The realization of extreme tornadic storm events under future anthropogenic global warming

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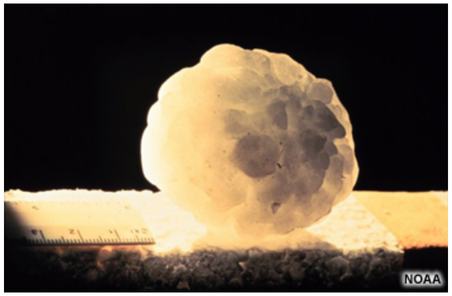
Motivation

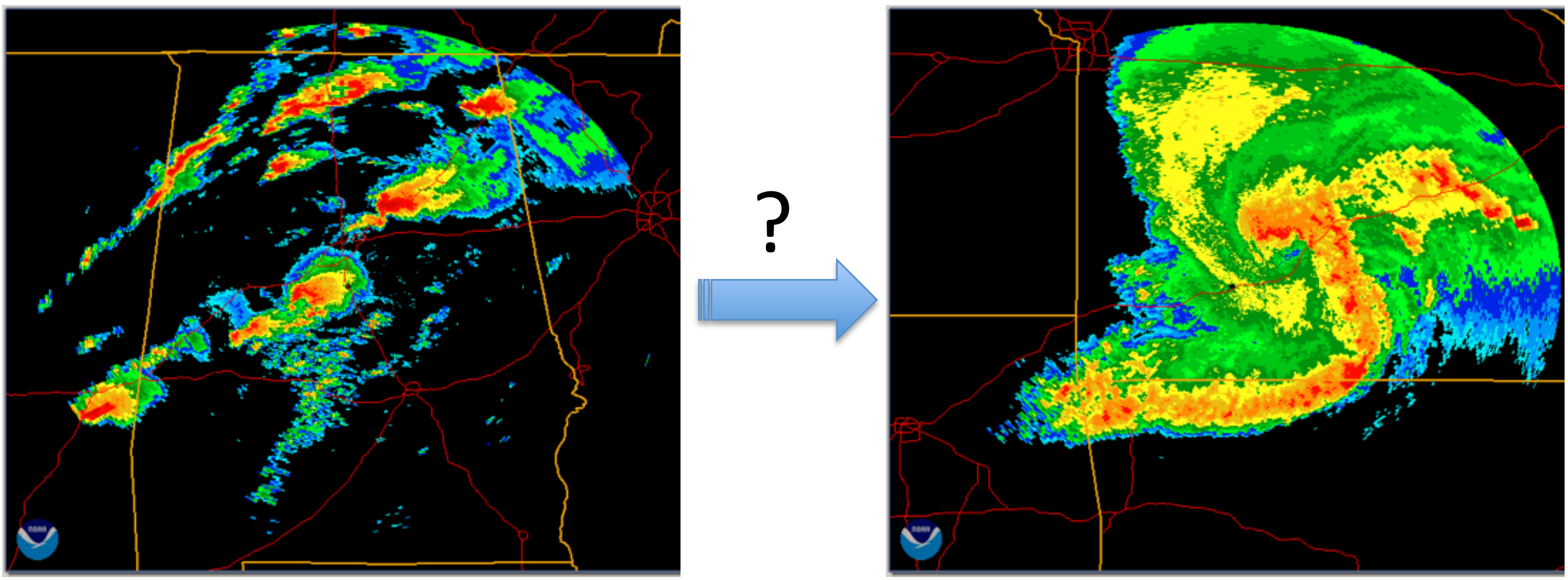
- <u>General, overarching question</u>: (How) will the intensity and frequency of severe *local-scale* thunderstorms change owing to increases in human-enhanced *global-scale* radiative forcing?



*Note: a **severe thunderstorm** = one that has generated a tornado, hail, and/or damaging "straight-line" winds*

<u>Particular sub-question:</u> ***Will the morphology of these storms tend to change such that supercells of today will become squall lines/bow echoes of tomorrow?***

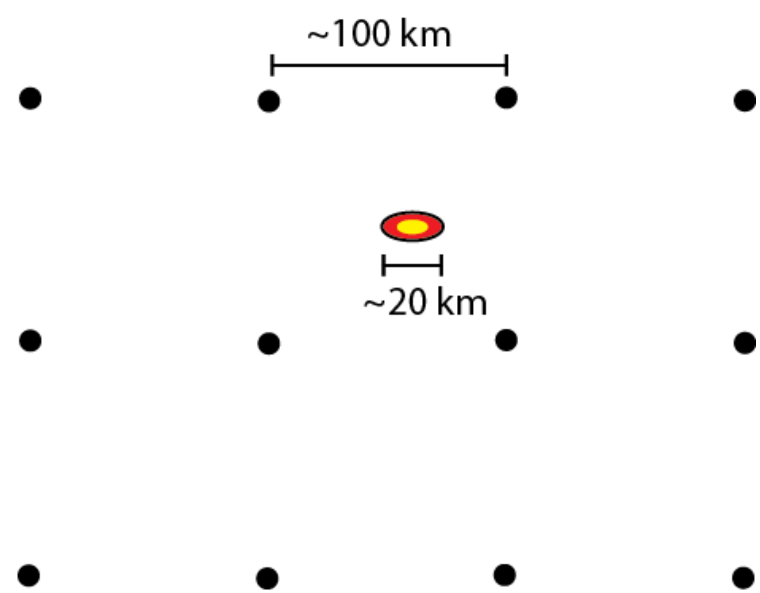
(as is frequently suggested based on theoretical considerations)



- **This question matters because hazard is strongly linked to mode**

How can we use climate models?

- Local convective storms are unresolved in (global, regional) climate models…



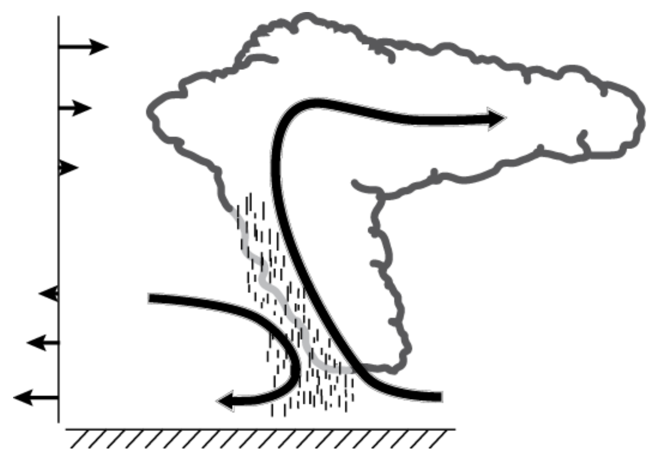
How can we use climate models?

- Local convective storms are unresolved in (global, regional) climate models, but we can still use such models by exploiting the fact that *storm organization is strongly controlled by the larger-scale wind, temperature, and humidity*
  - a thunderstorm's "environment" can be quantified at each model gridpoint
    - this is a form of *downscaling*

Downscaling via "environmental" parameters

- Two environmental parameters represent well the potential for severe thunderstorms:
  - convective available potential energy (CAPE)
  - vertical wind shear $\left(\mathrm{S06} = \left|\bar{\boldsymbol{V}}_{6km} - \bar{\boldsymbol{V}}_{0km}\right|\right)$

S06 helps organize up- and down-drafts as well as provides a source of rotation, which then affects the storm dynamics

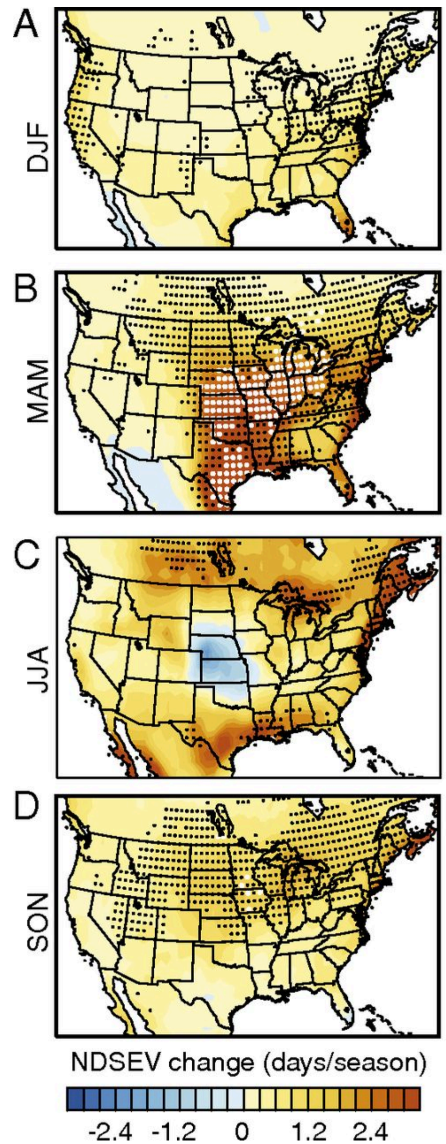


CAPE sets the theoretical maximum updraft speed

Change in # days/season locally supportive of severe thunderstorms

Key point:

Upon combining these two parameters and evaluating them using GCM simulations of future climate, we find evidence of a *robust increase in the future number of days supportive of severe thunderstorms in the U.S.*



DJF

MAM

JJA

SON

Diffenbaugh, Scherer, and Trapp (2013, *PNAS*)

A limitation of “environmental” parameter approach

- The approach only tells us the *potential* for severe thunderstorm formation, and does not discriminate well between morphologies and thus hazard.
- This approach also lacks concern about known historical events, and therefore about how these events might be projected in the future
- Thus, it doesn’t the question: ***will the (tornadic) supercells of yesterday and today be the (nontornadic) squall lines of tomorrow?***

“Pseudo-global warming” (PGW) approach: Another way to use climate models!

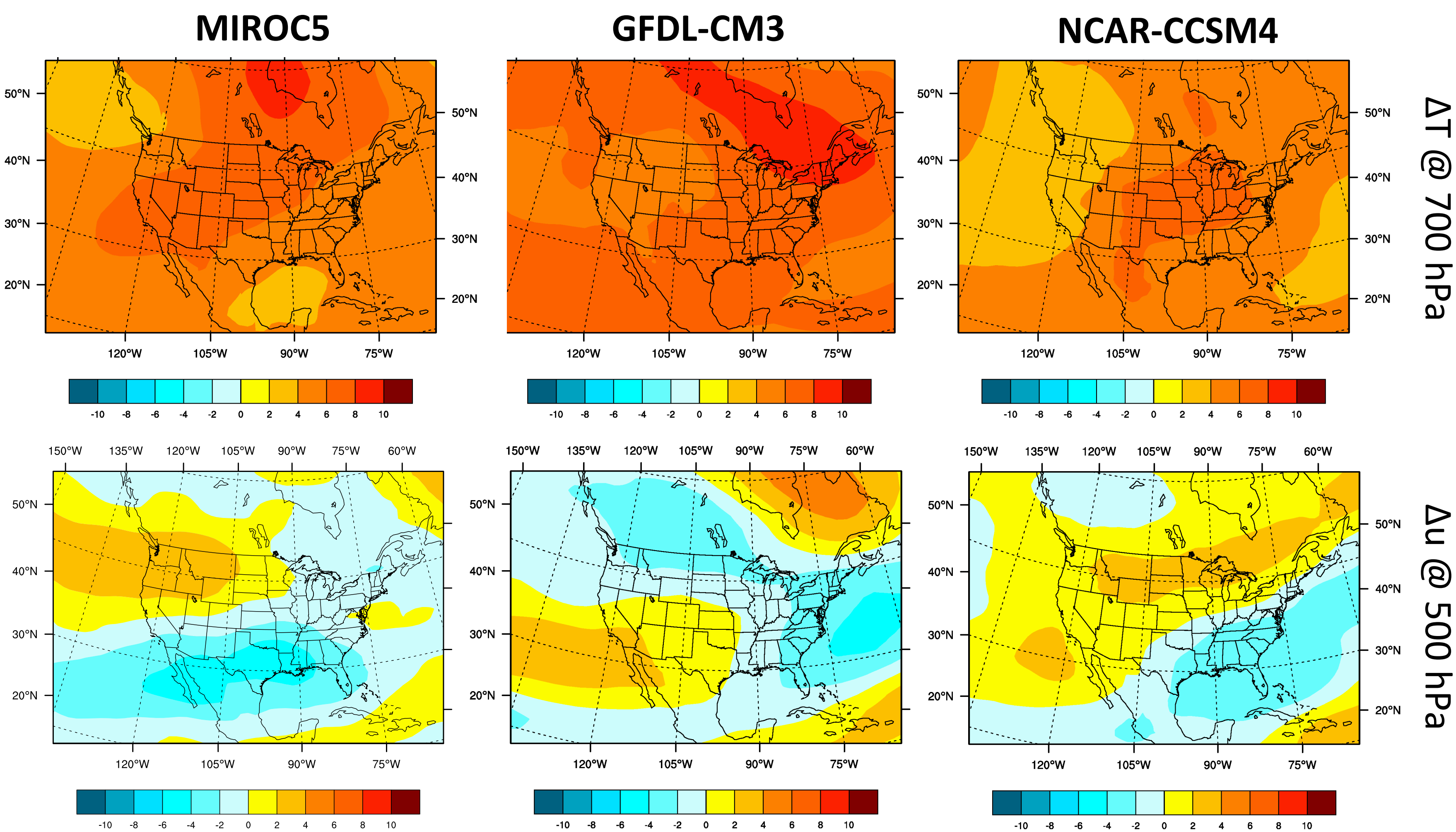
- PGW (Schär et al. 1996) is a numerical modeling approach that allows us to place a historical event in the future, and consider it in detail
- In essence, we simulate the historical event using its 3D meteorological forcing plus a **climate-change Δ**, e.g.

