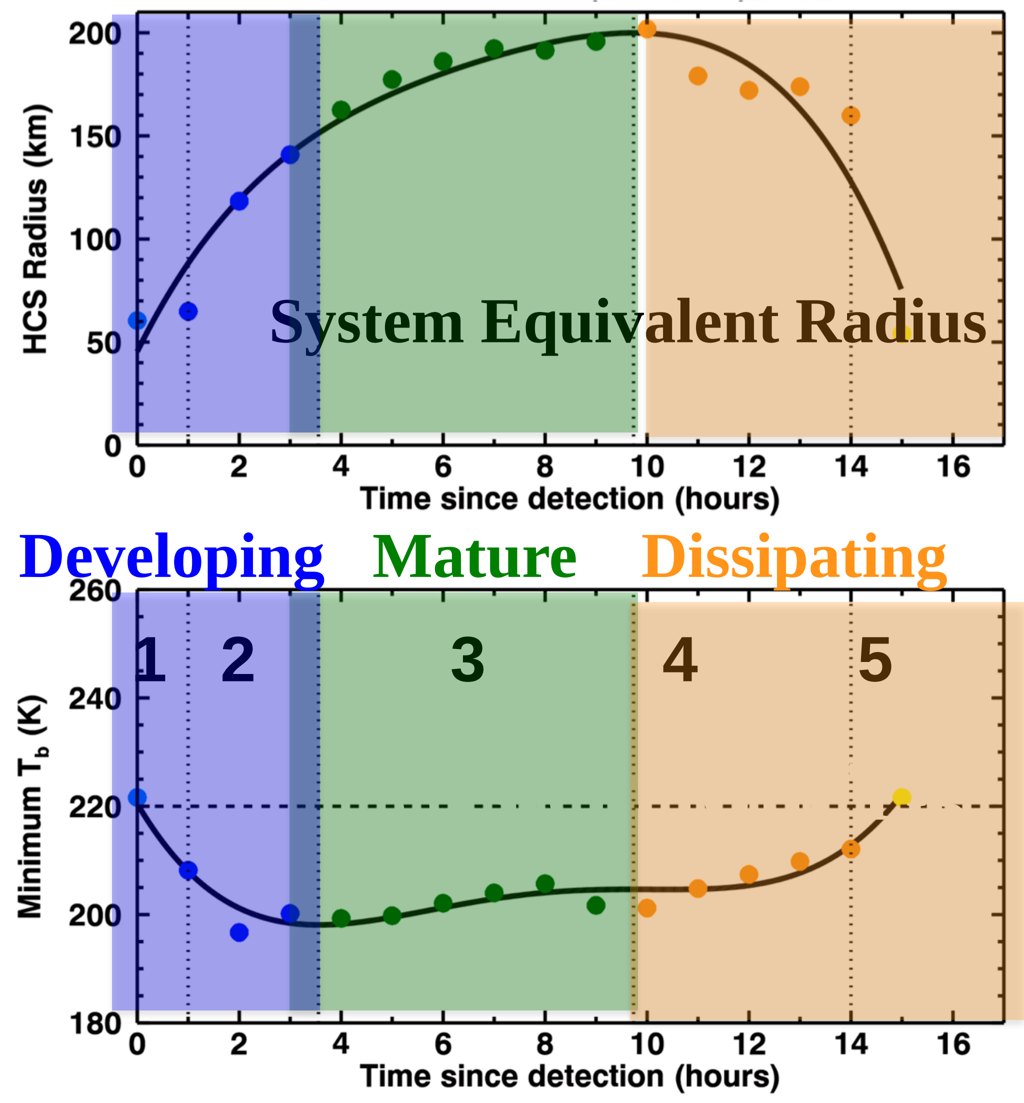


Feng et al. 2011

Define Life Cycle Stages

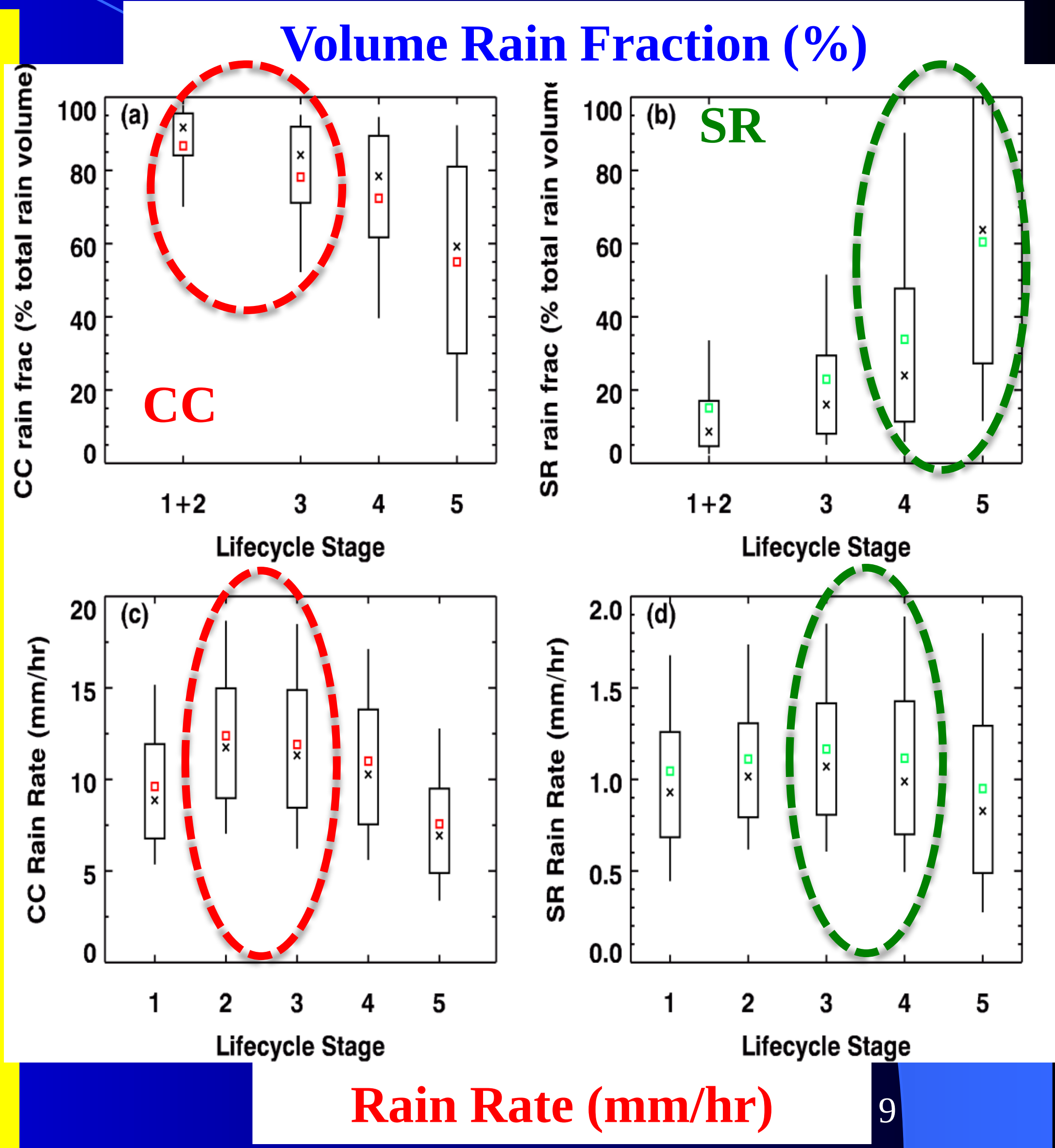
- **Based on tendency of system size and T_{IR}**
- **Developing (1, 2)**
  - **Before reaching min T_{IR}**
  - **Warm developing (T_{IR} > 220K)**
  - **Cold developing (T_{IR} < 220K)**
- **Mature (3)**
  - **Min T_{IR} < time < Max Radius**
- **Dissipating (4, 5)**
  - **Cold dissipating**
  - **Warm dissipating**
- **Group all systems based on defined stages**





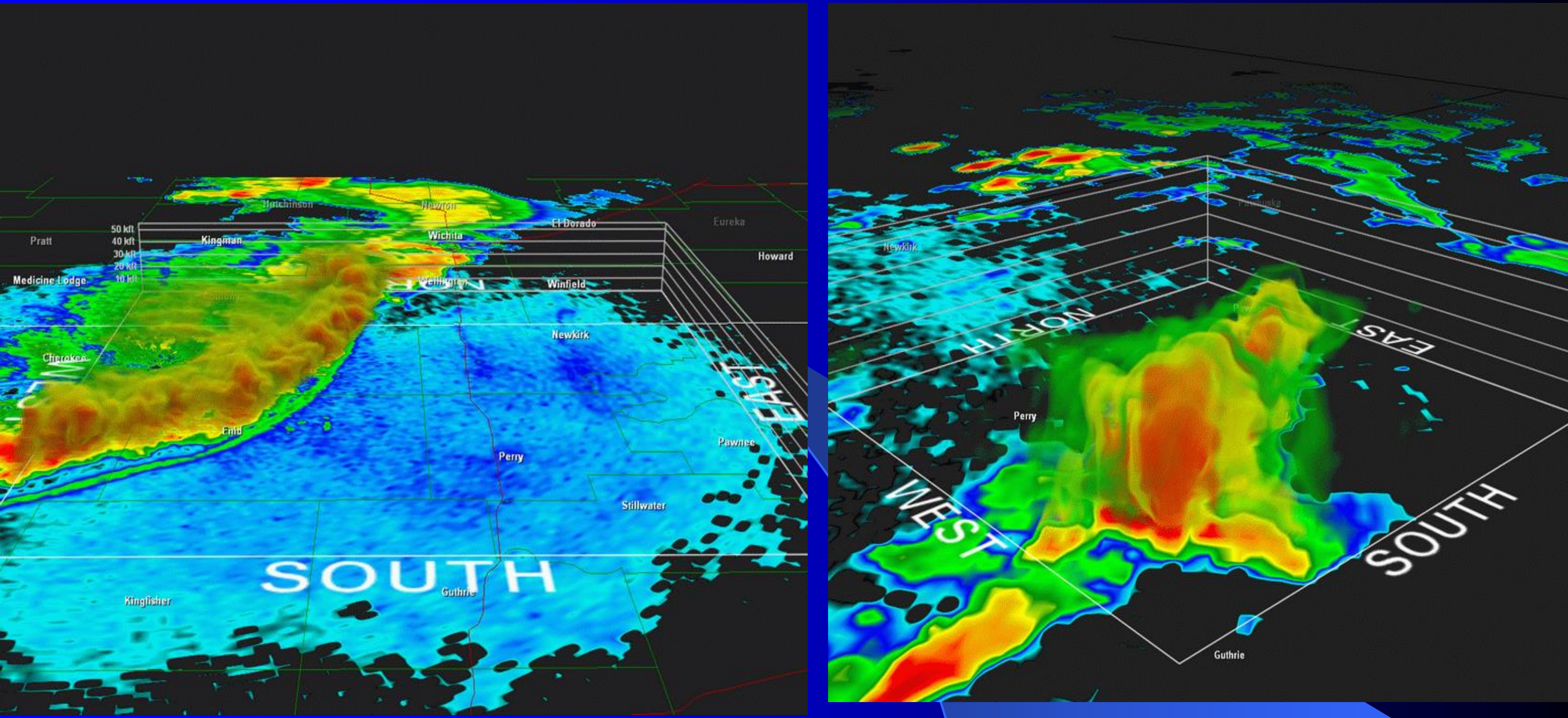
Precipitation Evolution

- **Precipitation comes almost exclusively from convective rain in developing and mature stage**
- **Stratiform rain gradually becomes more important as system dissipates**
- **CC/PR rain rate evolution similar to sizes**
- ***PR_{CC}* is 10× *PR_{SR}***


Volume Rain Fraction (%)

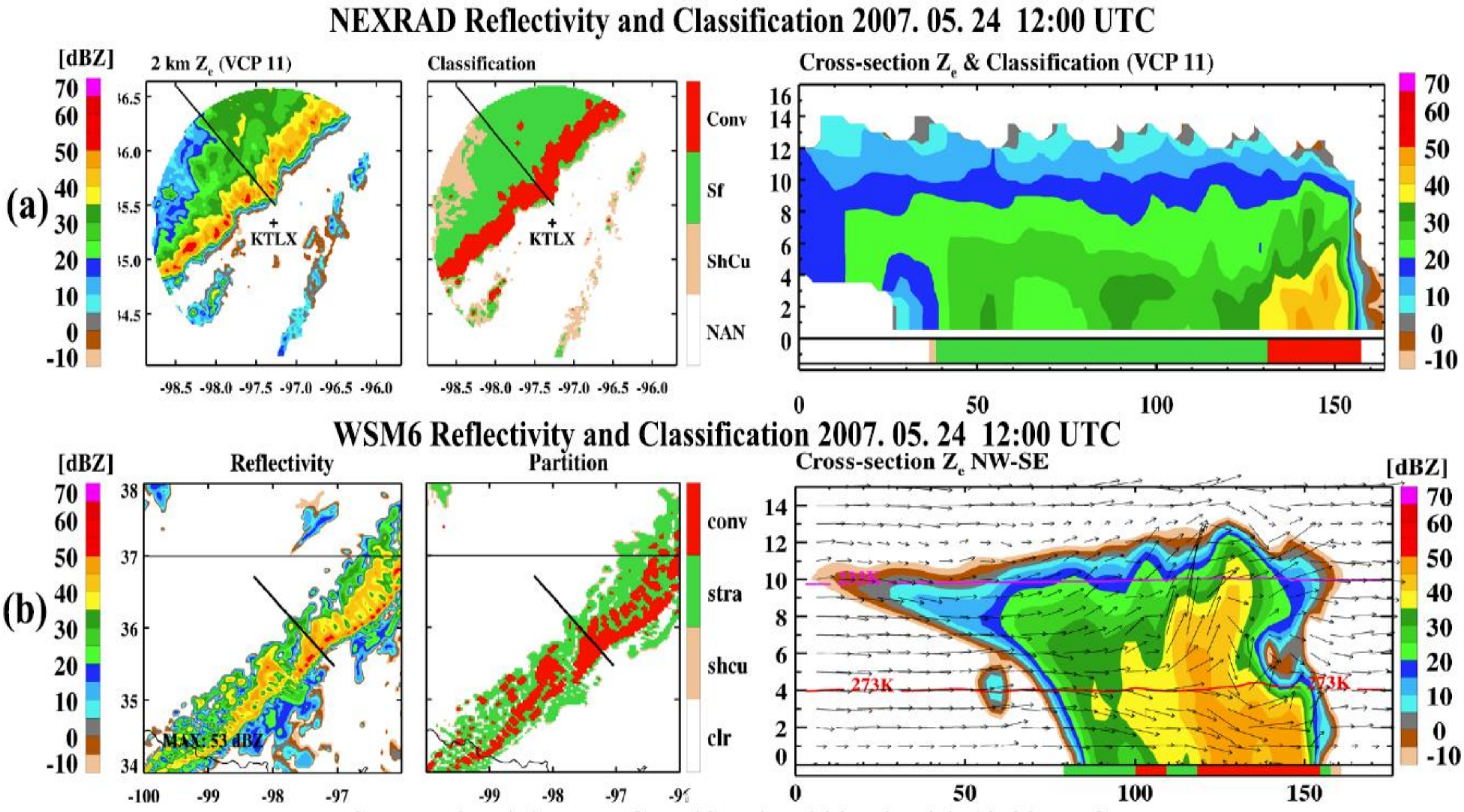
Rain Rate (mm/hr)

Challenge and difficulty for modeling DCS clouds



Quite often, models can simulate large-scale frontal systems, but not for local systems

Use Hybrid Classification product to evaluate WRF



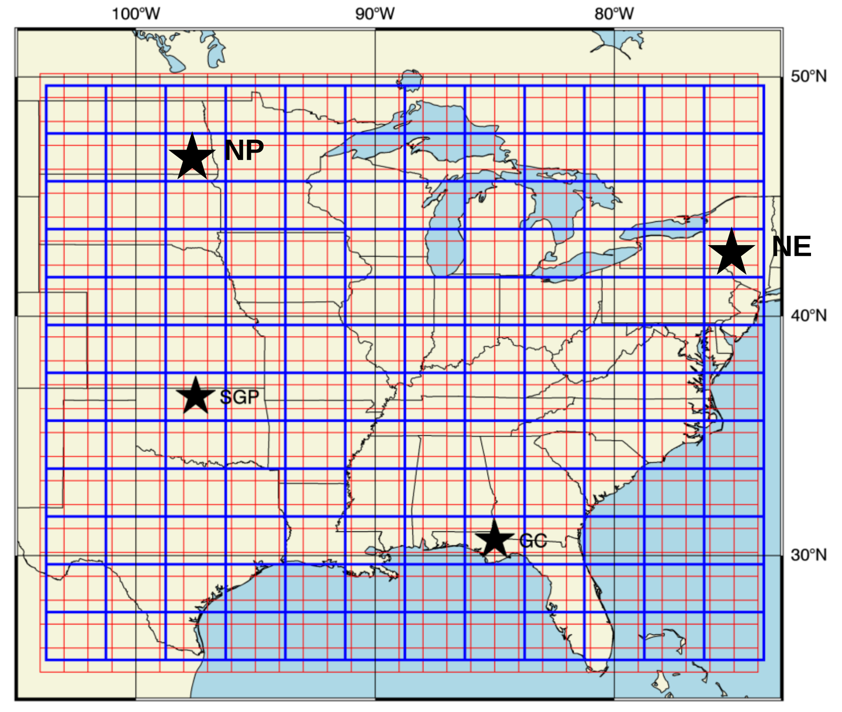
WRF WSM6 simulations have an excellent agreement with NEXRAD observations and UND classified DCSs in both horizontal and vertical structure.

From Wu et al. 2013 JGR

HWT Simulations from NSSL and NCEP

WRF Run	Core	Horizontal dx	Microphysics	PBL	Radiation	Initial Conditions	Region	Time Period	Days
NCEP	NMM	4 km	Ferrier	MYJ	GFDL/GFDL	NAM	CONUS	2010-2013	1126
NSSL	ARW	4 km	WSM6	MYJ	Dudhia/RRTM	NAM	CONUS	2010-2013*	1422

- **Utilize long-term database of HWT Simulations**
- **For synoptic typing and modeling reasons- focus on several regions**
- **Utilize prior work making use of climate model sized grids**



Blue boxes (2.5°×2° lon/lat grid)

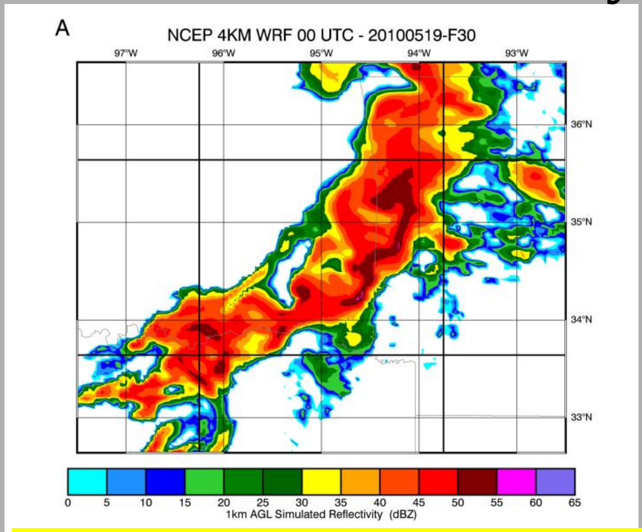
- **Southern Great Plains**
- **Northern Plains**
- **Gulf Coast**
- **Northeast**

- **Determine whether observed or simulated convection occurred within box to build database of cases**

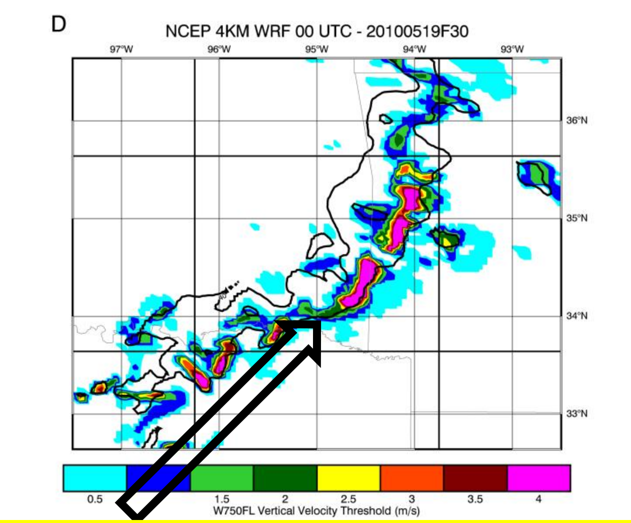
Updraft Based Criteria

Criteria	**Notation**	**Notes**
W ≥ Value **Depth (≥ 750 hPa – P_{FL})**	**W750FL** **Deep+Shallow Convection**	**Del Genio et al. (2012)**
W ≥ Value **Depth ≥ 450 hPa**	**WD450** **Deep Convection**	**Wu et al. (2009)**

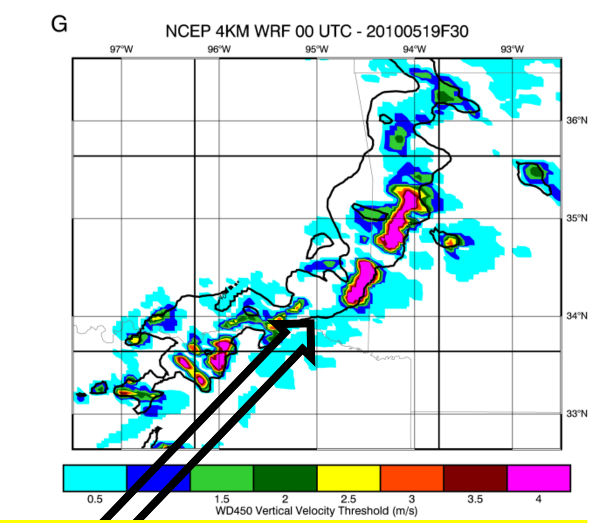
Simulated Reflectivity



W750FL



WD450



W750FL captures deep+shallow, while WD450 only deep.

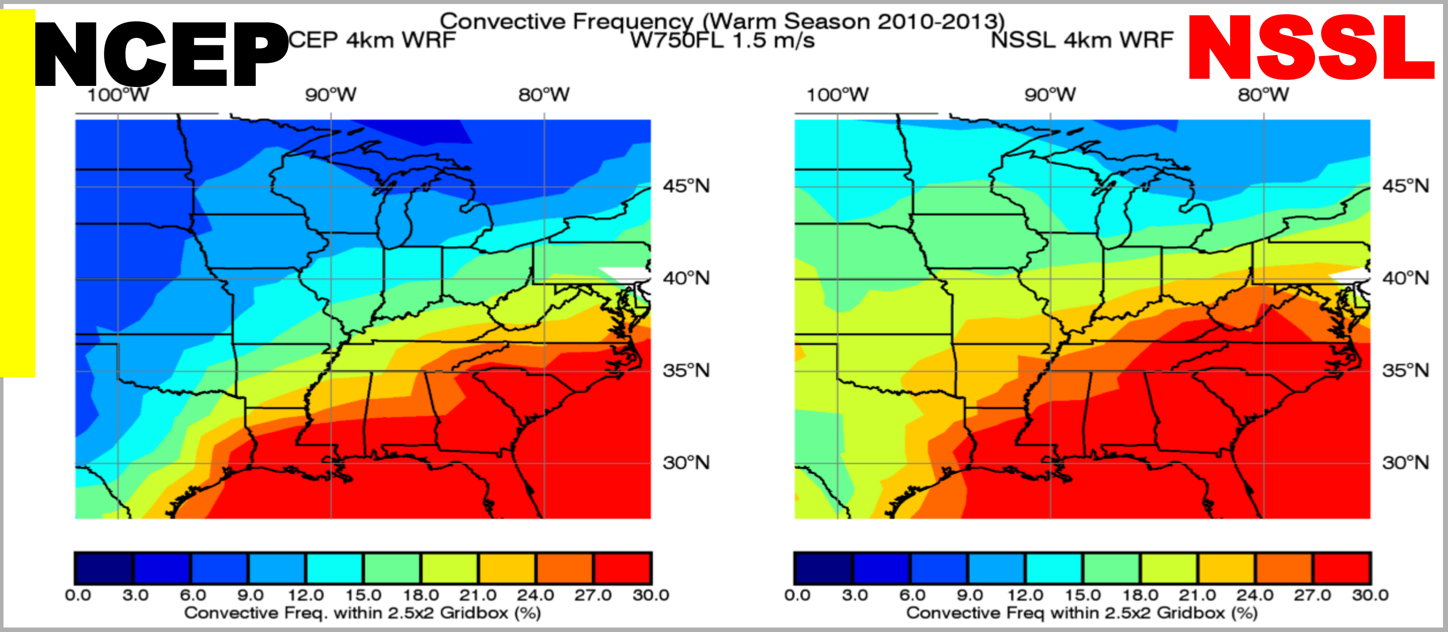
Preliminary Results

- **Spatial Analysis of simulated convective frequency and areal coverage**
  - **NSSL WRF has more frequent convection than NCEP WRF**
  - **NCEP WRF has more deep convection than the NSSL WRF**
- **Analysis of simulated convection over the SGP region (2.5°×2° lon/lat grid box)**
  - **Precipitation Analysis**
  - **Diurnal Cycle**

Convective Frequency (2010-2013)

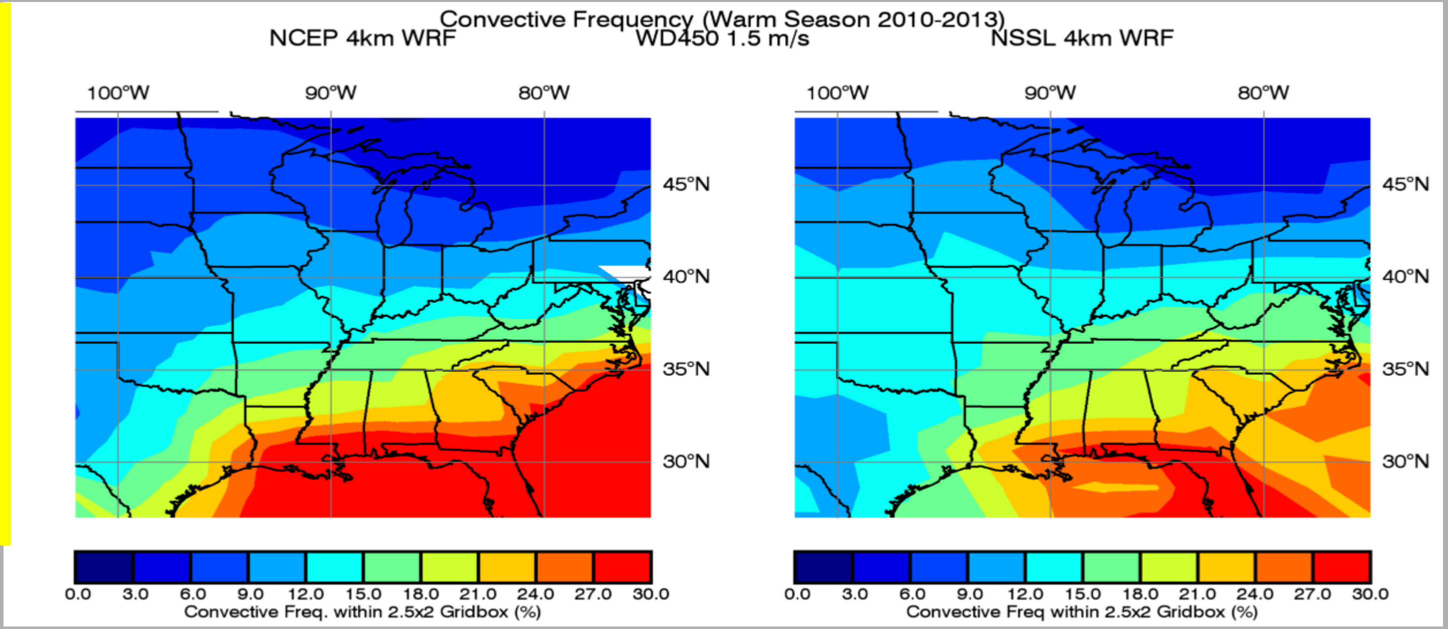
W750FL (shallow+deep)

NSSL WRF has more frequent convection



WD450 (deep convection)