$$T(x,y,z,t) = T(x,y,z,t) + \Delta T$$

where

$$\Delta T = \overline{T(x,y,z)}_{future} - \overline{T(x,y,z)}_{past}$$

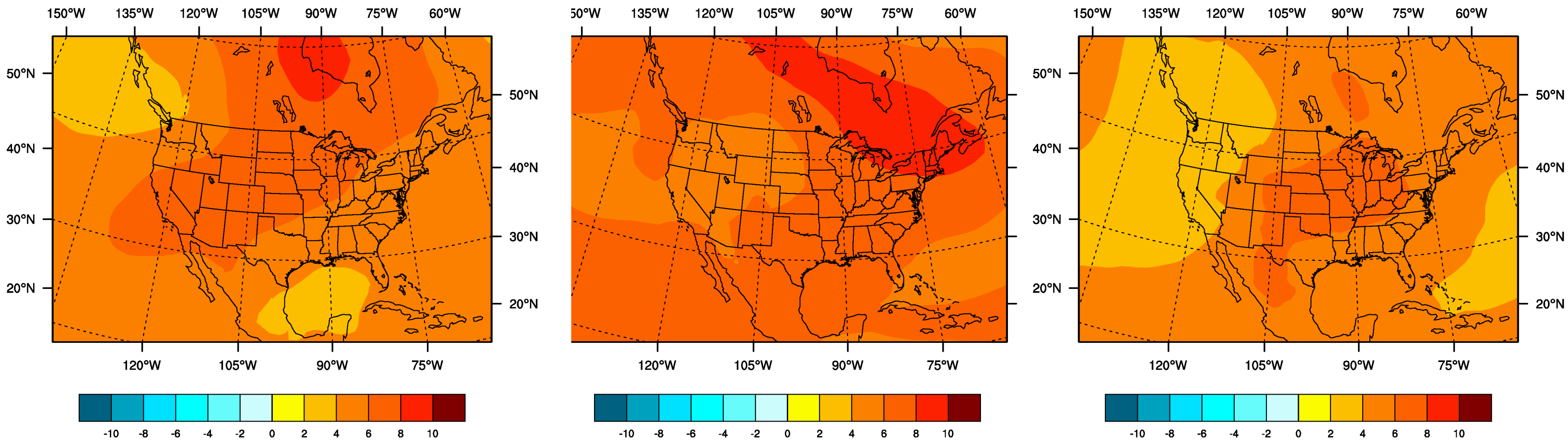
Examples of Δ's in temperature and wind for 3 different GCMs



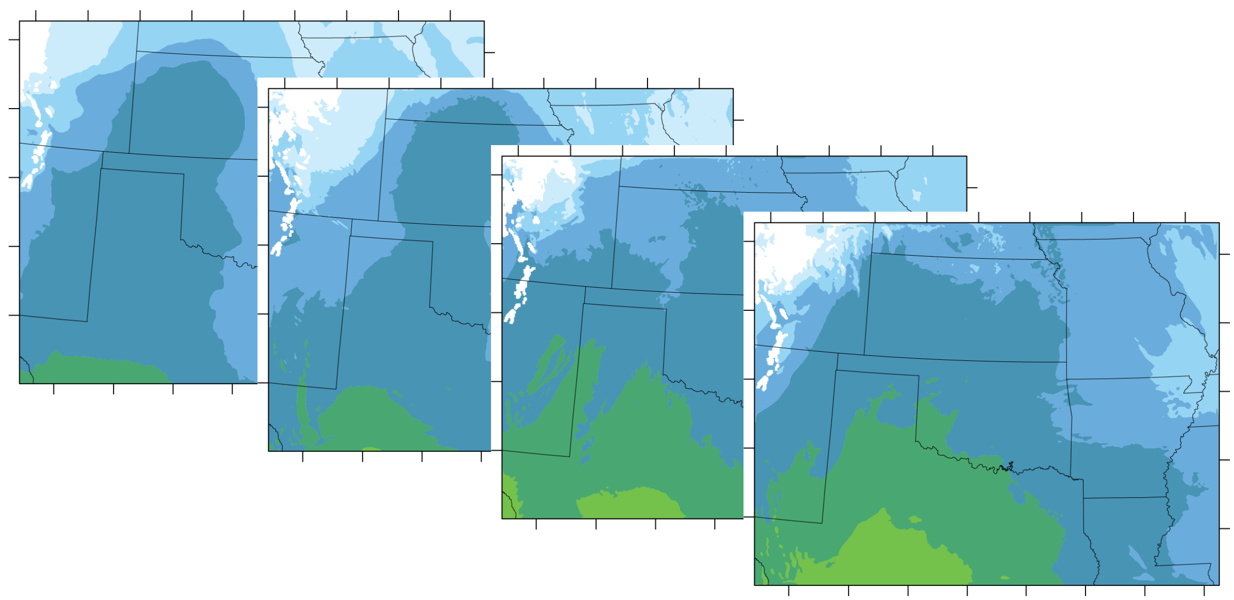
The Δ's are 2090-2099 minus 1990-1999 for the month of May

The PGW procedure:

Δ's



+ time-dependent forcing of an envent



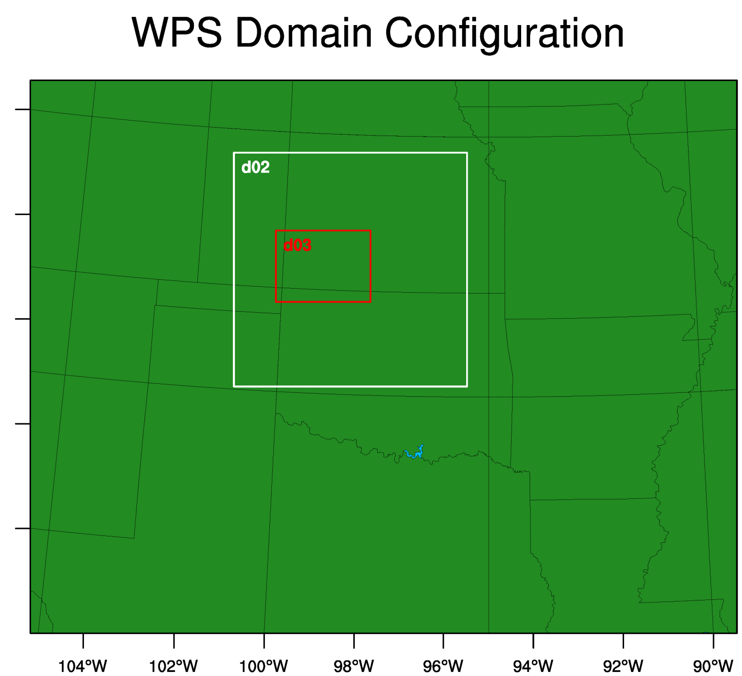
= PGW modified state

Extreme tornadic events

- Three high-end tornado events were chosen:
    - *EF-5 Greensburg, Kansas tornado of 4 May 2007*
    - *EF-5 Norman, Oklahoma tornado of 10 May 2010*
    - *EF-4 Shawnee, Oklahoma tornado of 19 May 2013*
- The respective tornadoes developed within *supercell thunderstorms*, in high-CAPE/high-shear environments (but not extraordinarily high)
    - **Introduction of PGW should thus reveal how "typical" extreme tornadic storm events might be realized under projected climatic conditions of the late 21st Century.**

Control and PGW simulations

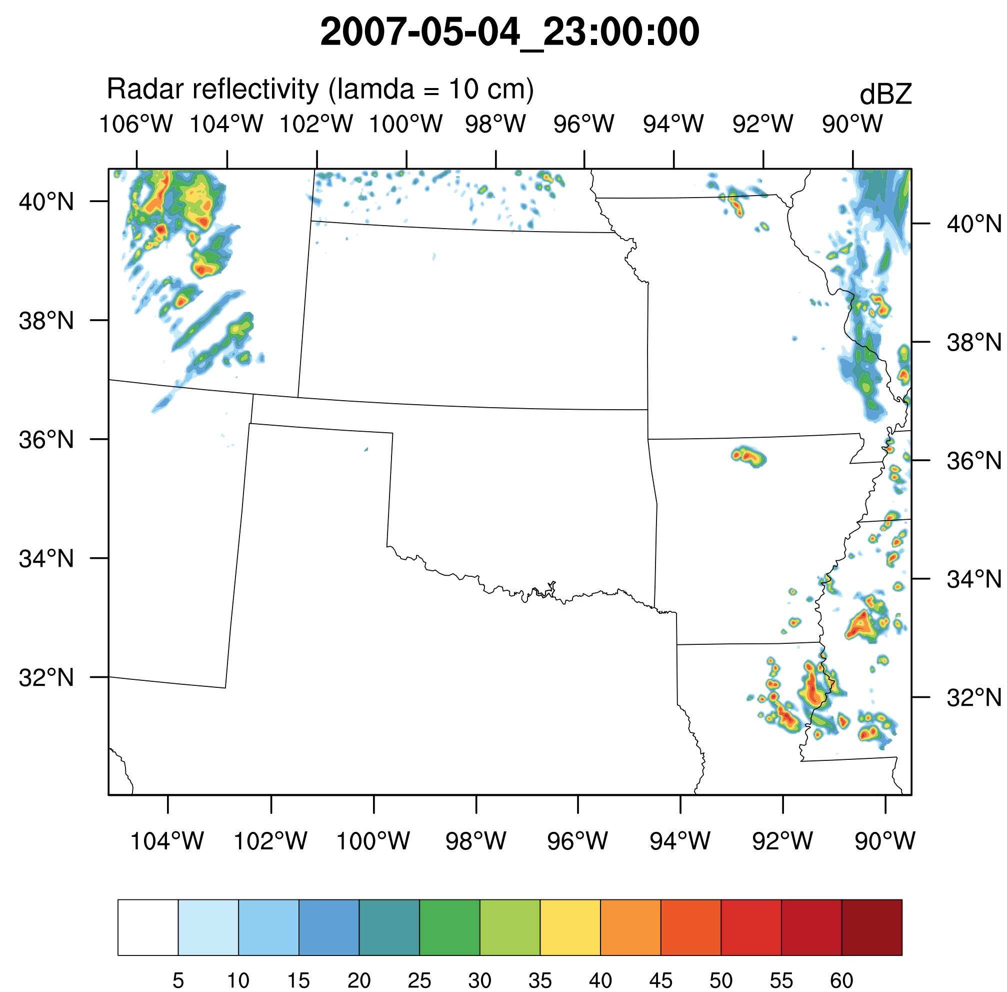
- Weather Research and Forecasting model (WRF)
  - *Notable details*:
    - ic/bc from NAM analysis
    - doubly nested domain (3 – 1 km grid lengths)
      - additional runs with 3 – 1 –.33 – .11 km grid lengths
    - 70 vertical levels
    - Morrison double moment microphysical parameterization (with hail)



PGW experimentation

- To evaluate the robustness of the results, and to tease out the most important climate-change effects, we performed the following experiments on each of the 3 historical events, using the Δ’s from each of the 3 GCMs:
  - wind-only Δ’s
  - thermodynamic-only Δ’s
  - no Δ’s in soil temperature and soil moisture
  - no relative humidity Δ’s