NCEP WRF looks to have more deep convection by NSSL

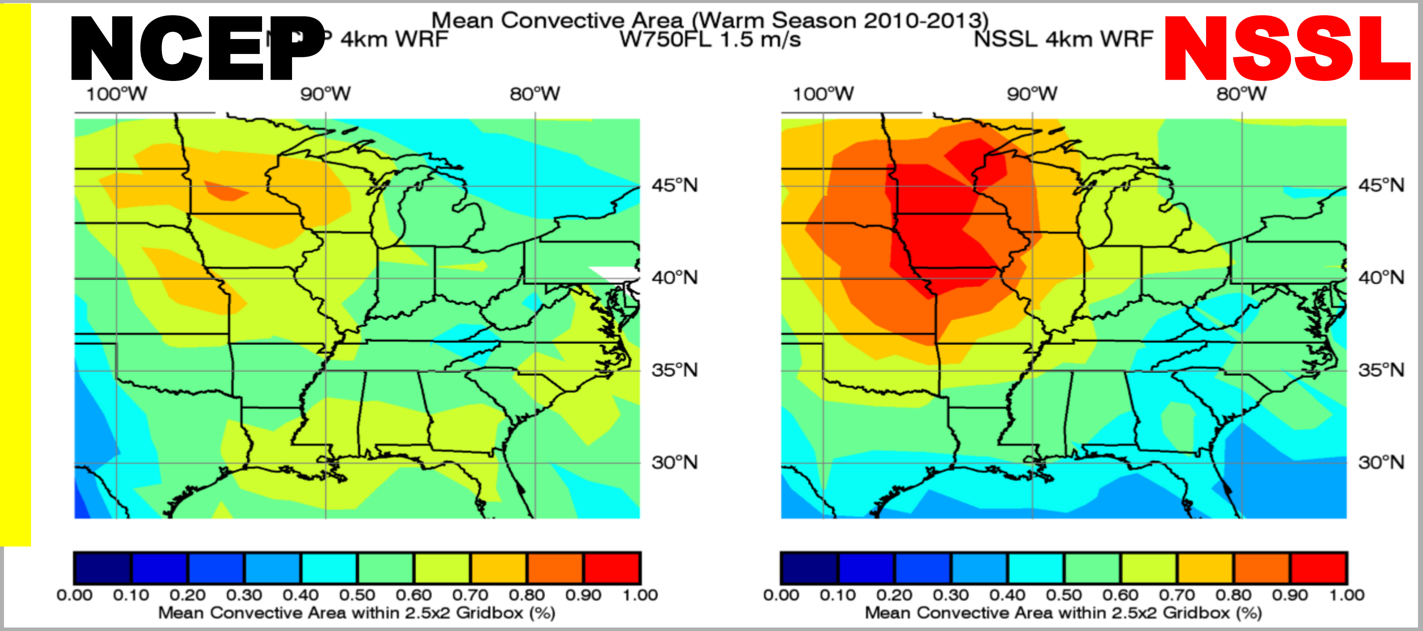


Convective Area (2010-2013)

(Mean convective area when present)

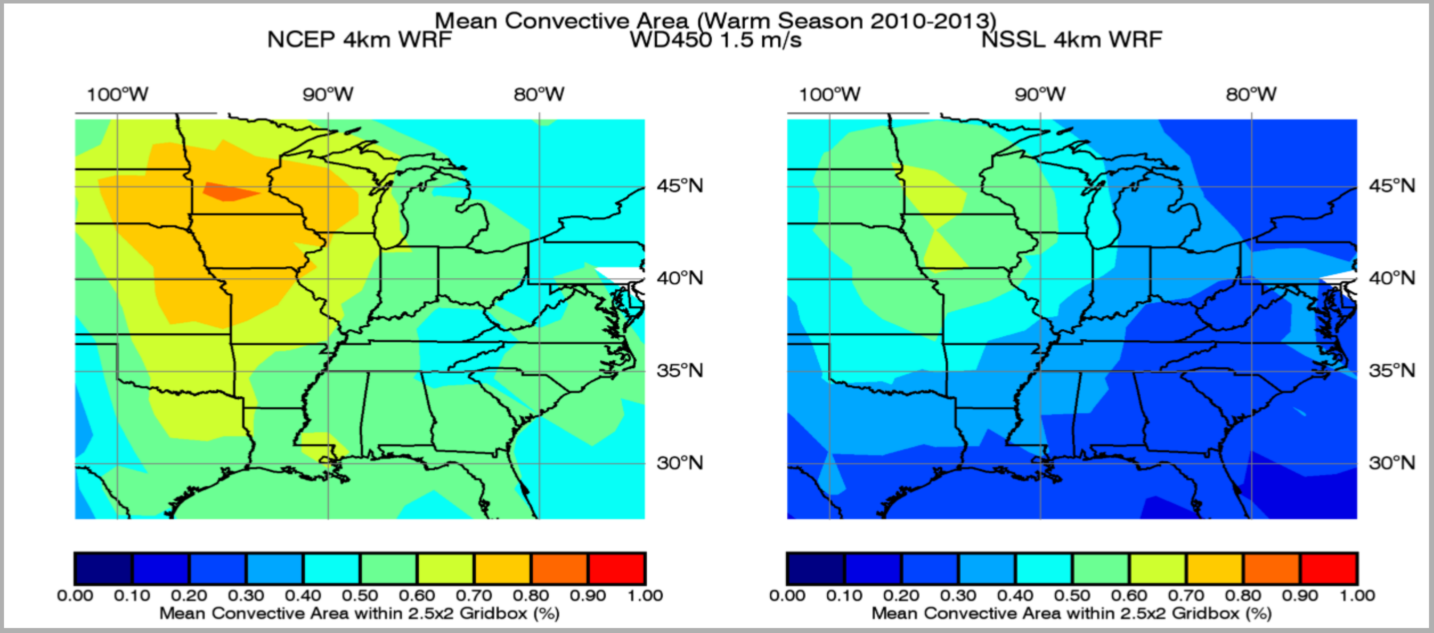
W750FL (shallow+deep)

NSSL > NCEP



WD450 (deep convection)

NCEP > NSSL

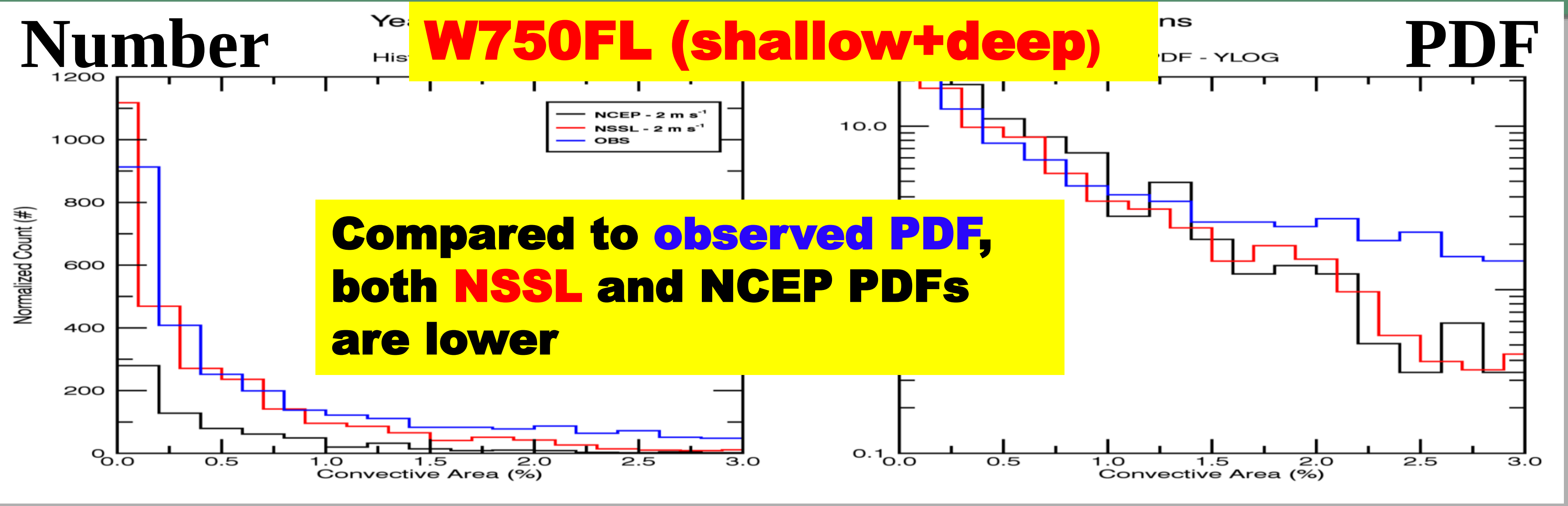


Convective Area over SGP

Number

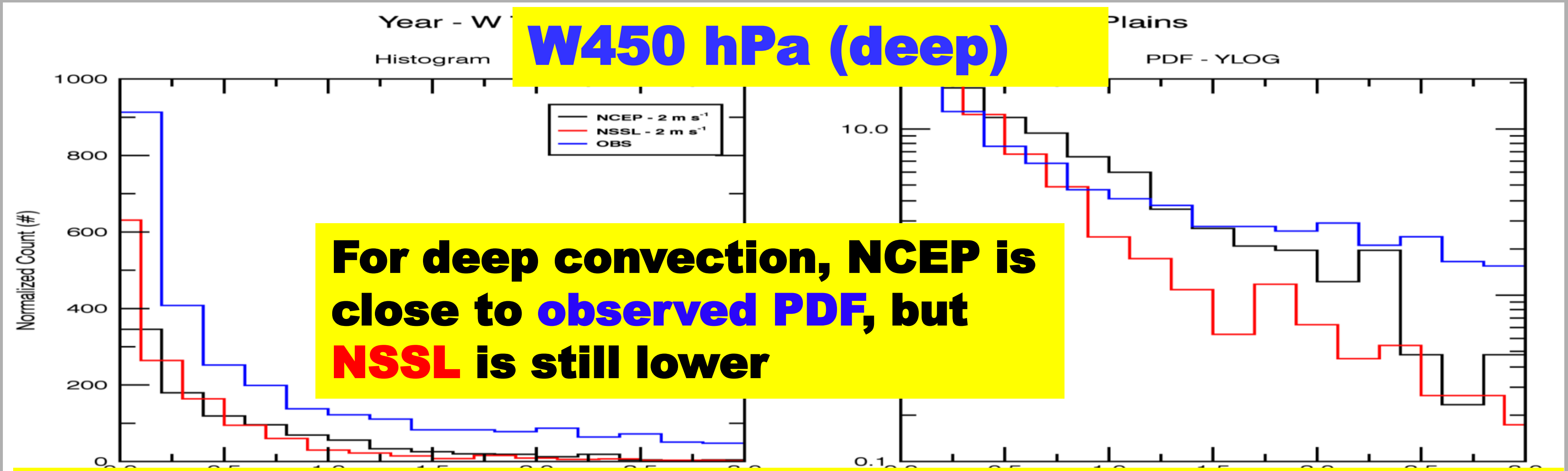
PDF

W750FL (shallow+deep)



Compared to observed PDF, both NSSL and NCEP PDFs are lower

W450 hPa (deep)



For deep convection, NCEP is close to observed PDF, but NSSL is still lower

These differences are possible caused by different methodology (updraft selection vs. radar reflectivity classification)→more work

Spatial Distribution of Precipitation

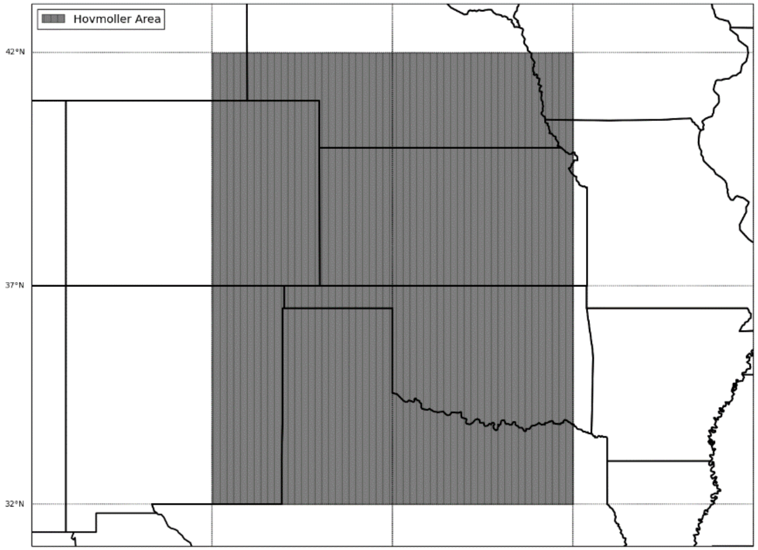
One Hour Convective Precipitation Rate Frequency

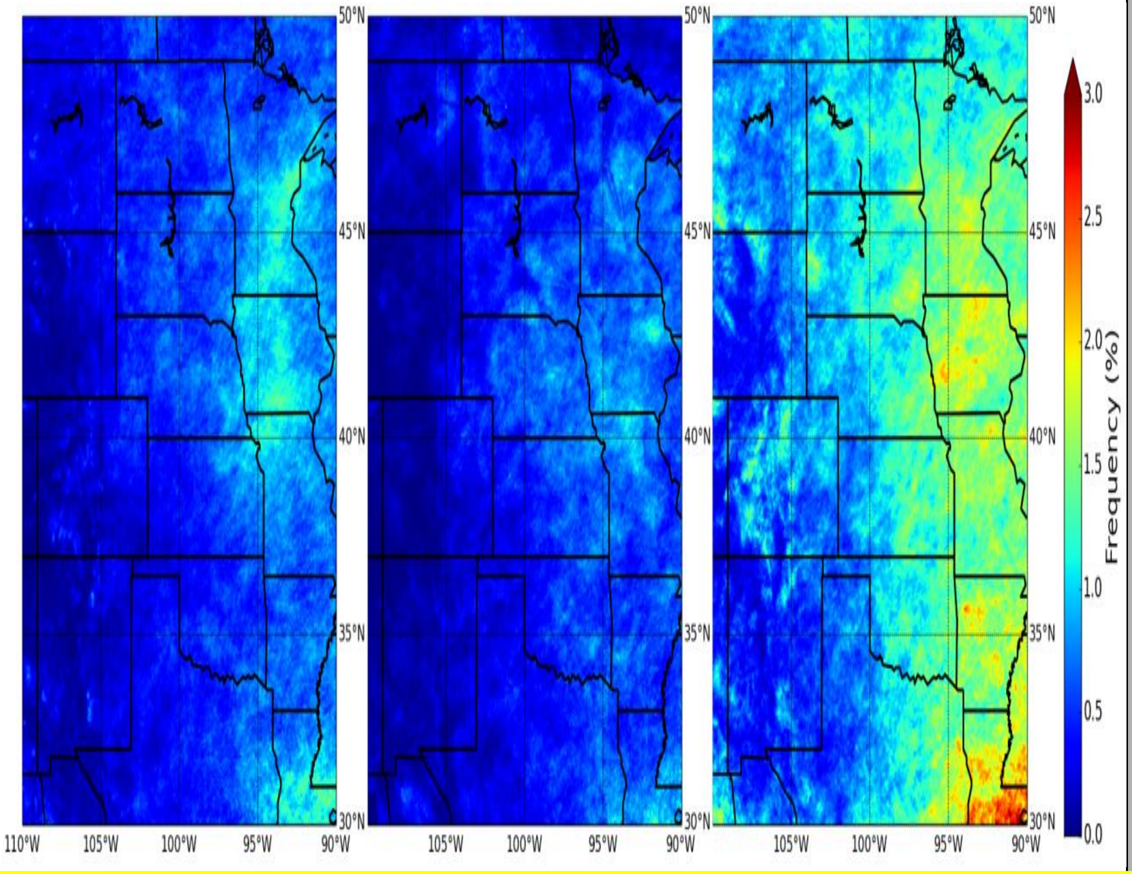
Observations - Stage-IV (4km)

- Radar + gauge
- Consider "convective" rain rates (hourly precip > threshold)

Zonal Hovmöller diagrams:

- **Latitude:32° N – 42° N**
- **Longitude:95° W – 105° W**





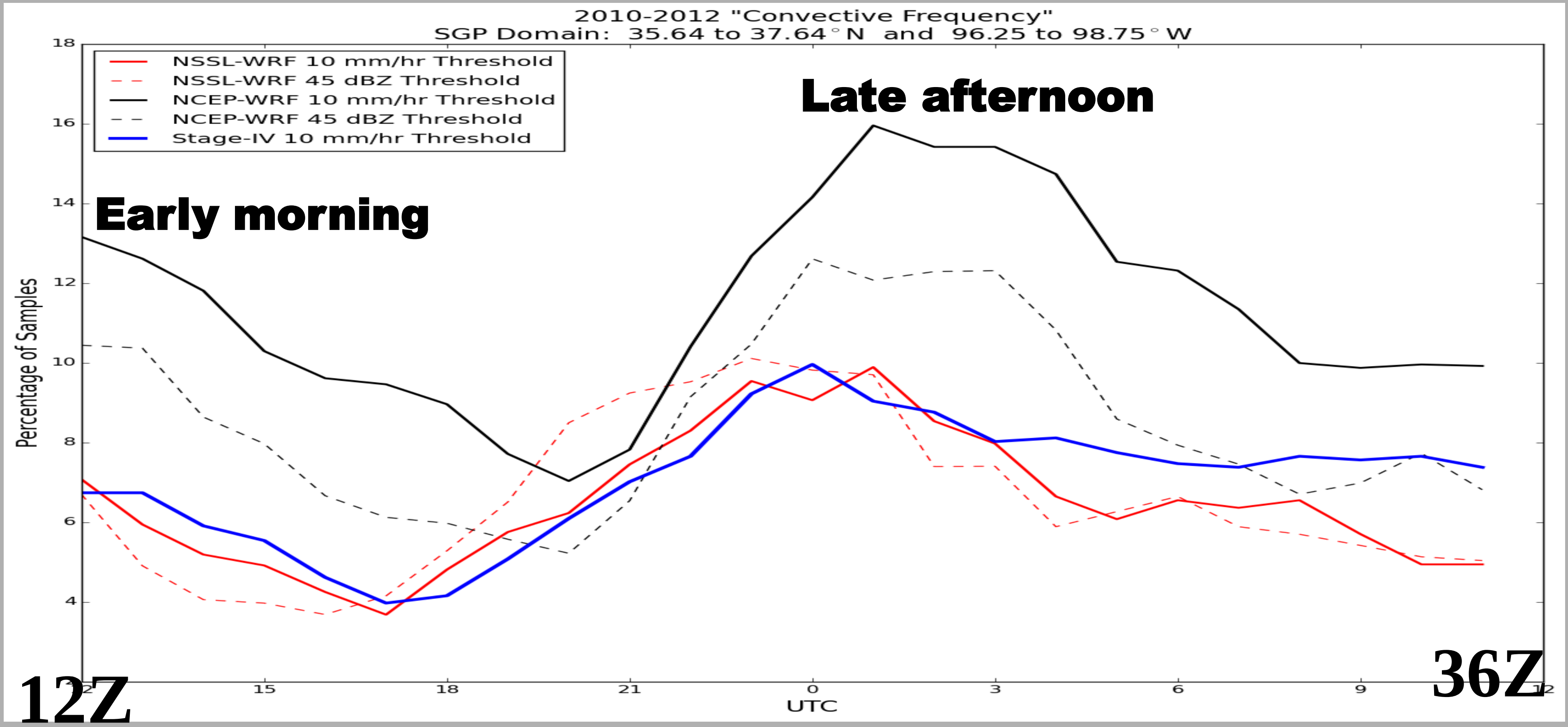
Warm season precipitation frequency (2010-13)

NSSL-WRF **Stage-IV** **NCEP-WRF**

Precipitation Freq increases from West to East. NSSL is close to Stage-IV, while NCEP is much higher

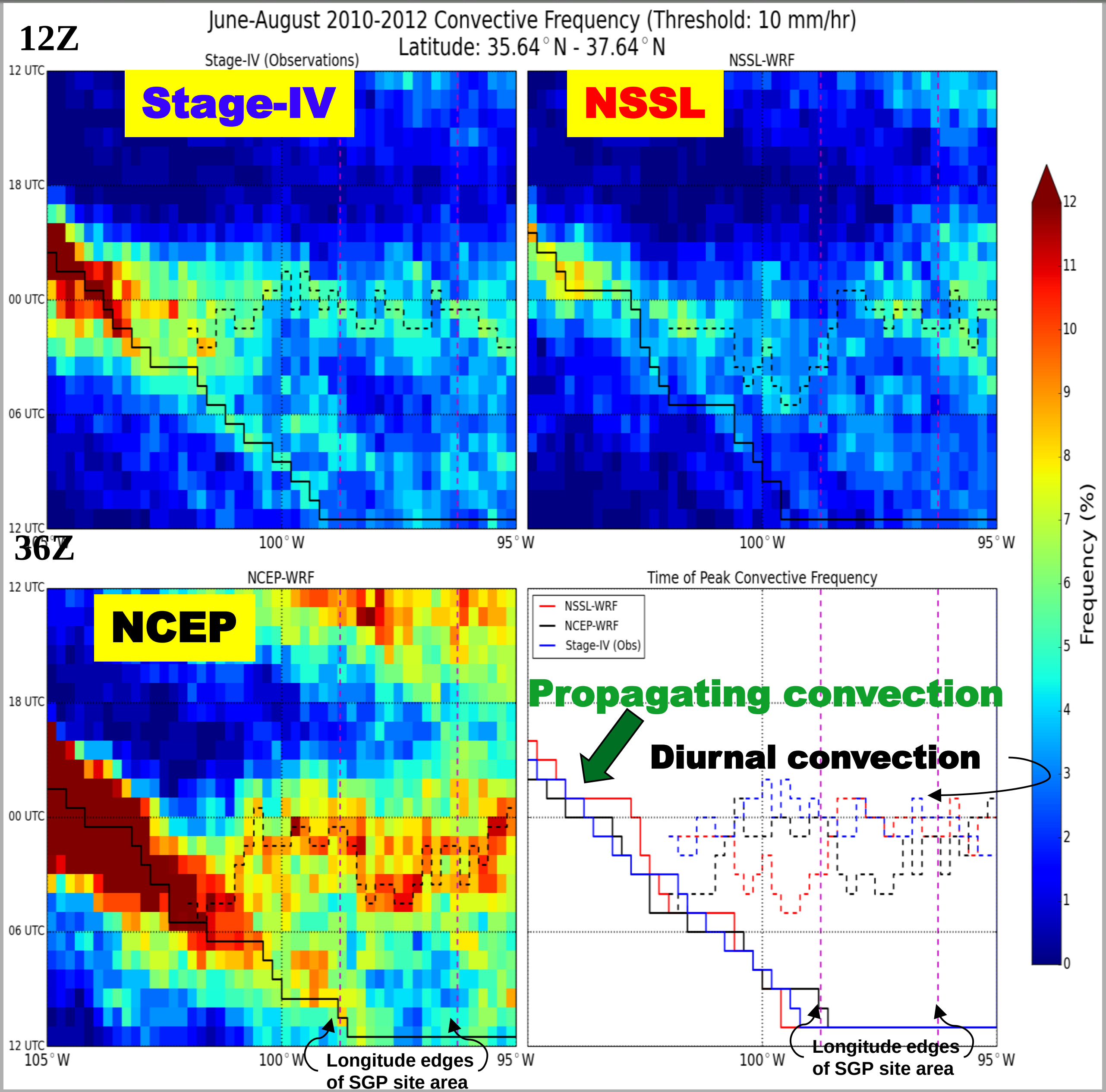
Diurnal Variation of Precipitation

Convective Precipitation Frequency over the ARM-SGP site



- **Two peaks in convective frequency: Morning (~12Z) and evening (~24Z) from Stage-IV/NSSL/NCEP**
- **Delay in NCEP-WRF evening convective frequency peak.**
  - **Is this common for entire U.S. Great Plains?**
  - **Due to propagating convective systems or “pop up” diurnal convection?**

Hovmöller of Convective Precipitation Frequency over ARM-SGP



June-August 2010-2012 Convective Frequency (Threshold: 10 mm/hr)
Latitude: 35.64°N - 37.64°N

Stage-IV

NSSL

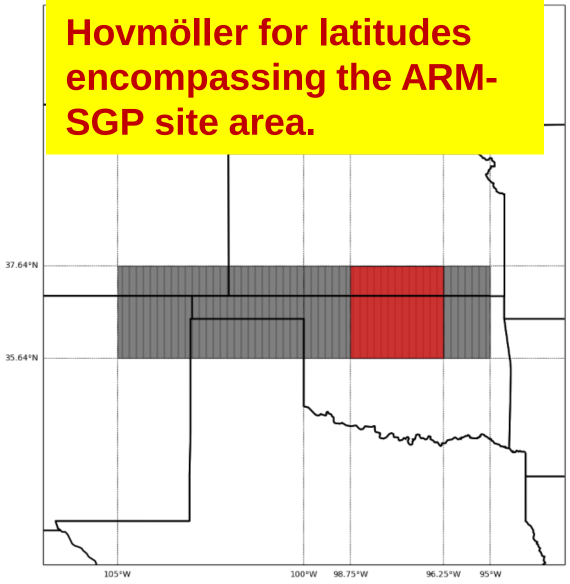
NCEP

Propagating convection

Diurnal convection

Longitude edges of SGP site area

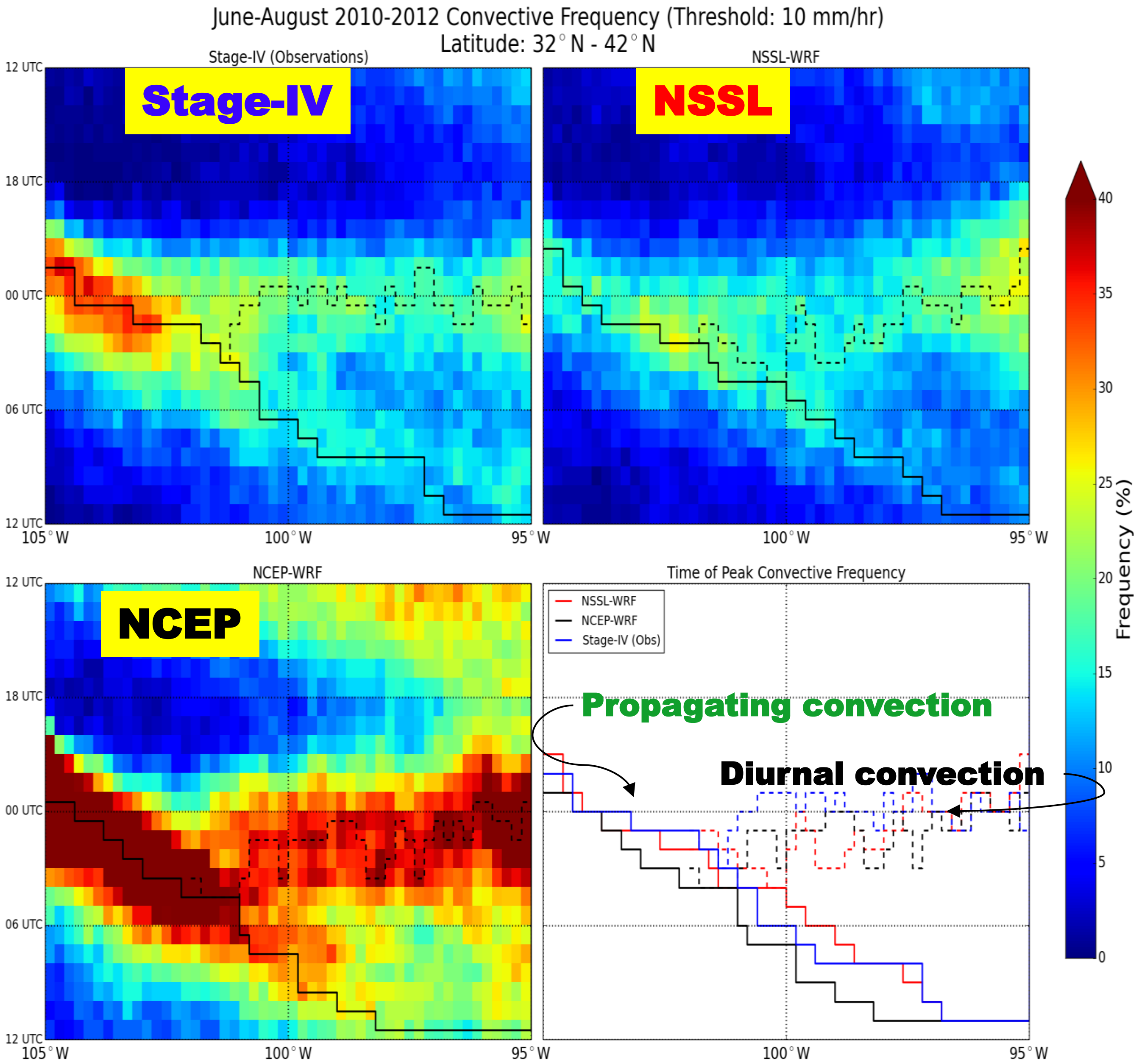
Longitude edges of SGP site area



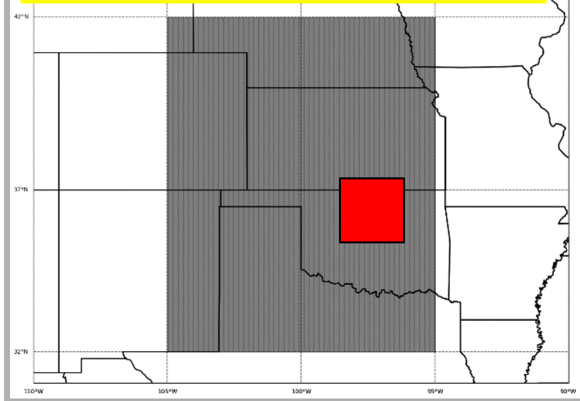
Hovmöller for latitudes encompassing the ARM-SGP site area.