Control
radar reflectivity



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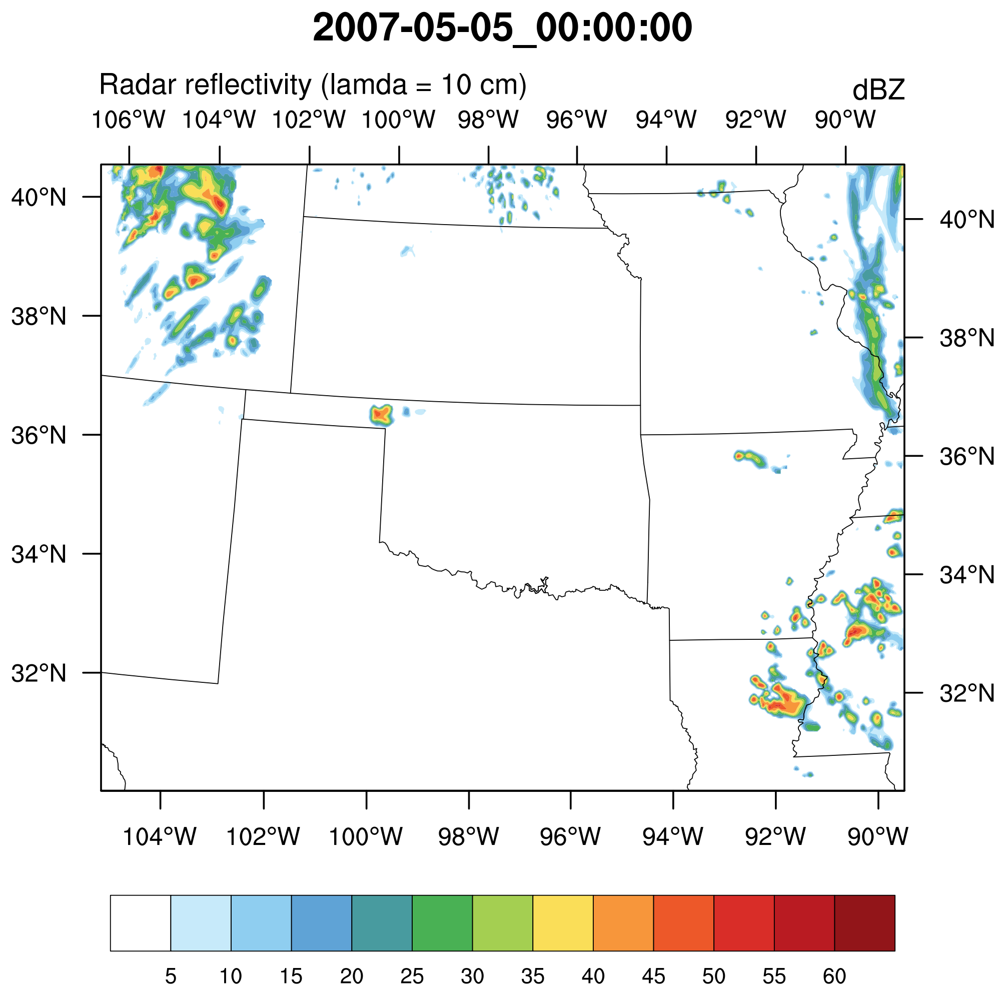

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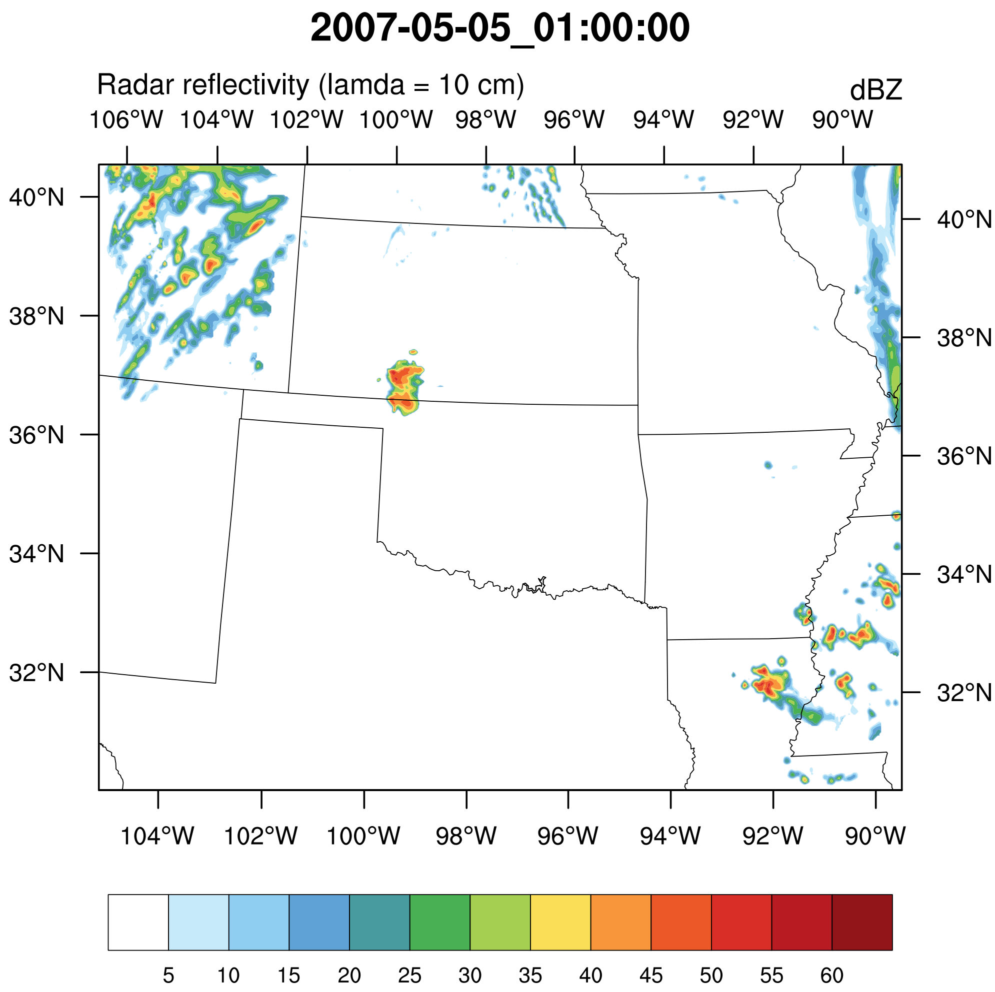

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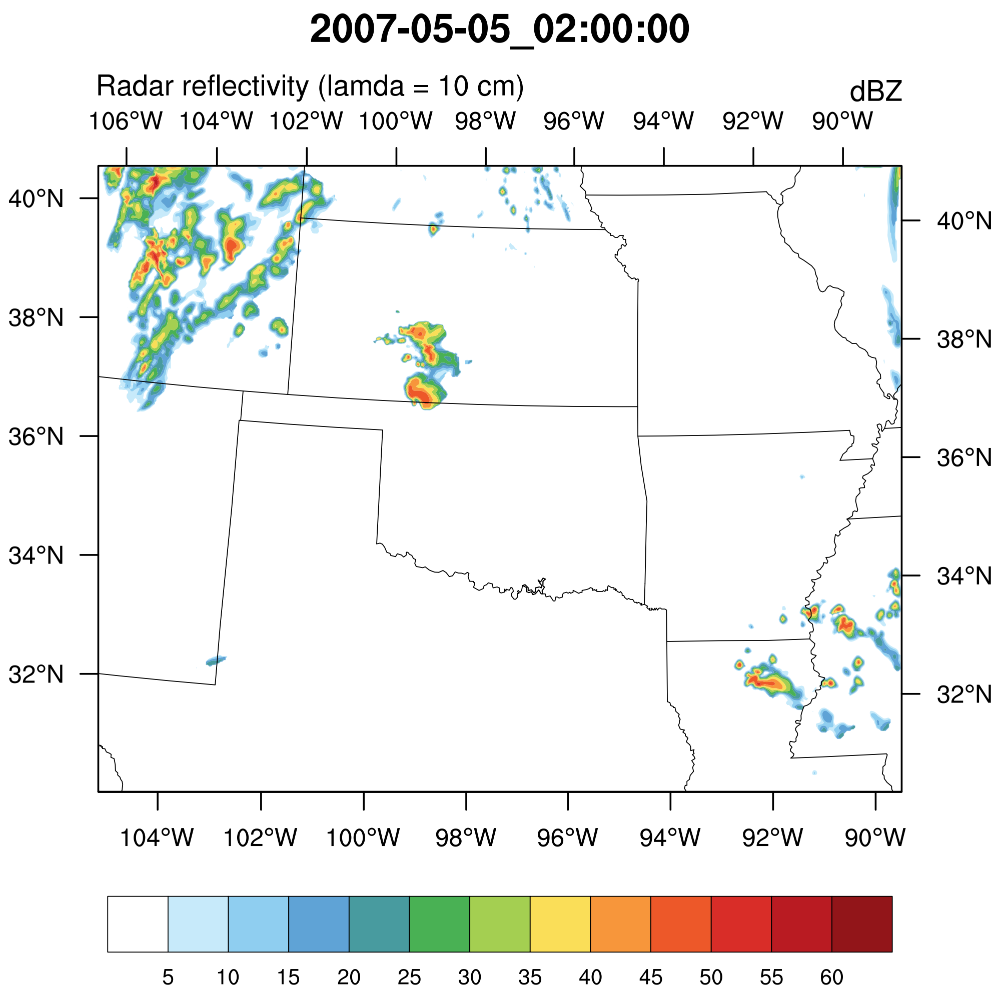

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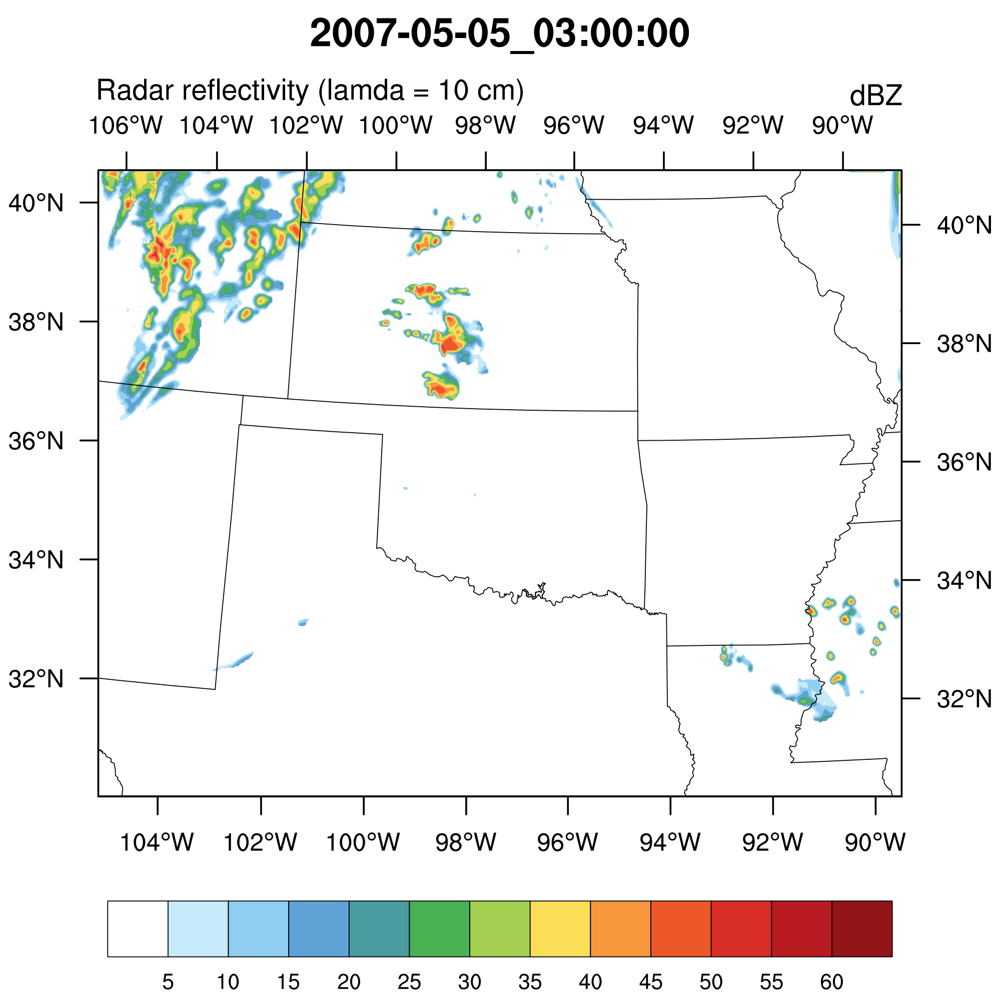
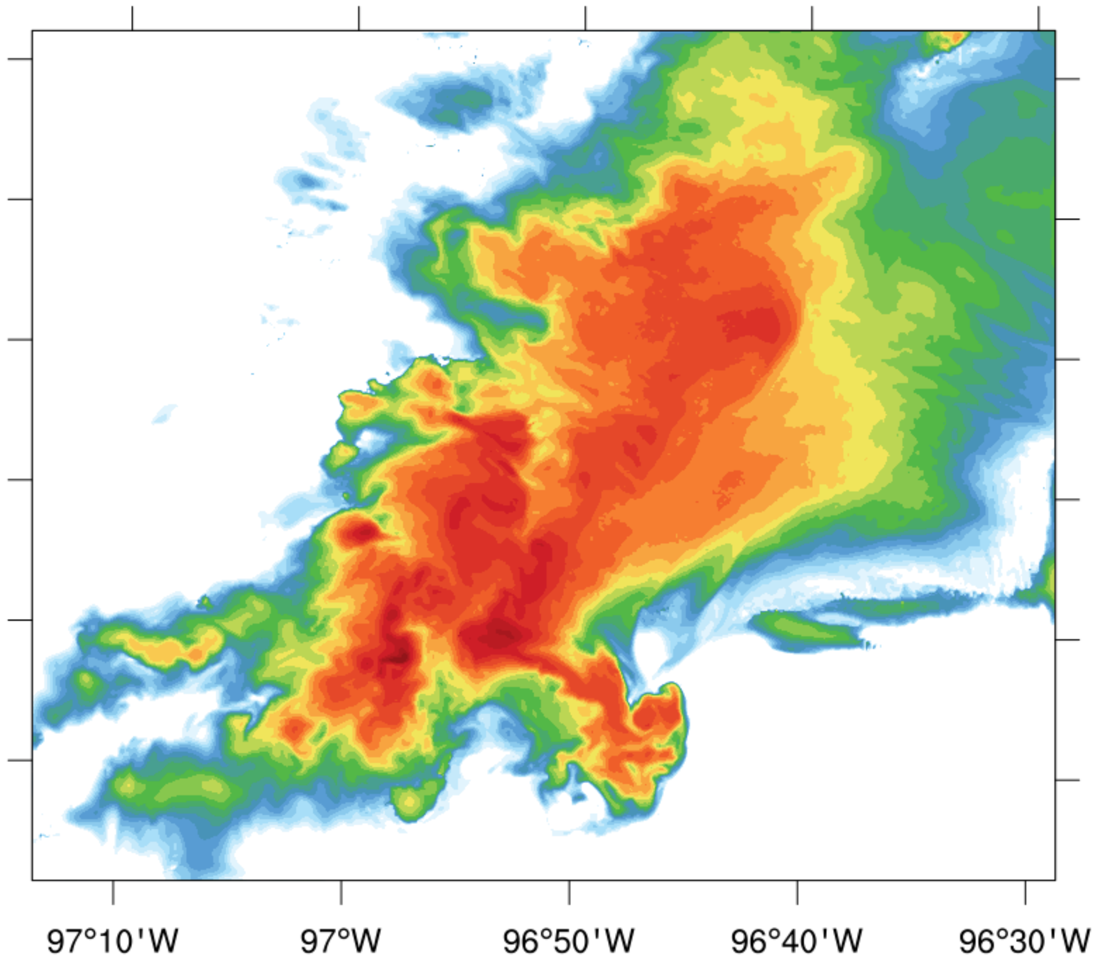
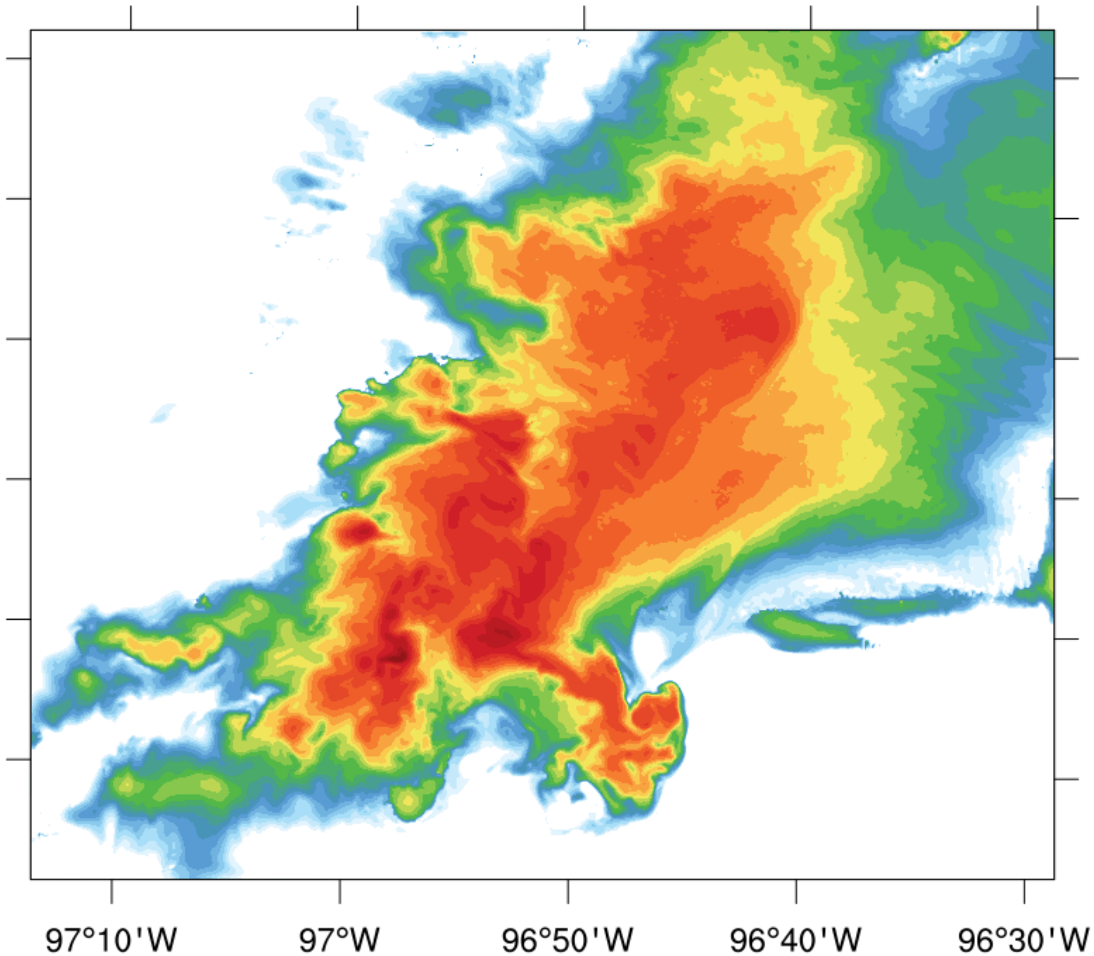


Challenge: quantify supercell existence, and provide a means of comparison with PGW experiments





Quantify (tornadic) supercell existence using *updraft helicity* (UH)

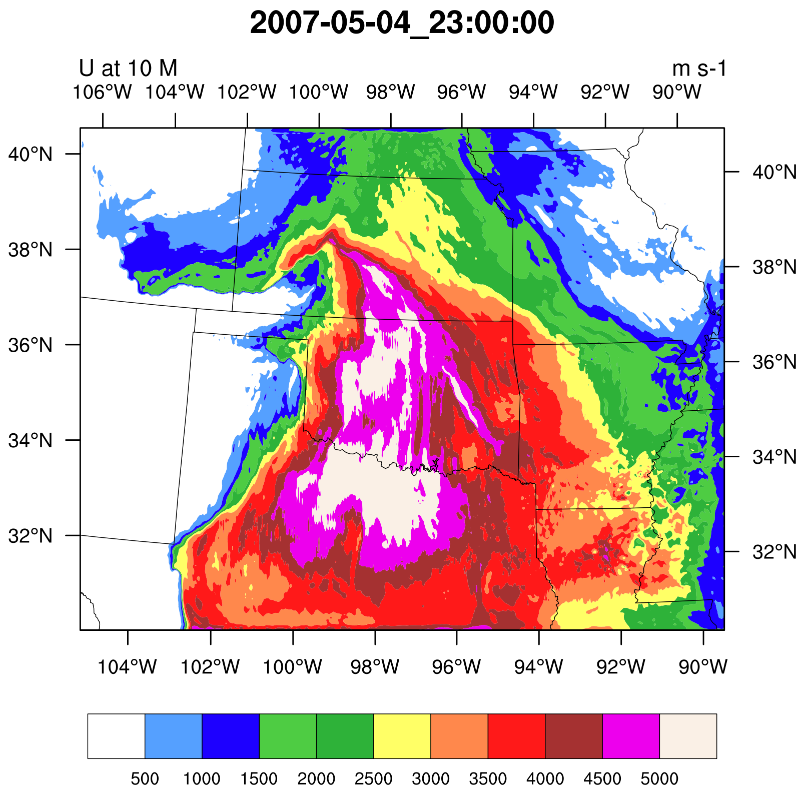
$$UH = \int_{z=2\,km}^{z=5\,km} w\zeta \, dz$$

and *radar reflectivity* (REFL)

Before consulting the WRF simulations, what are your expectations based on environmental CAPE (J/kg)?

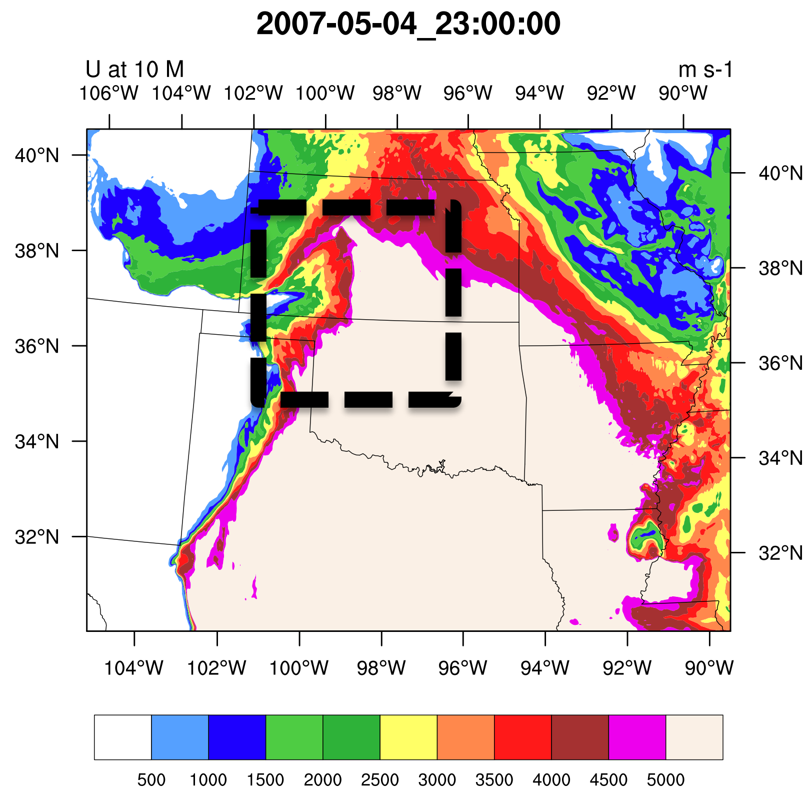
CTRL

CAPE



GFDL PGW

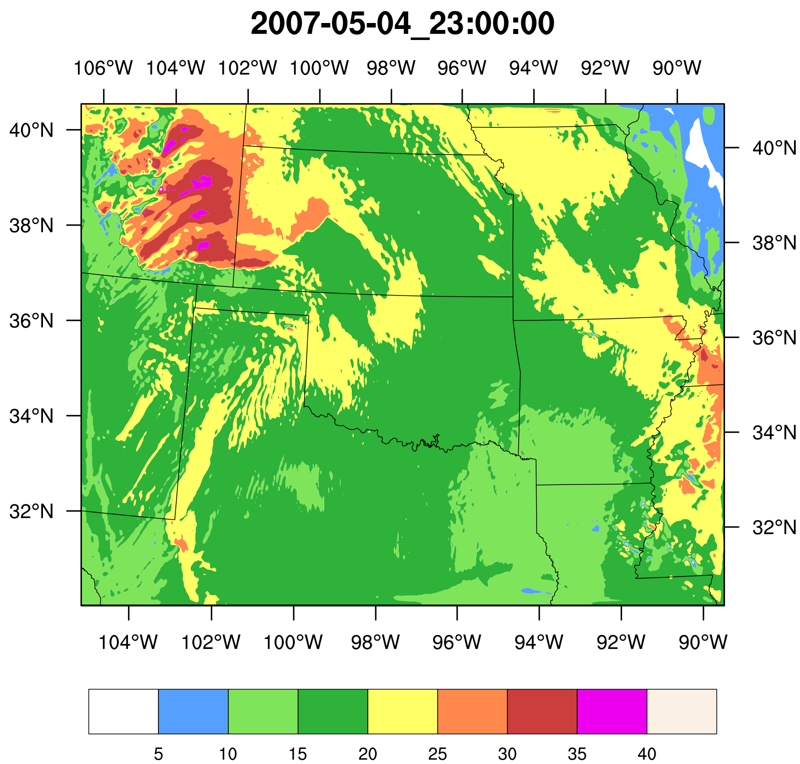
CAPE



Before consulting the WRF simulations, what are your expectations based on 0-6 km wind shear (S06; m/s)?