- **Peak convective frequency over the ARM SGP site is dominated by diurnal convection, not propagating convection.**
- **Evidence of peak in convection during morning hours in NCEP-WRF Hovmöller diagram.**

Hovmöller of Convective Precipitation Frequency over U.S. Great Plains



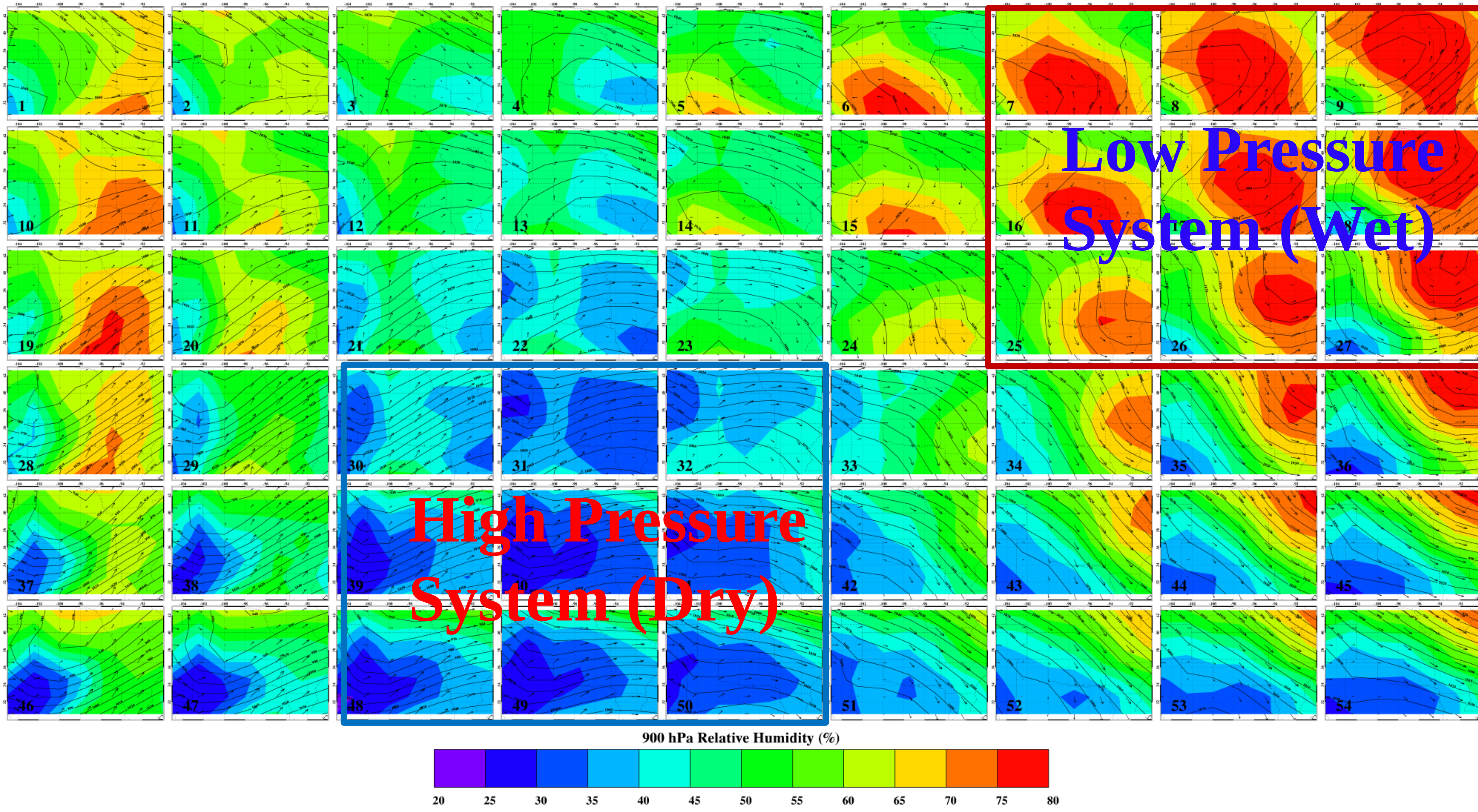
Hovmöller for latitude band of 32°N - 42°N encompassing the ARM-SGP site area.



- **NCEP-WRF propagating convection appears to be slower than NSSL-WRF and Stage-IV.**
- **More agreement in models and observation with timing of peak in diurnal convection frequency.**

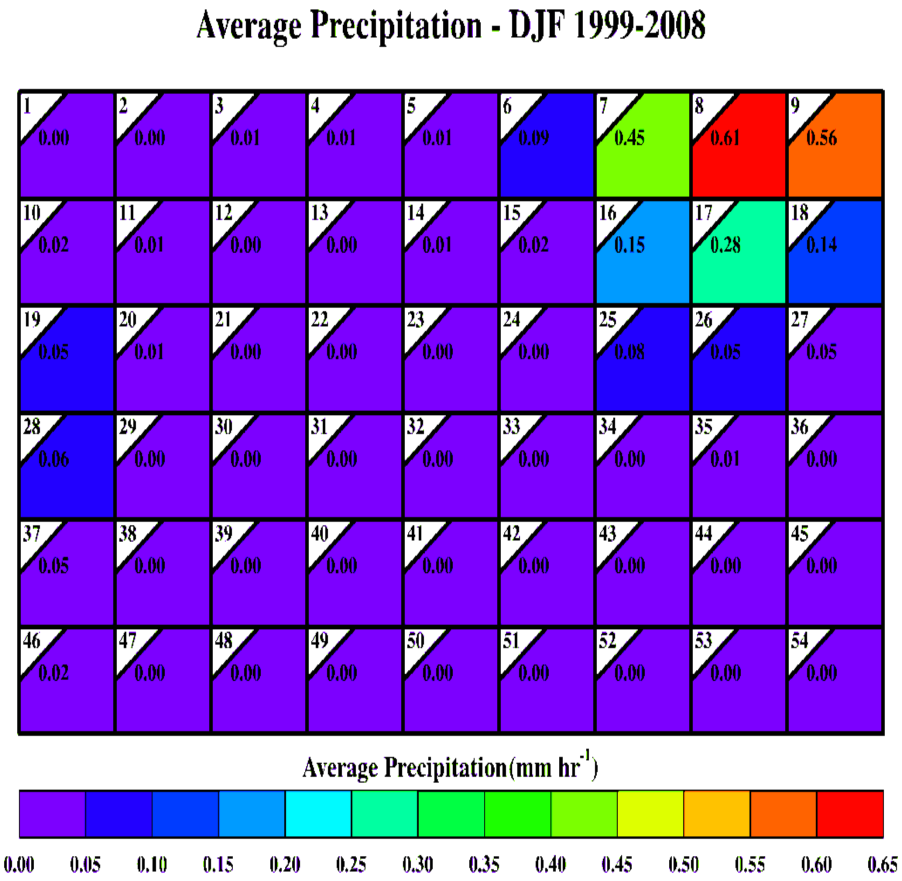
Future work: Link Precipitation with Synoptic Pattern

DJF 1999-2008 SOM - 900 hPa Analysis



Synoptic patterns classified by MSLP, RH, U, V, and Geopotential Height

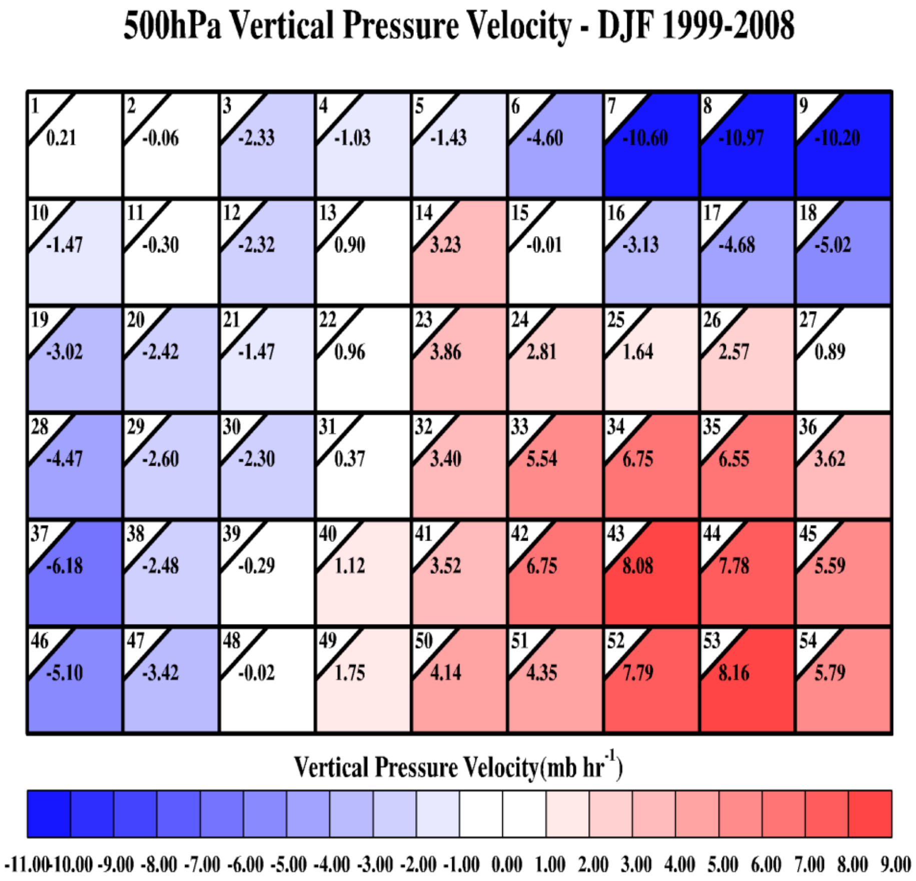
Winter Precipitation and Vertical Motion



Average Precipitation - DJF 1999-2008

1 0.00	2 0.00	3 0.01	4 0.01	5 0.01	6 0.09	7 0.45	8 0.61	9 0.56
10 0.02	11 0.01	12 0.00	13 0.00	14 0.01	15 0.02	16 0.15	17 0.28	18 0.14
19 0.05	20 0.01	21 0.00	22 0.00	23 0.00	24 0.00	25 0.08	26 0.05	27 0.05
28 0.06	29 0.00	30 0.00	31 0.00	32 0.00	33 0.00	34 0.00	35 0.01	36 0.00
37 0.05	38 0.00	39 0.00	40 0.00	41 0.00	42 0.00	43 0.00	44 0.00	45 0.00
46 0.02	47 0.00	48 0.00	49 0.00	50 0.00	51 0.00	52 0.00	53 0.00	54 0.00

Average Precipitation(mm hr^{-1})



500hPa Vertical Pressure Velocity - DJF 1999-2008

1 0.21	2 -0.06	3 -2.33	4 -1.03	5 -1.43	6 -4.60	7 -10.60	8 -10.97	9 -10.20
10 -1.47	11 -0.30	12 -2.32	13 0.90	14 3.23	15 -0.01	16 -3.13	17 -4.68	18 -5.02
19 -3.02	20 -2.42	21 -1.47	22 0.96	23 3.86	24 2.81	25 1.64	26 2.57	27 0.89
28 -4.47	29 -2.60	30 -2.30	31 0.37	32 3.40	33 5.54	34 6.75	35 6.55	36 3.62
37 -6.18	38 -2.48	39 -0.29	40 1.12	41 3.52	42 6.75	43 8.08	44 7.78	45 5.59
46 -5.10	47 -3.42	48 -0.02	49 1.75	50 4.14	51 4.35	52 7.79	53 8.16	54 5.79

Vertical Pressure Velocity(mb hr^{-1})

Over 60% of seasonal precipitation associated with classes #7-9.

We will produce SOMs based off convective cases identified by NSSL, NCEP and observations, which should be used to judge independent properties of models: microphysics schemes.

Objective 2:
Develop and determine best practices for a microphysics based WRF ensemble

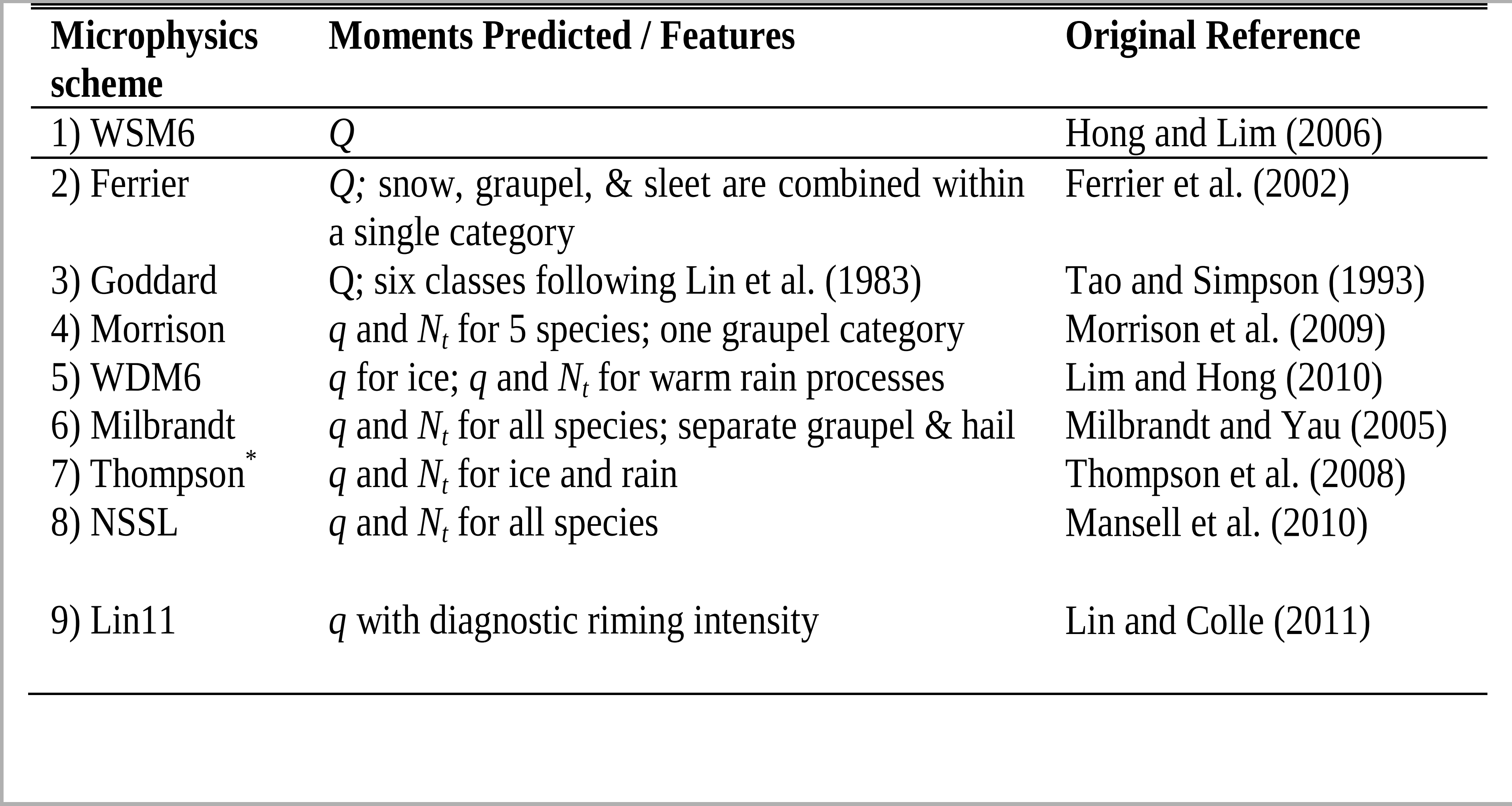
We will develop a microphysics ensemble forecasting system for WRF using WSM6, Ferrier and 7 other microphysical schemes. These simulations will be tested for their ability to simulate convective systems and precipitation based on the dataset generated in Objective 1.