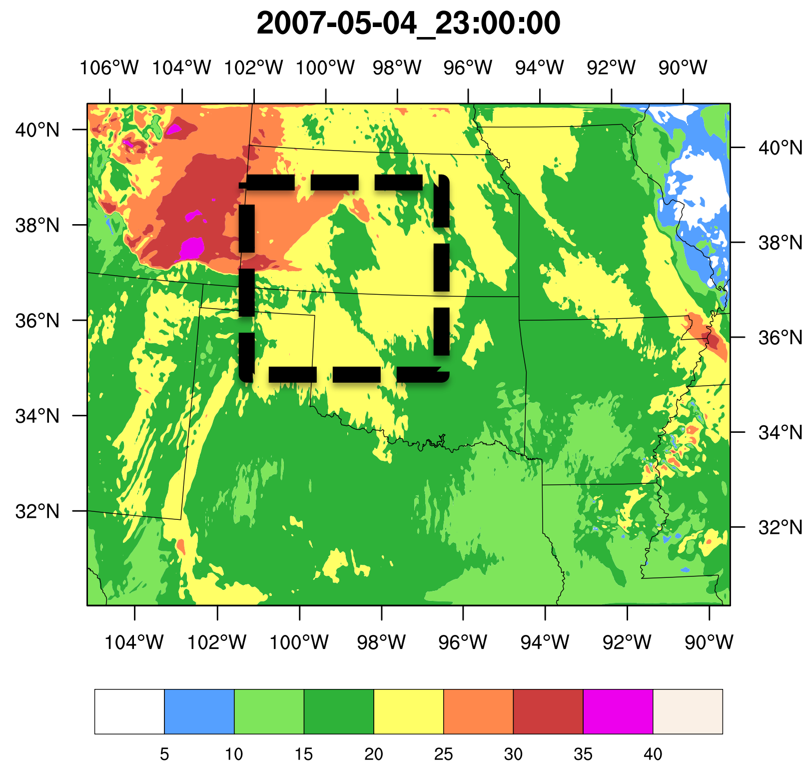
CTRL

S06



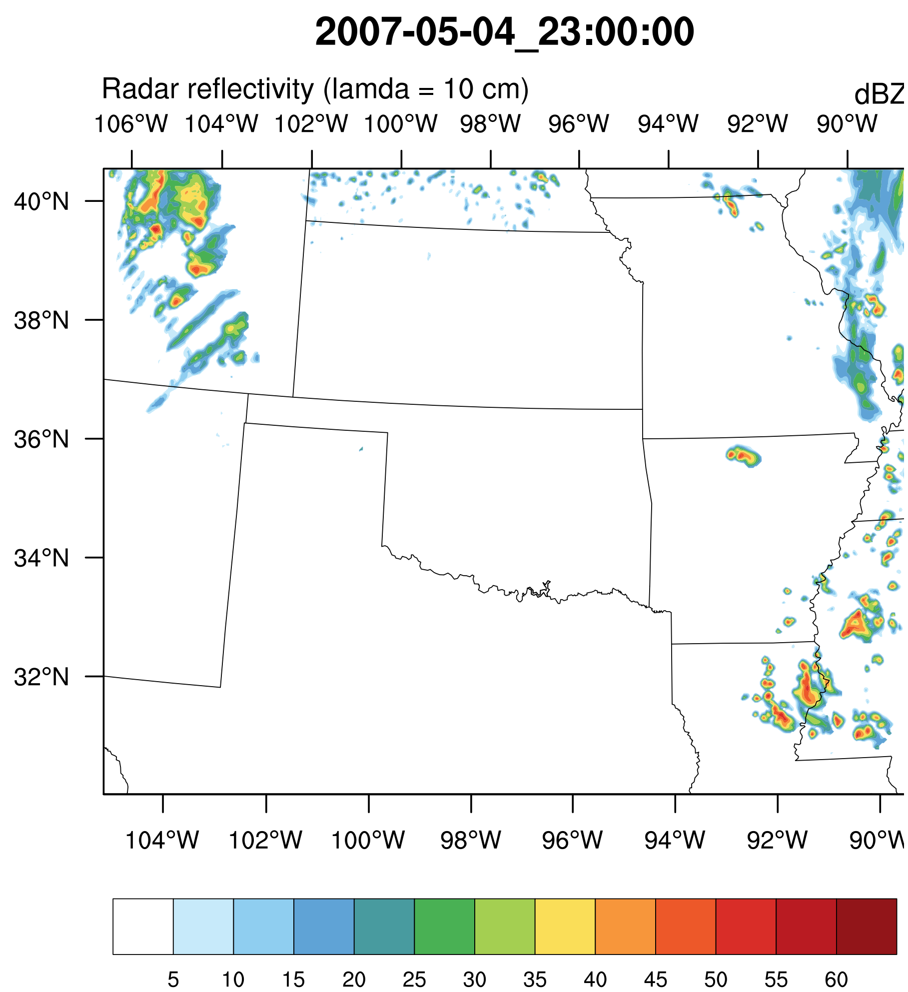
GFDL PGW

S06



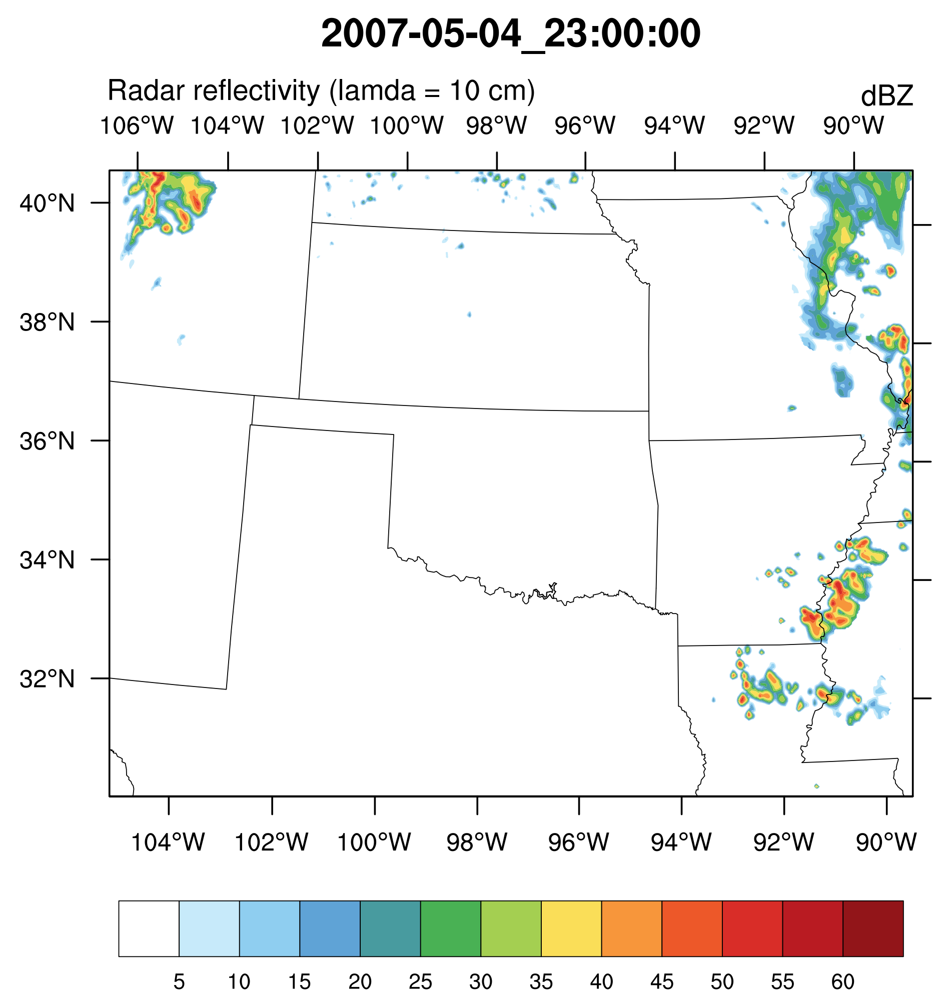
Control

radar reflectivity



GFDL-PGW

radar reflectivity



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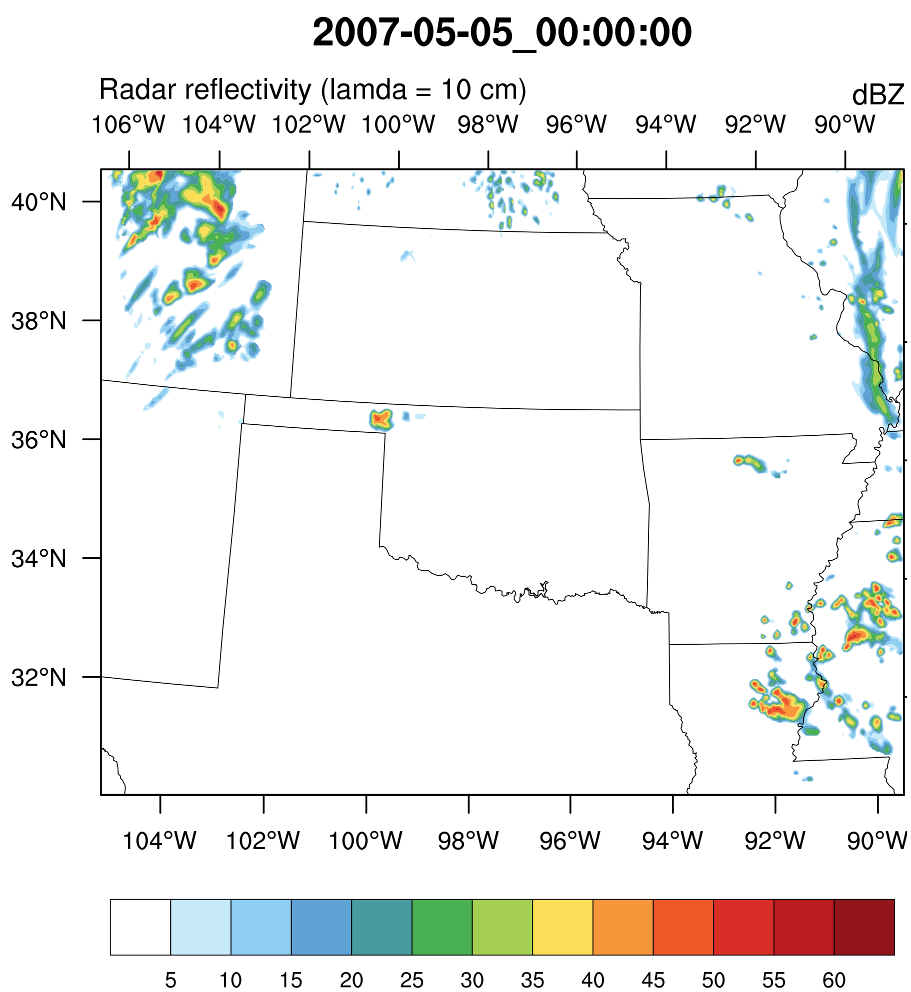
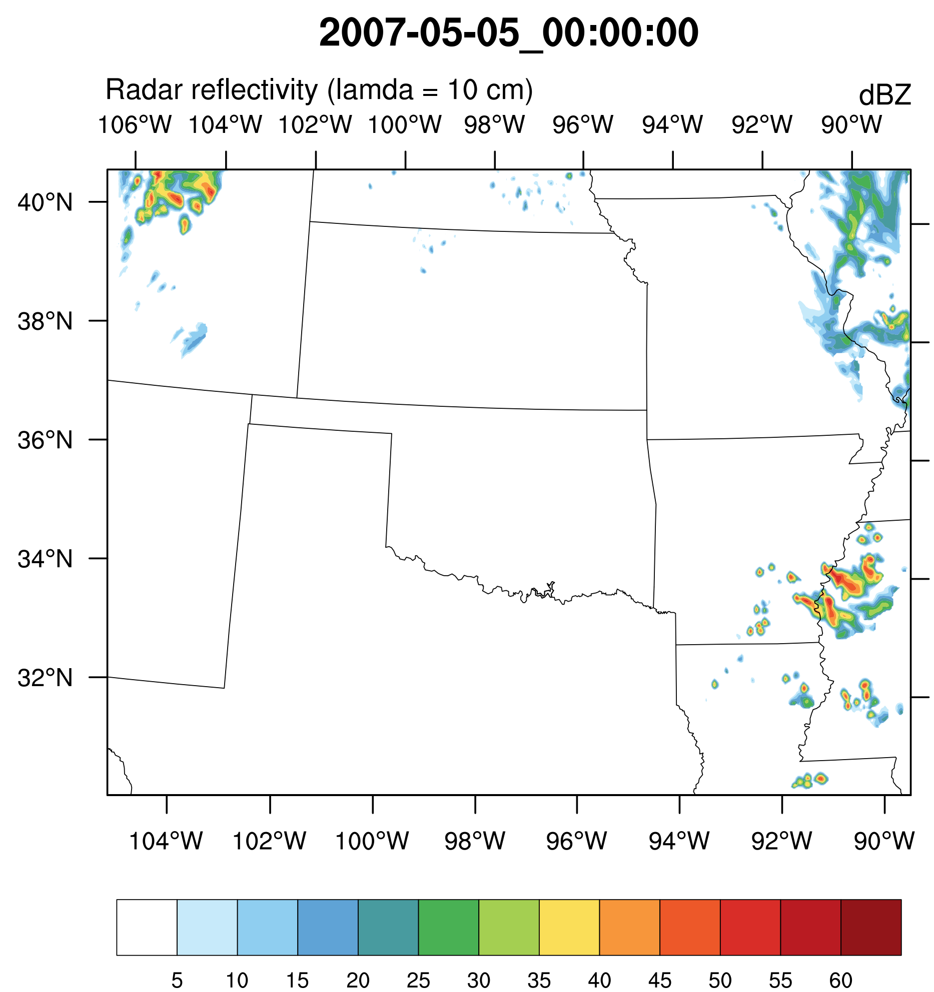
radar reflectivity



GFDL-PGW
radar reflectivity



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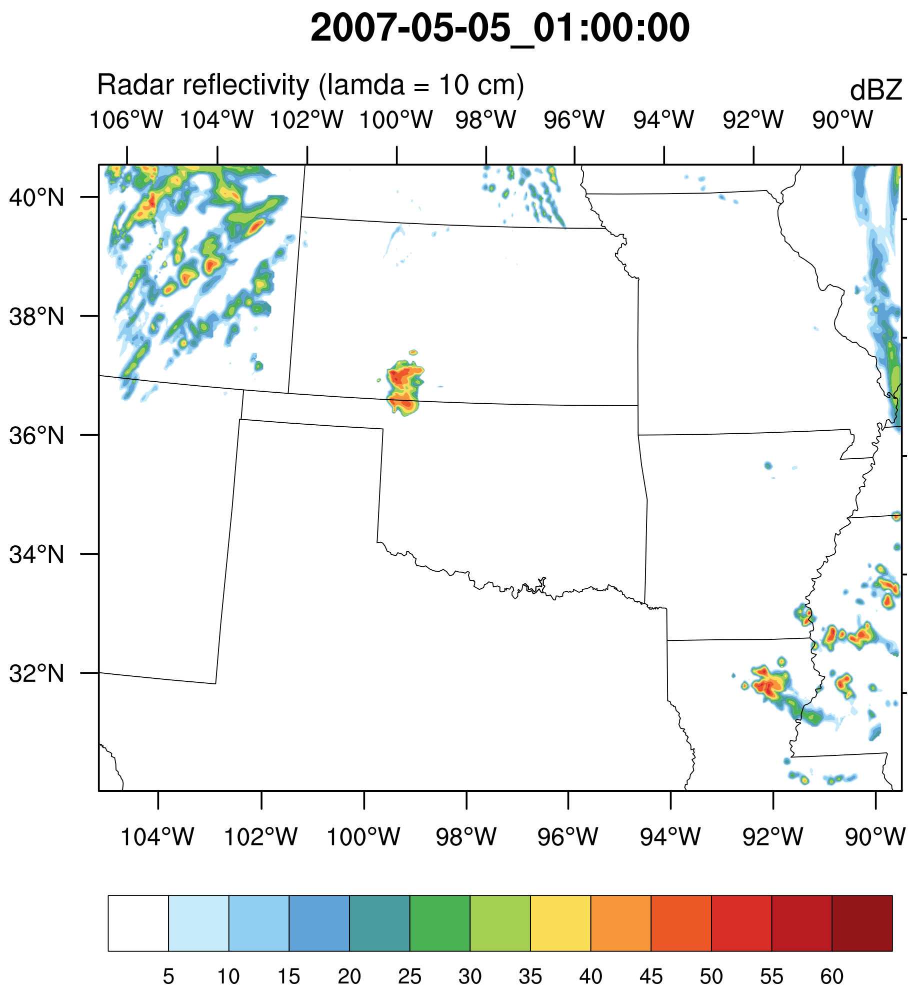

GFDL-PGW
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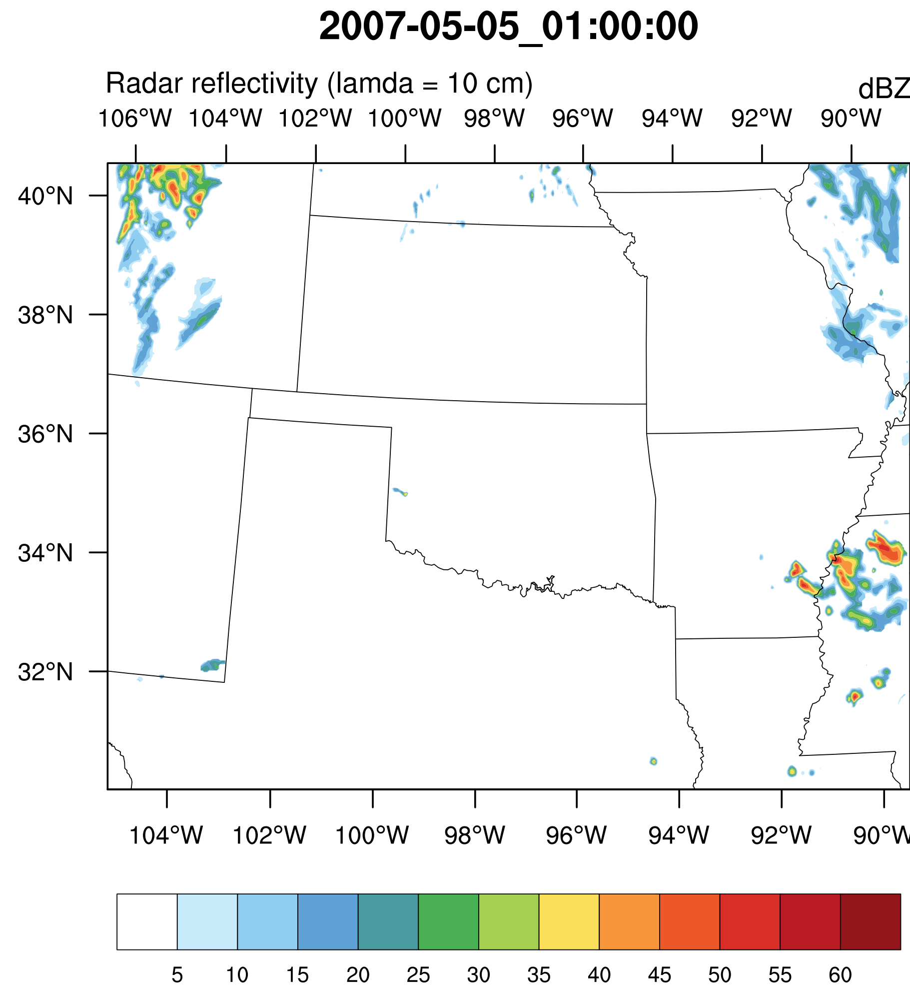

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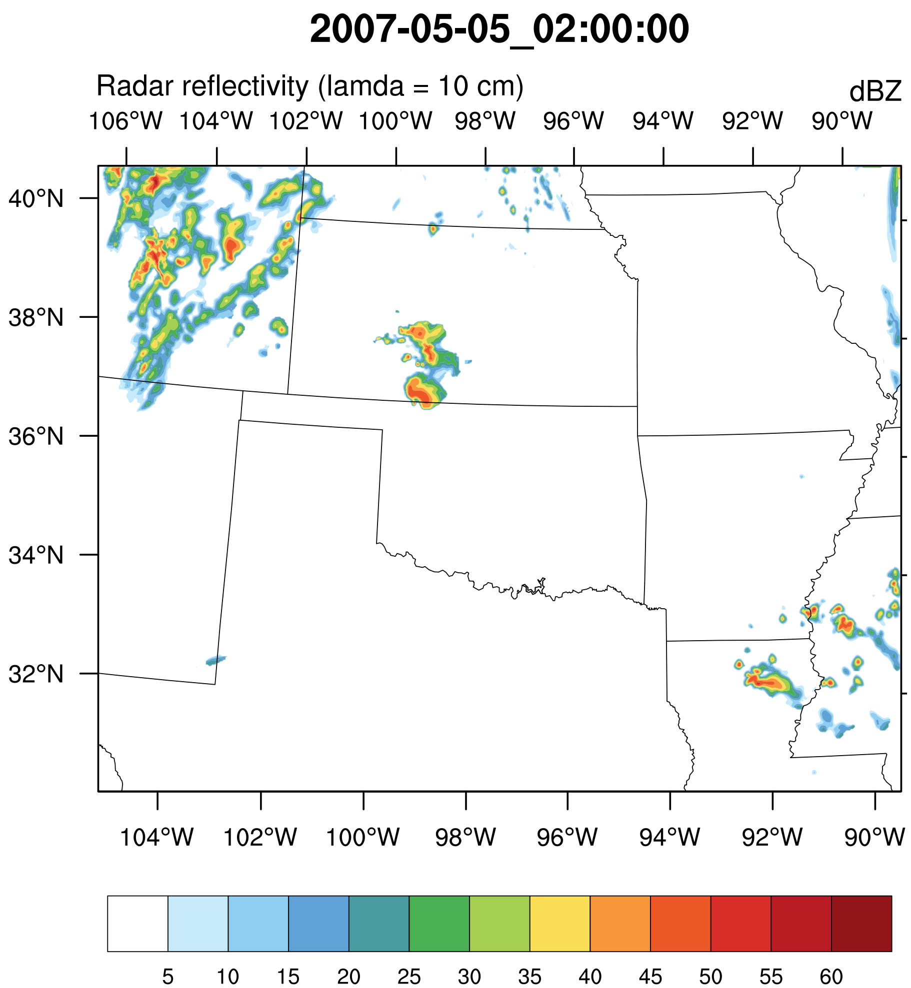
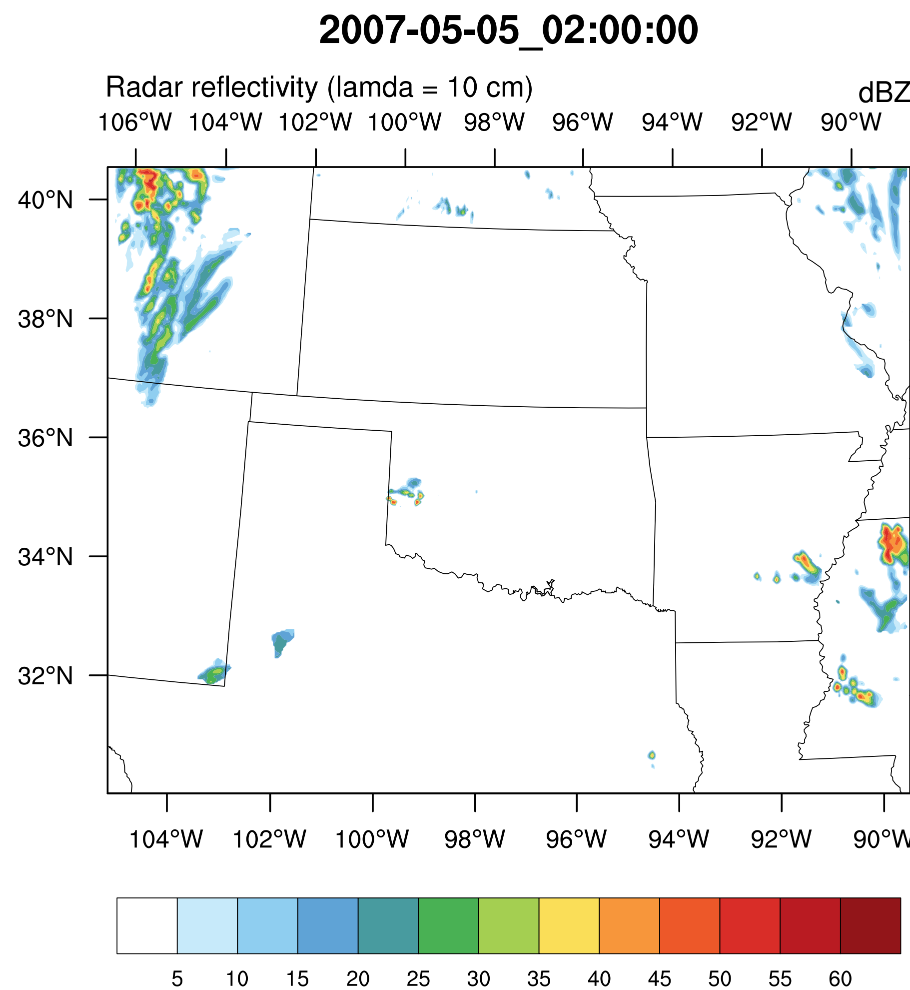
radar reflectivity