After this initial assessment, a best-practice ensemble suite will be developed and compared to the current NSSL ensemble to understand best practices for the next generation of convection permitting ensembles.

The efforts of this proposed work will lead to better understanding of the strengths and weaknesses of convection-permitting models for hazardous weather events and lead to better utilization of these simulations amongst forecasters.

Objective 2 – Ensemble Development

- **Microphysics Ensemble will consist of the following schemes**
- **Some schemes are more complex than others. Meaning, some schemes predict more variables than others (i.e. mixing ratio (q) and number concentration (N))**

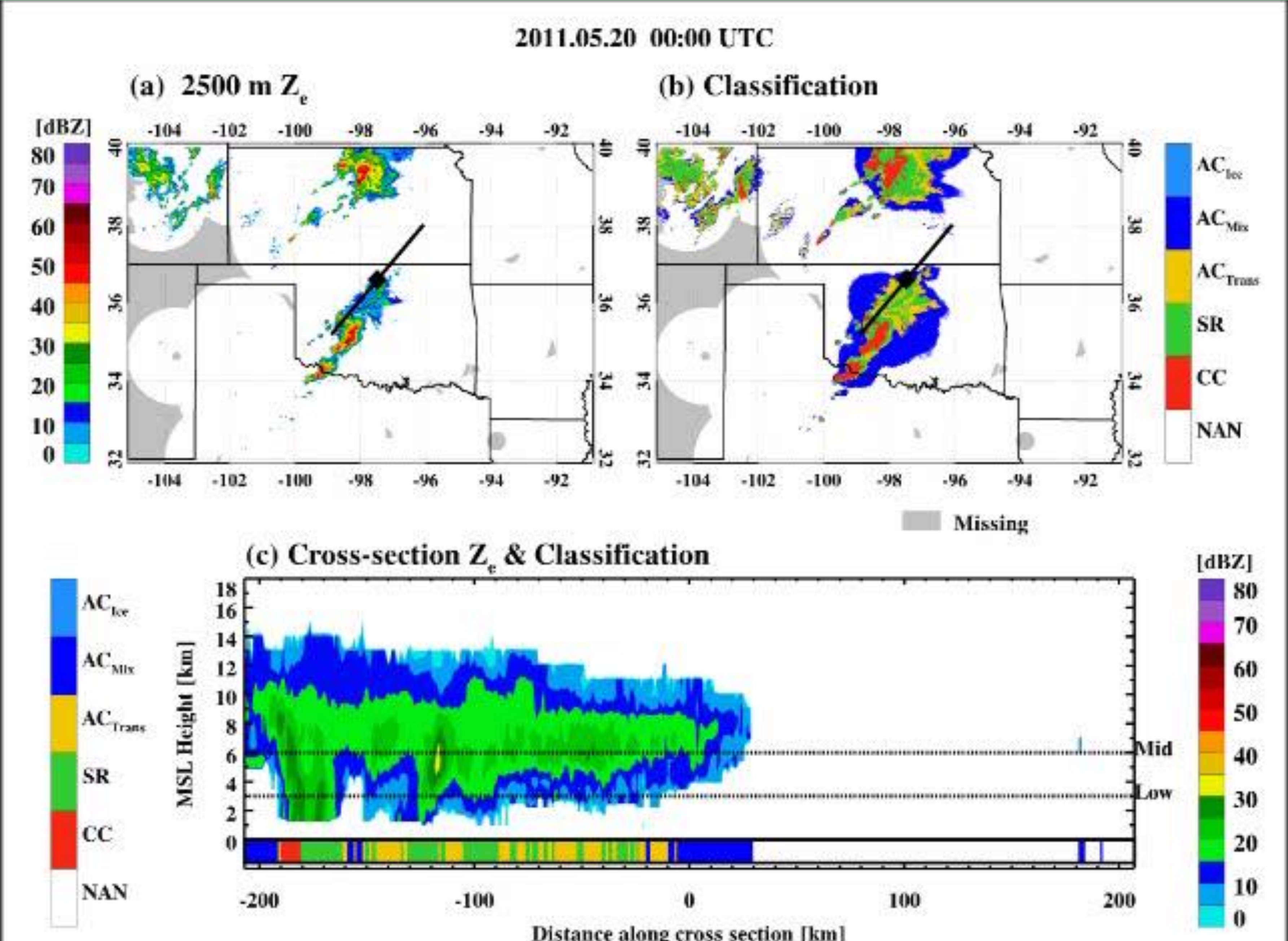


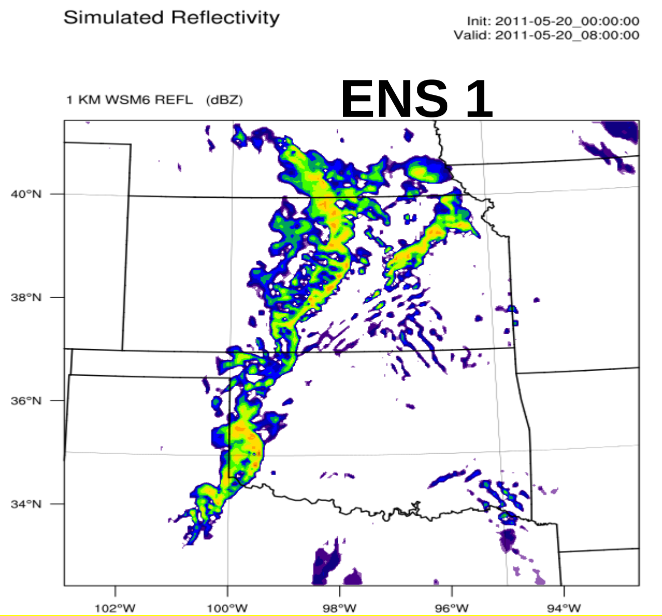
Microphysics scheme	Moments Predicted / Features	Original Reference
1) WSM6	Q	Hong and Lim (2006)
2) Ferrier	Q; snow, graupel, & sleet are combined within a single category	Ferrier et al. (2002)
3) Goddard	Q; six classes following Lin et al. (1983)	Tao and Simpson (1993)
4) Morrison	q and N_t for 5 species; one graupel category	Morrison et al. (2009)
5) WDM6	q for ice; q and N_t for warm rain processes	Lim and Hong (2010)
6) Milbrandt	q and N_t for all species; separate graupel & hail	Milbrandt and Yau (2005)
7) Thompson[*]	q and N_t for ice and rain	Thompson et al. (2008)
8) NSSL	q and N_t for all species	Mansell et al. (2010)
9) Lin11	q with diagnostic riming intensity	Lin and Colle (2011)

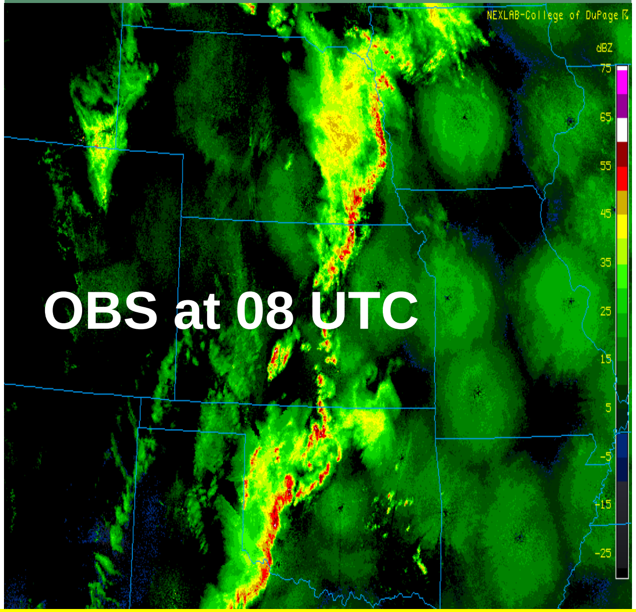
Objective 2 – WRF Configuration

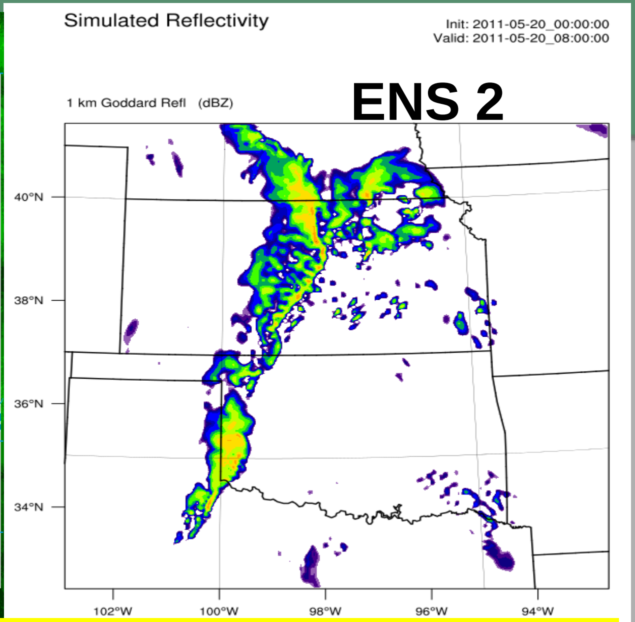
- **WRF model (v3.4.1), Advanced Research WRF (ARW) dynamical core.**
- **35 vertical levels.**
- **Initial and boundary conditions are obtained from 40 km NAM model.**
- **Nested Domain:**
  - **d01 – 12 km grid length**
  - **d02 – 4 km grid length**

Test Case (5/20/2011) during MC3E

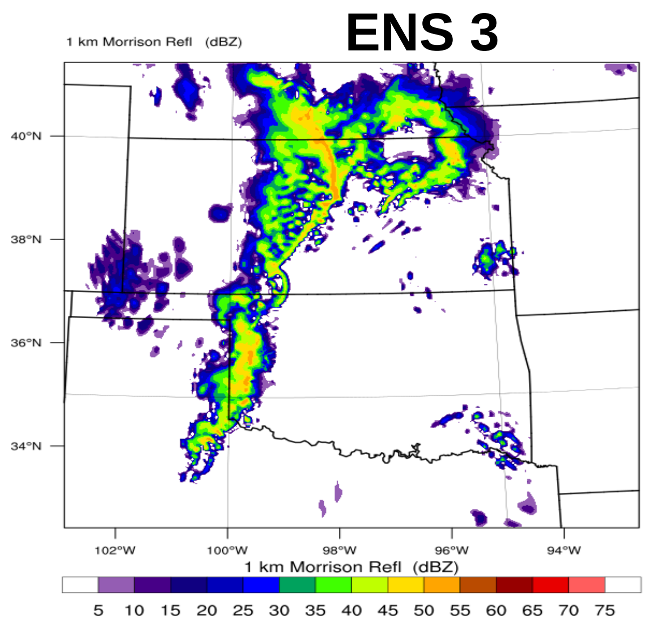


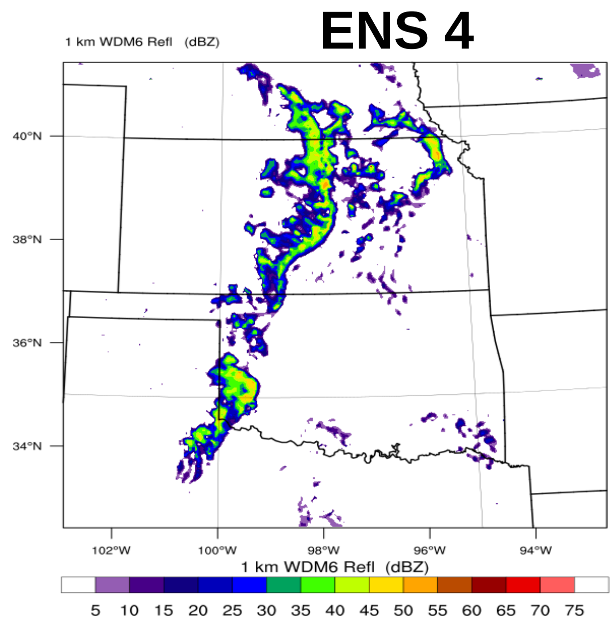

ENS 1

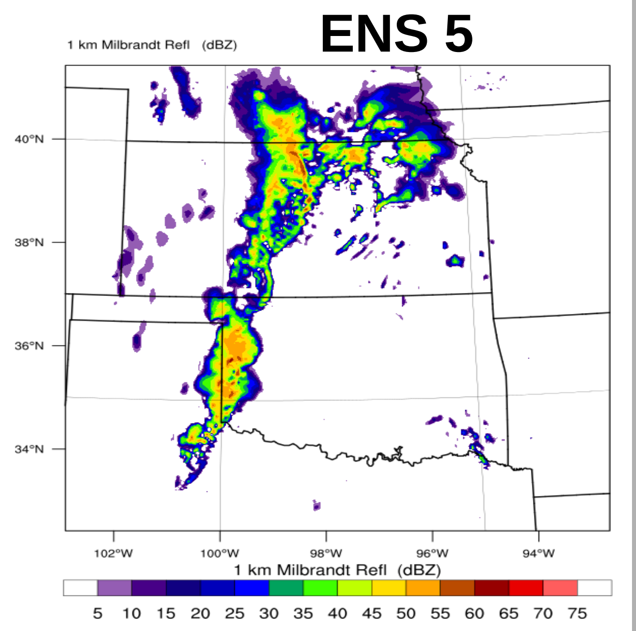

OBS at 08 UTC

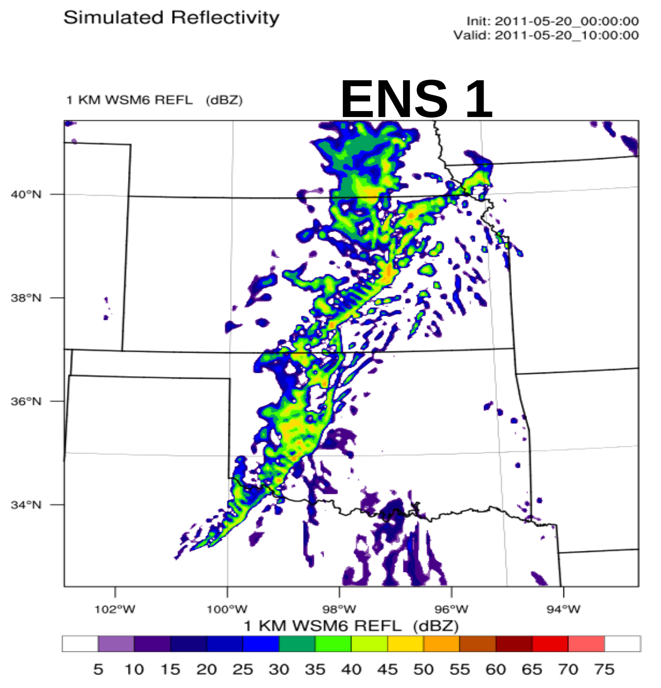

ENS 2

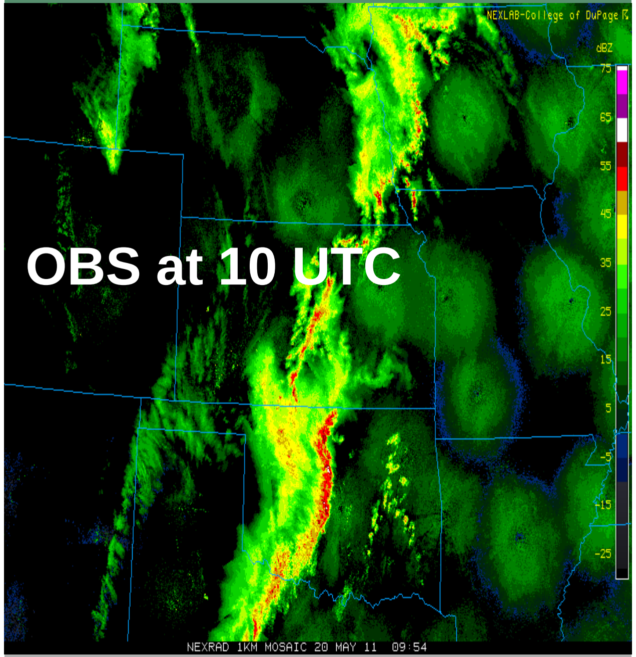
All five models can capture the squall line structure very well with some differences with temporal evolution