GFDL-PGW
radar reflectivity



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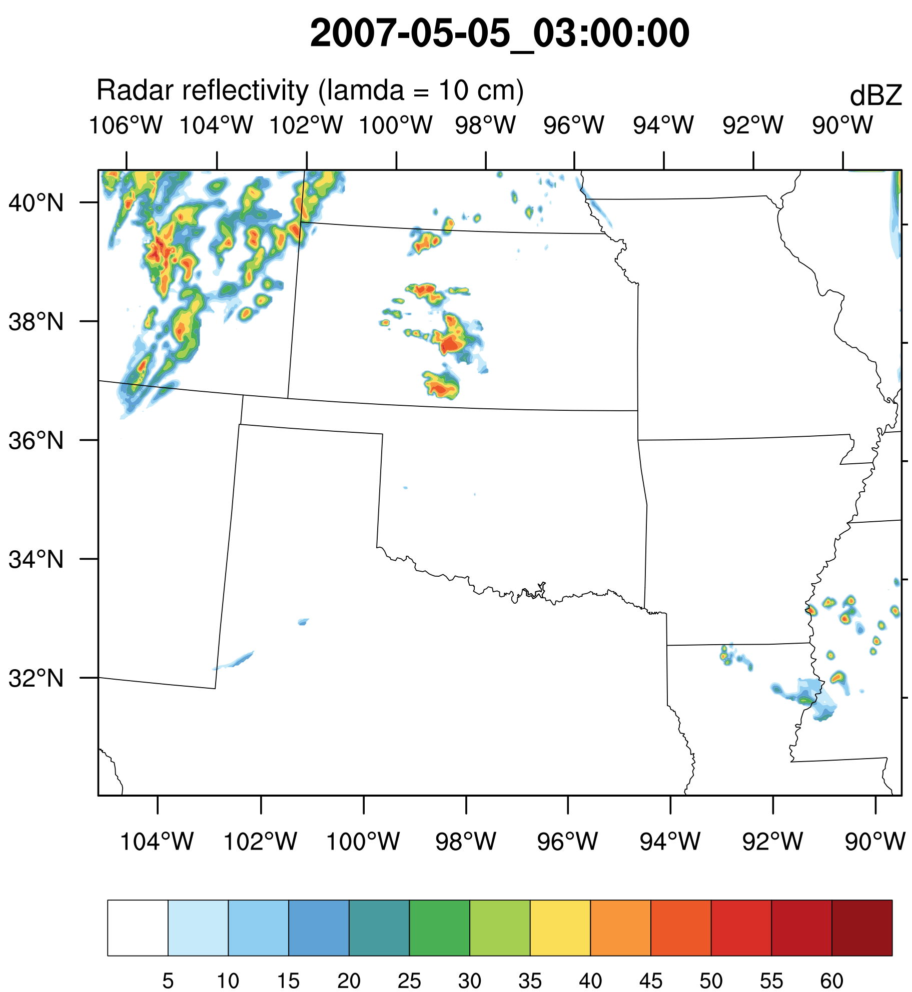
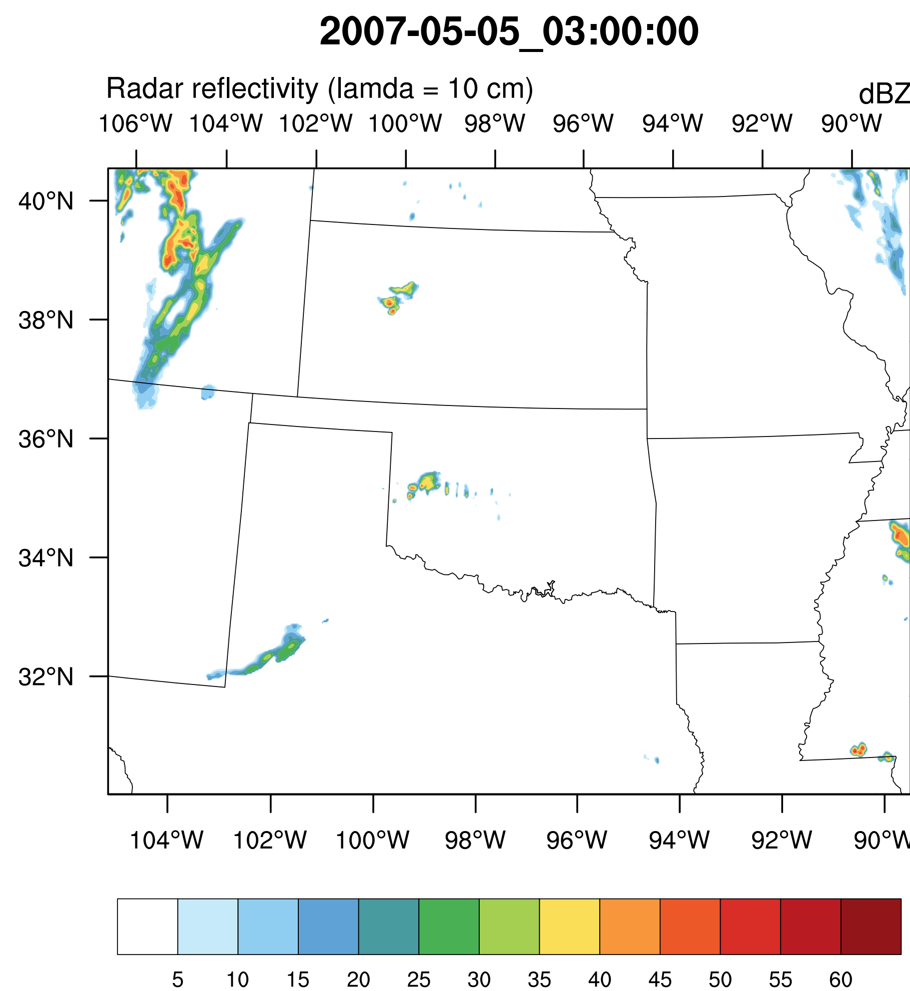
radar reflectivity