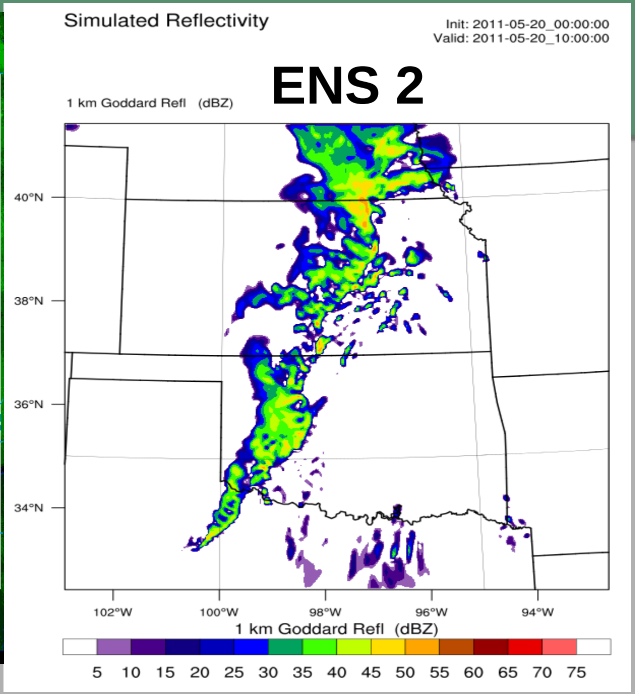

ENS 3

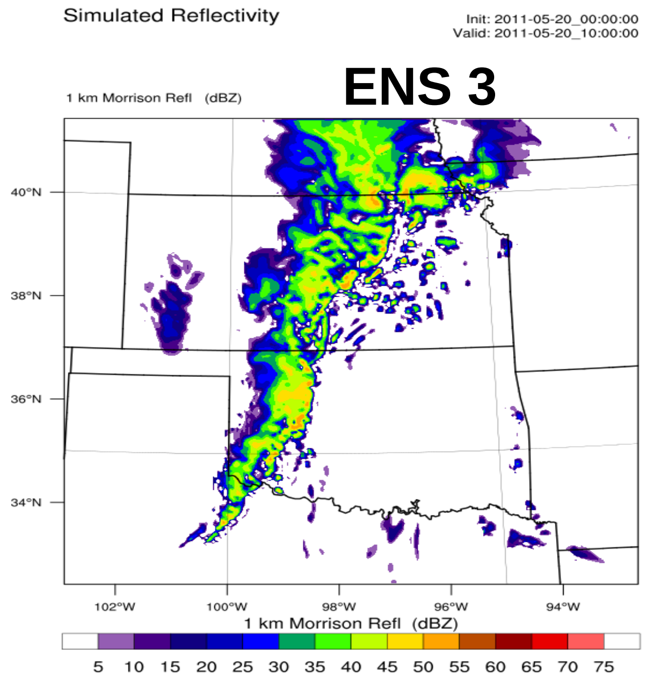

ENS 4

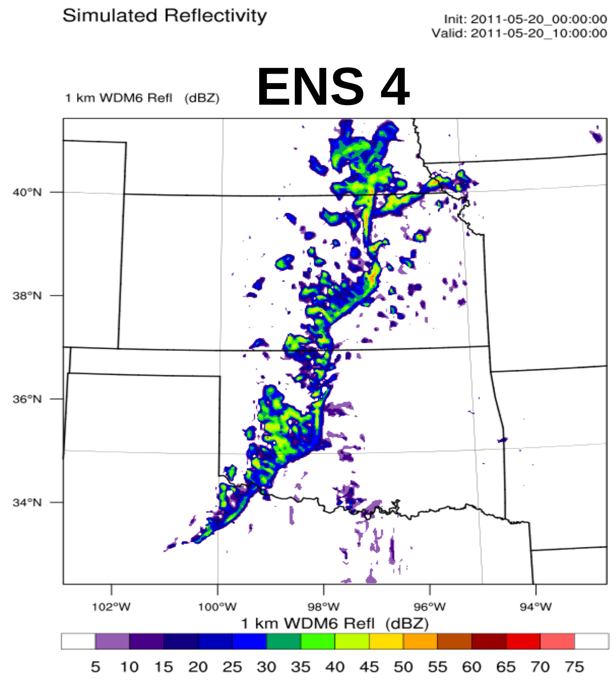

ENS 5

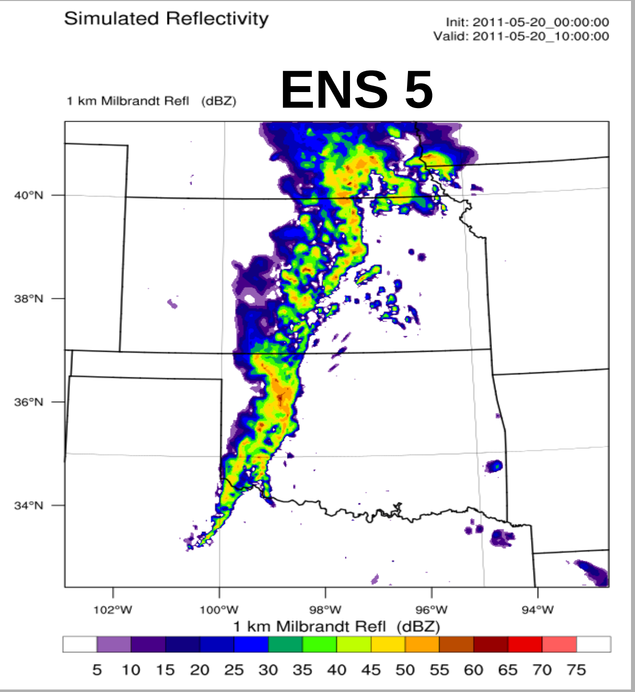

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_10:00:00
ENS 1
1 KM WSM6 REFL (dBZ)
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 KM WSM6 REFL (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

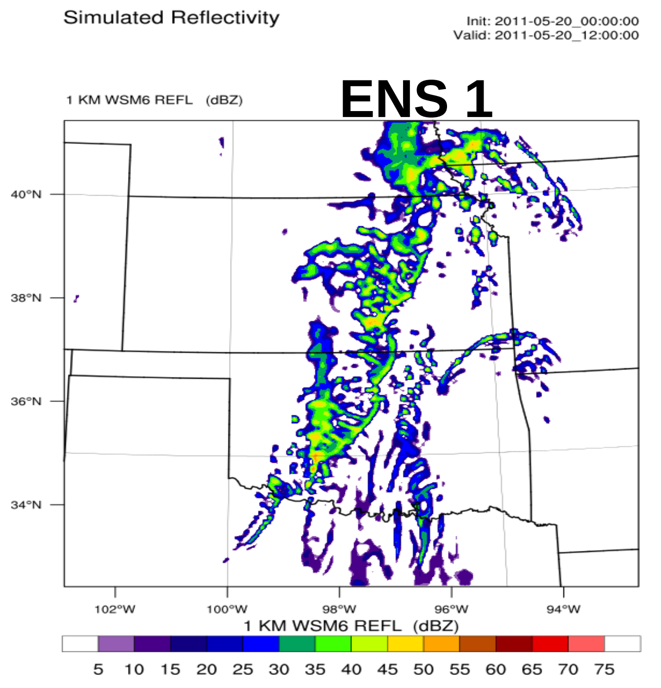

OBS at 10 UTC
NEXLAB-College of DuPage
dBZ
75
65
55
45
35
25
15
5
-5
-15
-25
NEXRAD 1KM MOSAIC 20 MAY 11 09:54

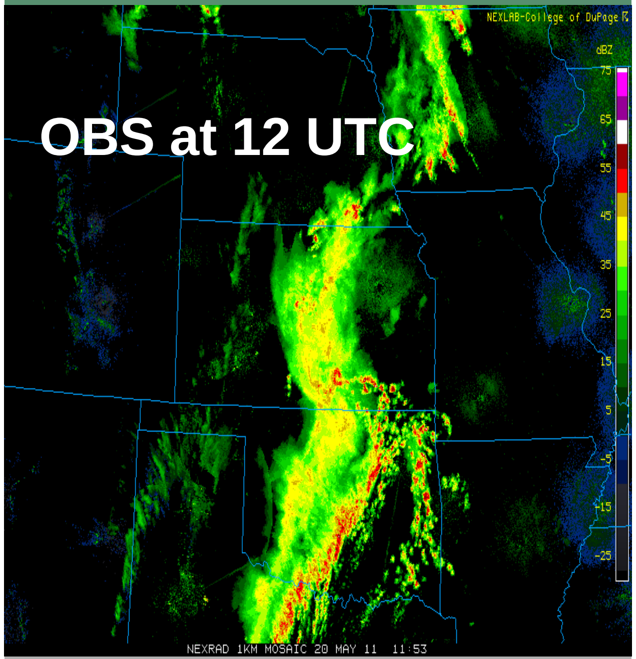

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_10:00:00
ENS 2
1 km Goddard Refl (dBZ)
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Goddard Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

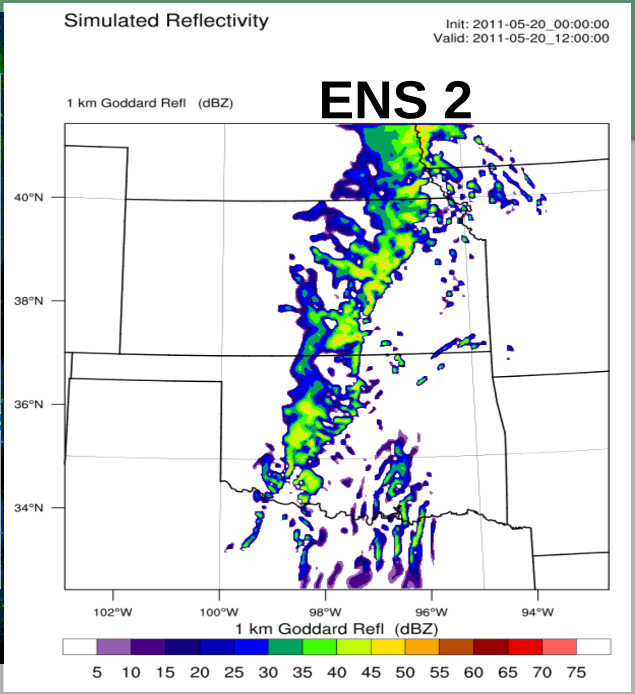

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_10:00:00
ENS 3
1 km Morrison Refl (dBZ)
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Morrison Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

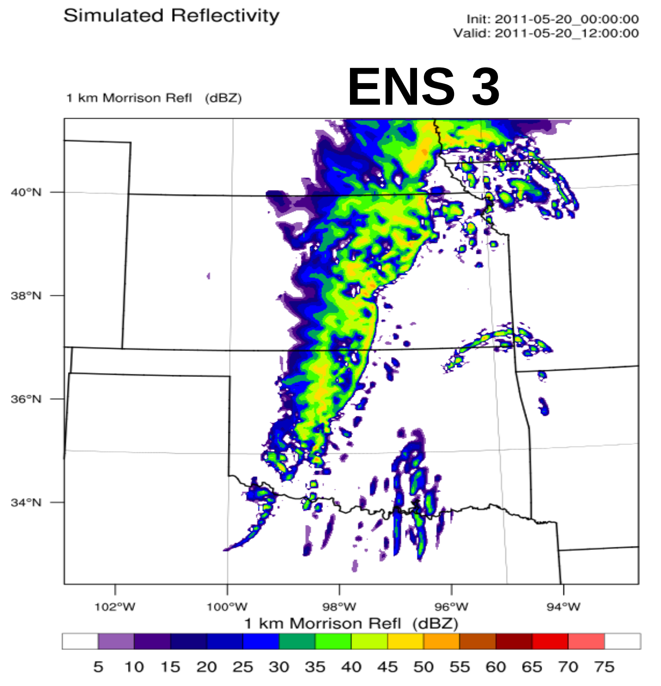

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_10:00:00
ENS 4
1 km WDM6 Refl (dBZ)
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km WDM6 Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

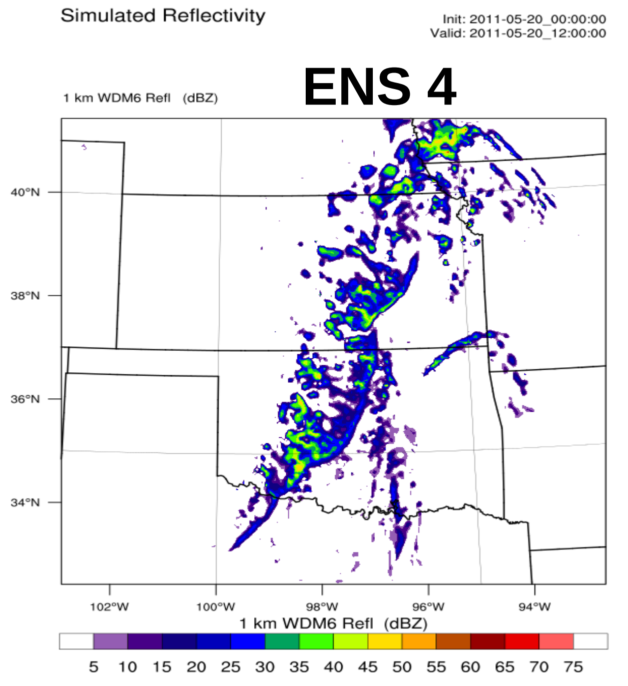

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_10:00:00
ENS 5
1 km Milbrandt Refl (dBZ)
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Milbrandt Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

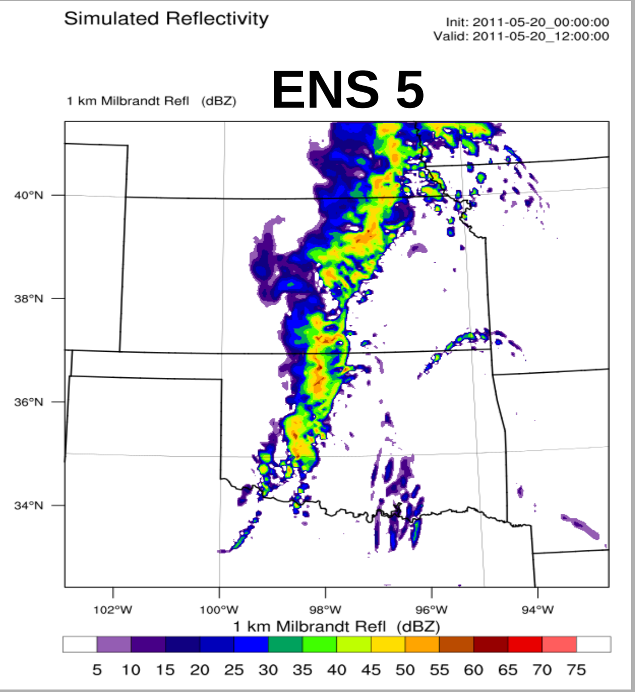

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_12:00:00
1 KM WSM6 REFL (dBZ)
ENS 1
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 KM WSM6 REFL (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75


OBS at 12 UTC
NEXLAB-College of DuPage
dBZ
75
65
55
45
35
25
15
5
-5
-15
-25
NEXRAD 1KM MOSAIC 20 MAY 11 11:53


Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_12:00:00
1 km Goddard Refl (dBZ)
ENS 2
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Goddard Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

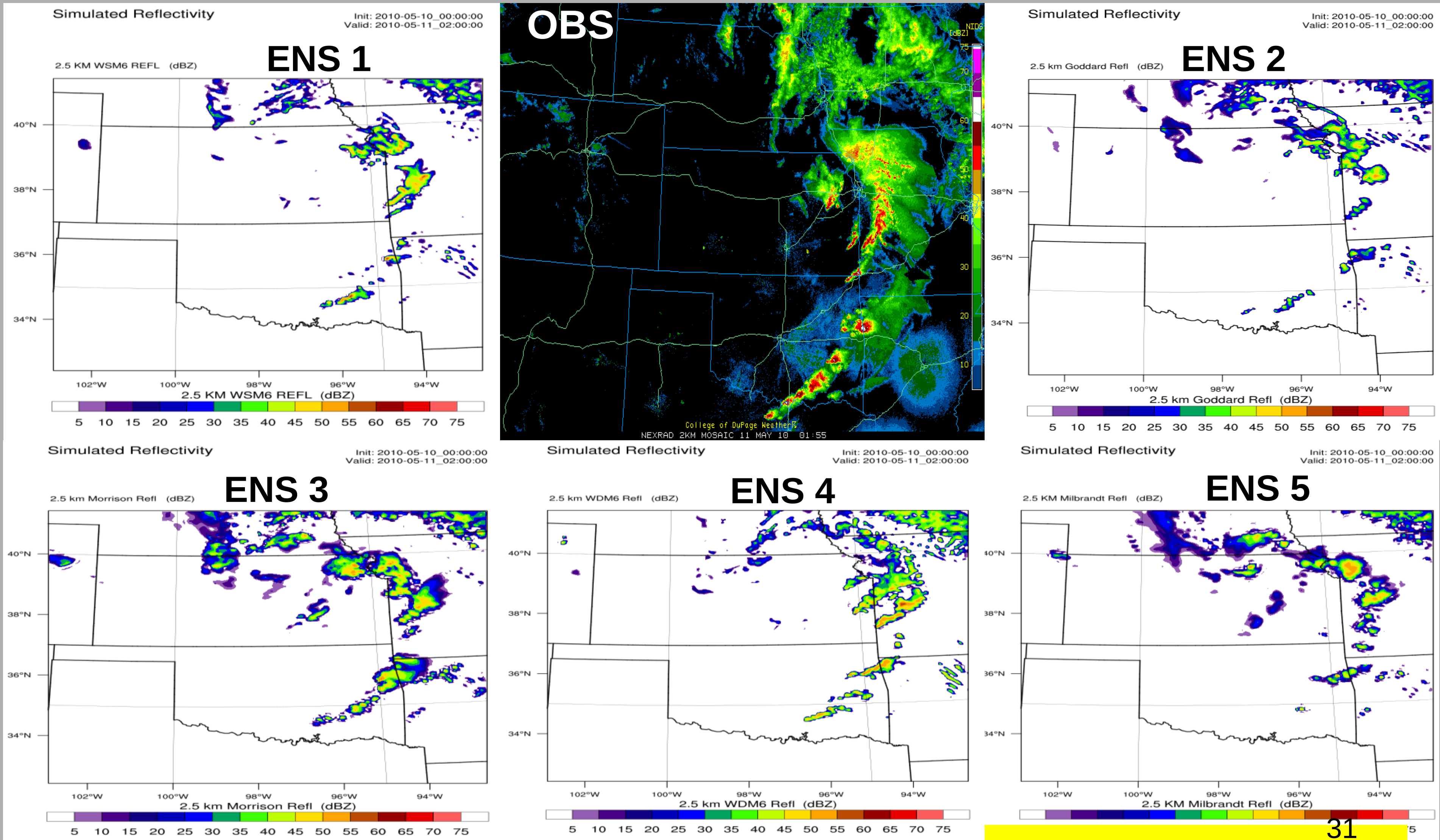

Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_12:00:00
1 km Morrison Refl (dBZ)
ENS 3
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Morrison Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75


Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_12:00:00
1 km WDM6 Refl (dBZ)
ENS 4
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km WDM6 Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75


Simulated Reflectivity
Init: 2011-05-20_00:00:00
Valid: 2011-05-20_12:00:00
1 km Milbrandt Refl (dBZ)
ENS 5
40°N
38°N
36°N
34°N
102°W
100°W
98°W
96°W
94°W
1 km Milbrandt Refl (dBZ)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

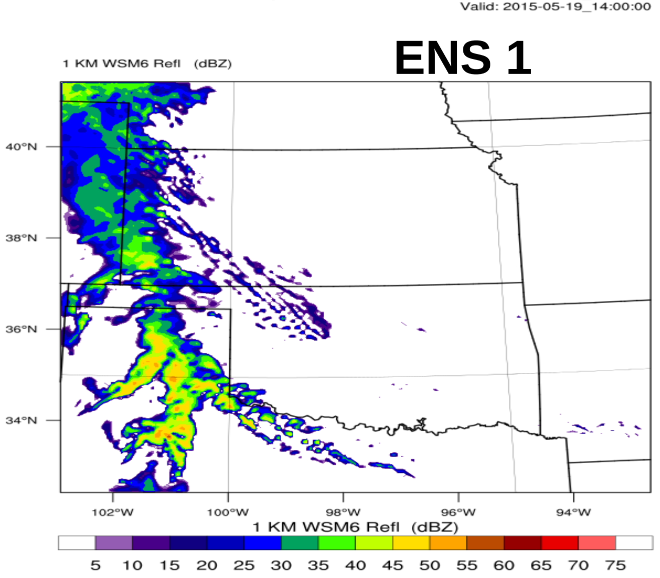
Objective 2 – Test Case (5/10/2010)

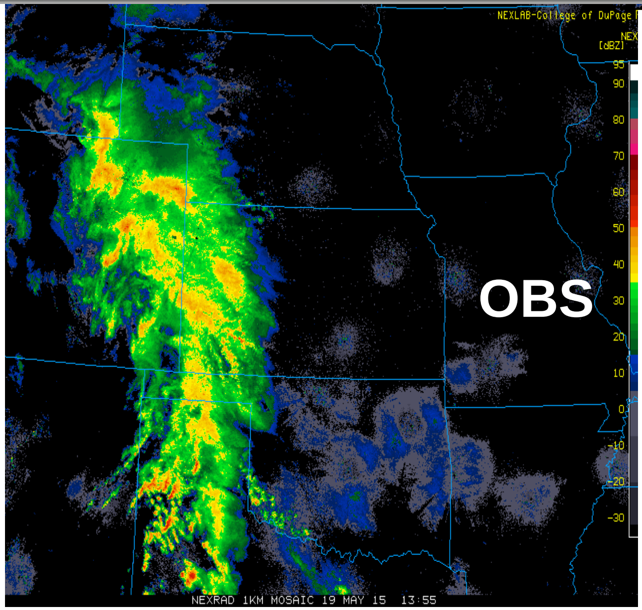
Sample of the Ensemble members for a test case

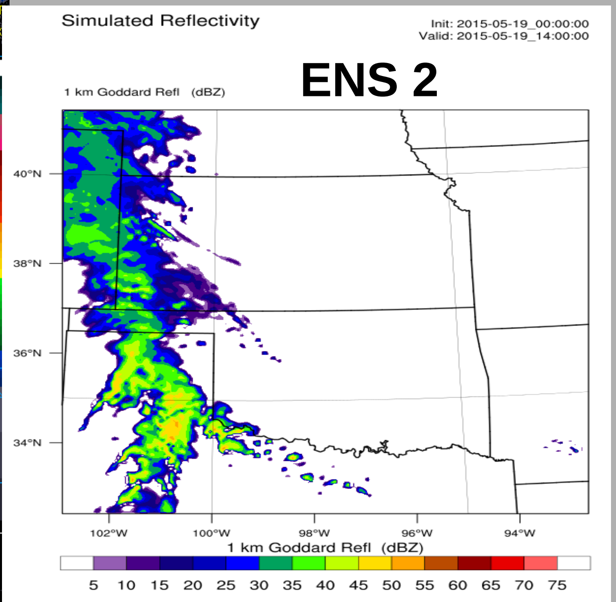


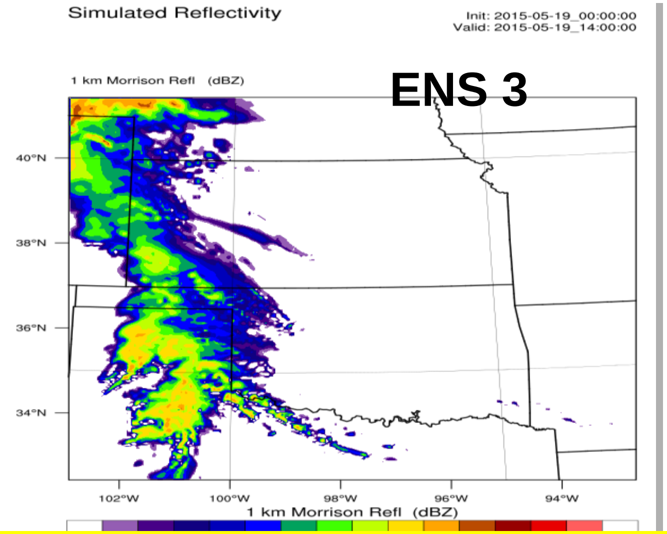
Simulations can capture individual supercells.

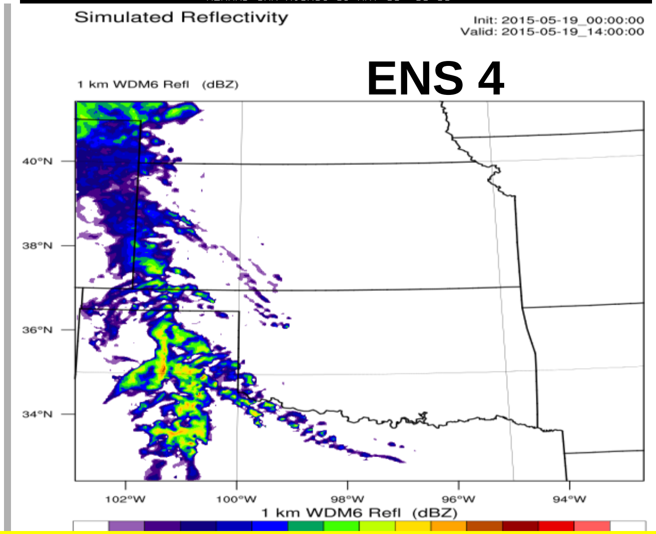
Objective 2 – Test Case (5/19/2015)

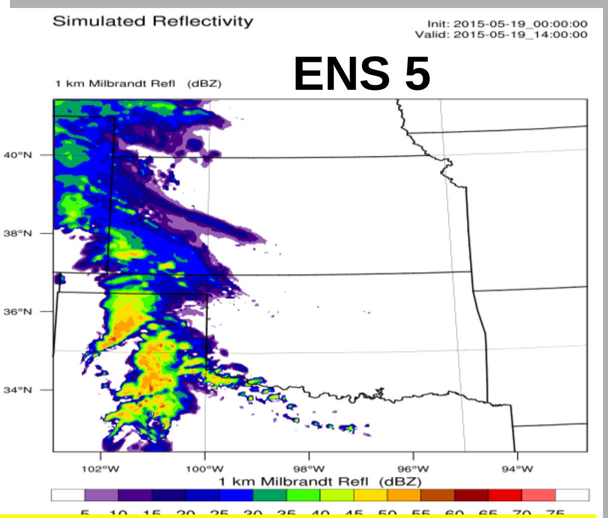












In this case, all simulations agree better with observations.
Notice that they all are squall line systems, not local convective systems.
More cases are needed to get statistical results (more quantitatively).

Personnel

Professors **and their graduate student**

PI: Xiquan Dong, Professor

- Remote sensing of cloud and precipitation properties
- R2O Role
    - Cloud-Precipitation Properties and Processes
    - Stratiform/convective classification

Ronald Stenz

Co-I: Matt Gilmore, Associate Professor

- Modeling / Microphysics Parameterizations
- R2O Role
    - WRF Microphysics Ensemble

Joshua Markel

Co-I: Aaron Kennedy, Assistant Professor

- Remote Sensing / Modeling / Synoptic Typing
- R2O Role
    - Performance of prior HWT simulations
    - Database of convective events
    - Synoptic classification (SOM)

David Goines