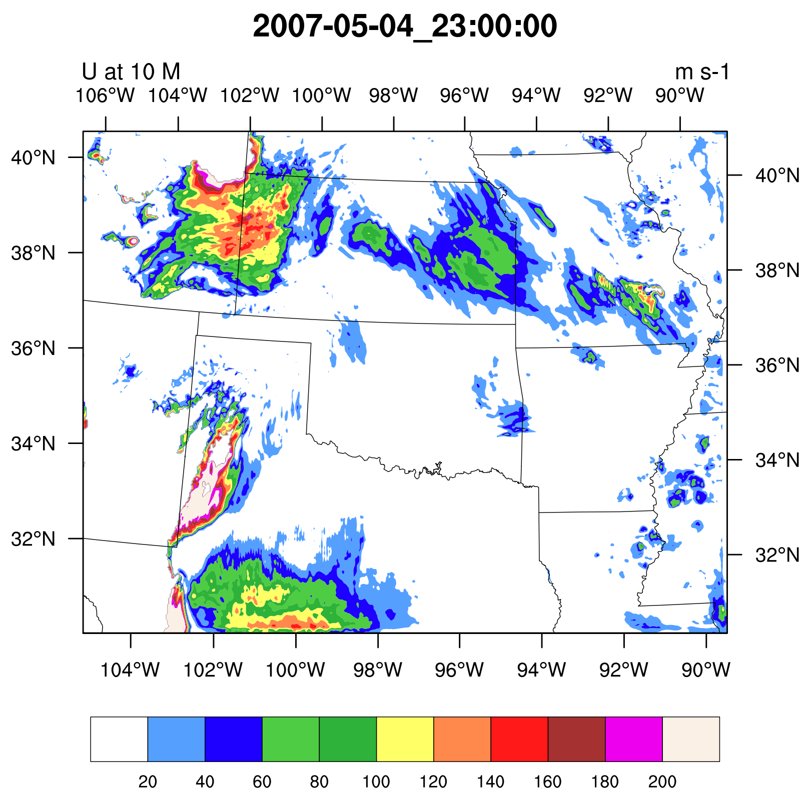
GFDL-PGW
radar reflectivity



Not accounted for was the effect of PGW on convective inhibition (CIN; J/kg)…

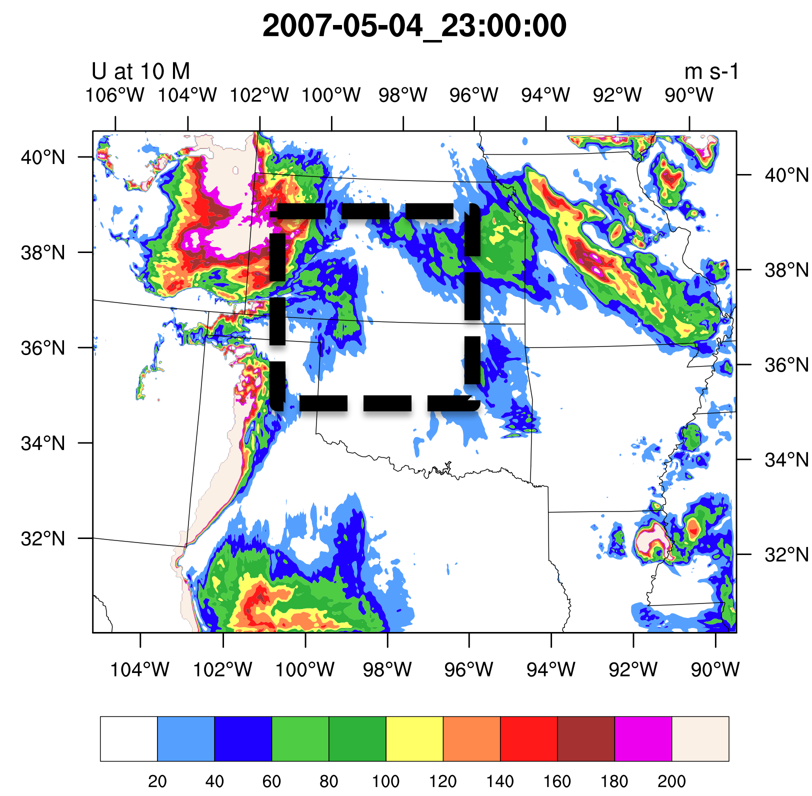
CTRL

CIN

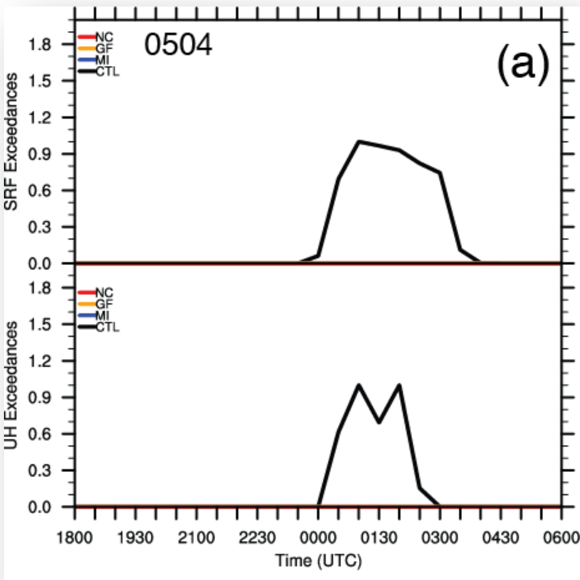


GFDL PGW

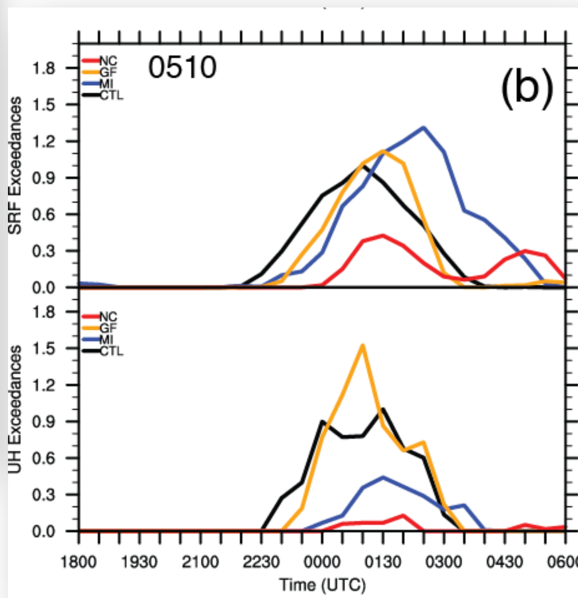
CIN

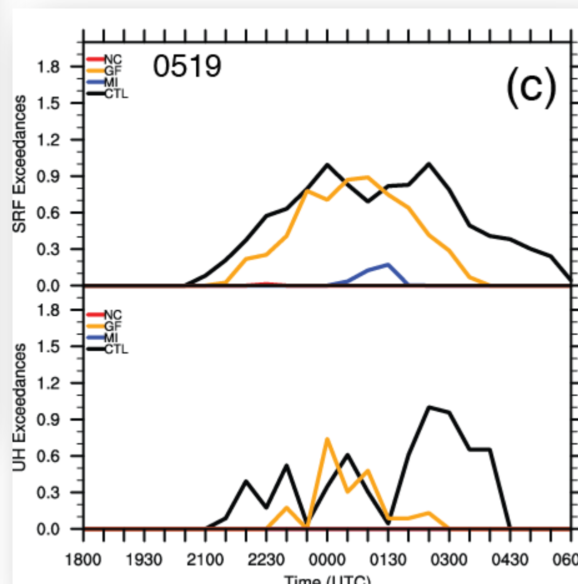


Confirmation of supercelullar mode in PGW runs using time series of UH (>150 m^2/s^2) and reflectivity (>40 dBZ) counts



none of the 0504 PGW runs initiated significant deep convective storms!





Trapp and Hoogewind (2016, *J. Climate*)

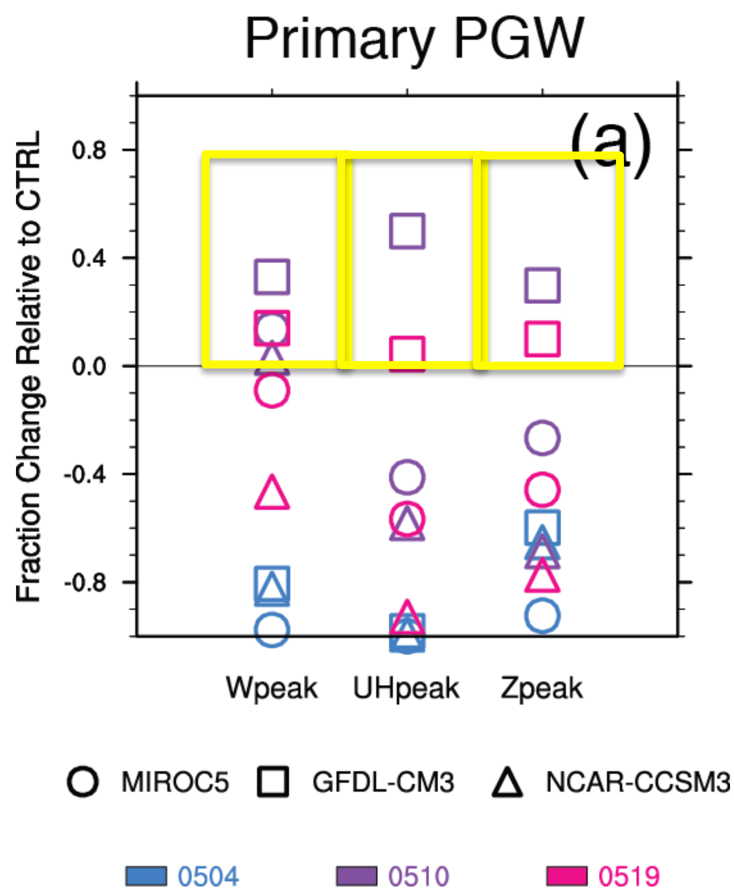
Summary of peak values in PGW runs:

updraft helicity (UH), vertical velocity (W), vertical vorticity (Z)

3 of the 4 PGW runs with supercells had more intense updrafts than CTRL

The GFDL-PGW runs were most likely to have more intense updrafts, with stronger rotation

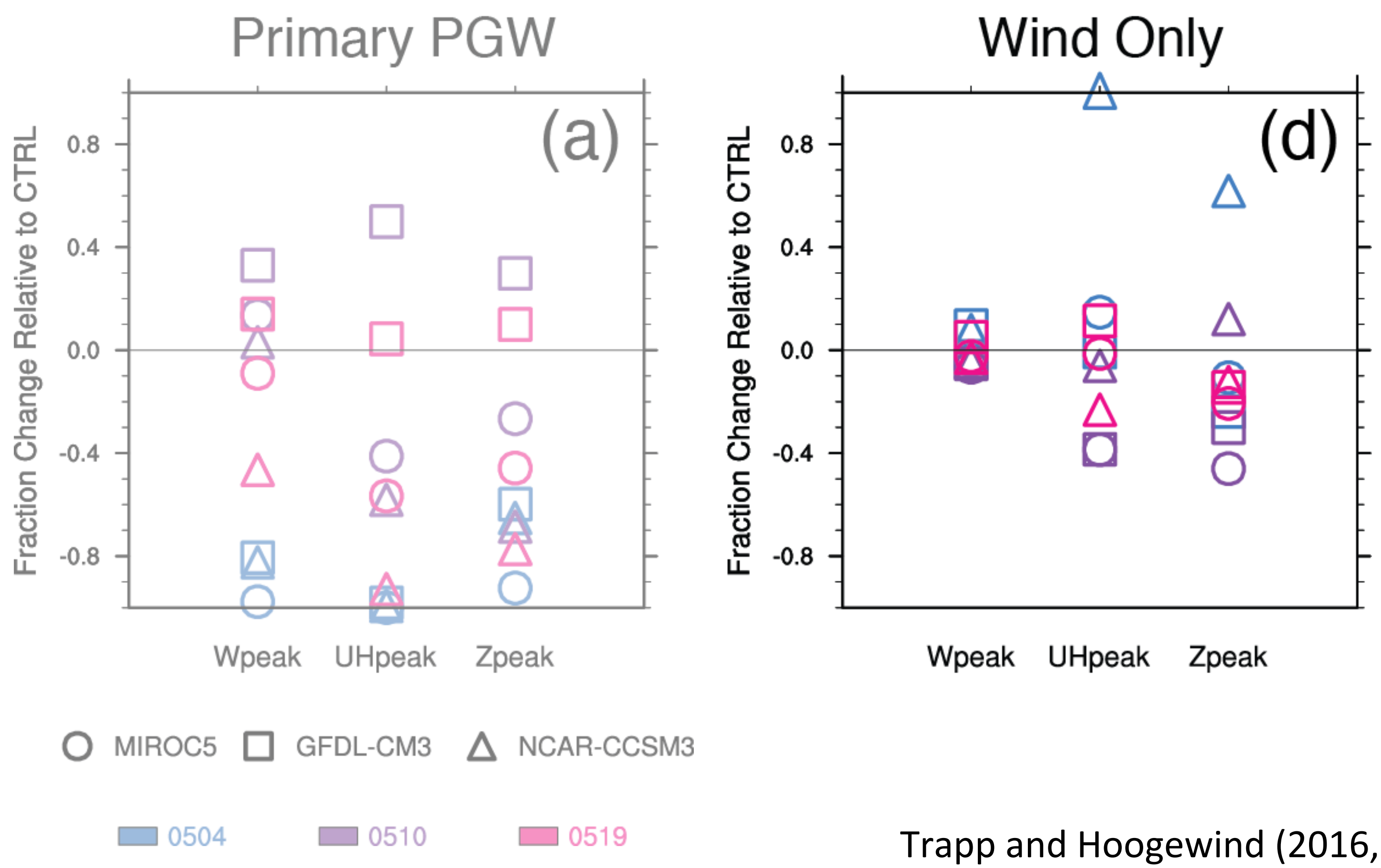
One of the possible outcomes of PGW is a more intensely rotating (tornadic?) storm!



Trapp and Hoogewind (2016, *J. Climate*)

PGW experimentation: Wind-only deltas

By withholding the thermodynamic Δ's, we deduce that such Δ's had the largest impact on the tendency for storms to develop, and generally the largest impact on storm intensity

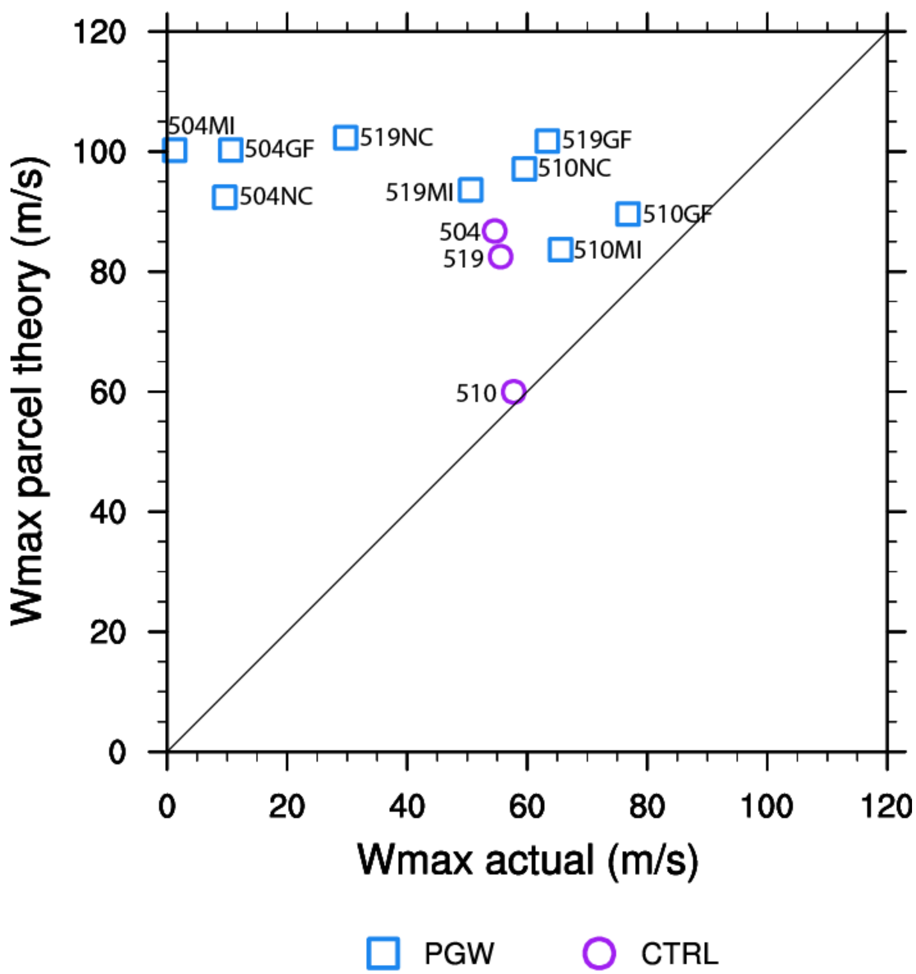


Trapp and Hoogewind (2016, *J. Climate*)

<u>A note on storm intensity</u>: If supercellular convection was generated under PGW, it was associated with strong updrafts, but these updrafts tended to *realize relatively less parcel buoyancy* than those of CTRL

From parcel theory:

$$w_{max} = (2 \text{x} CAPE)^{1/2}$$



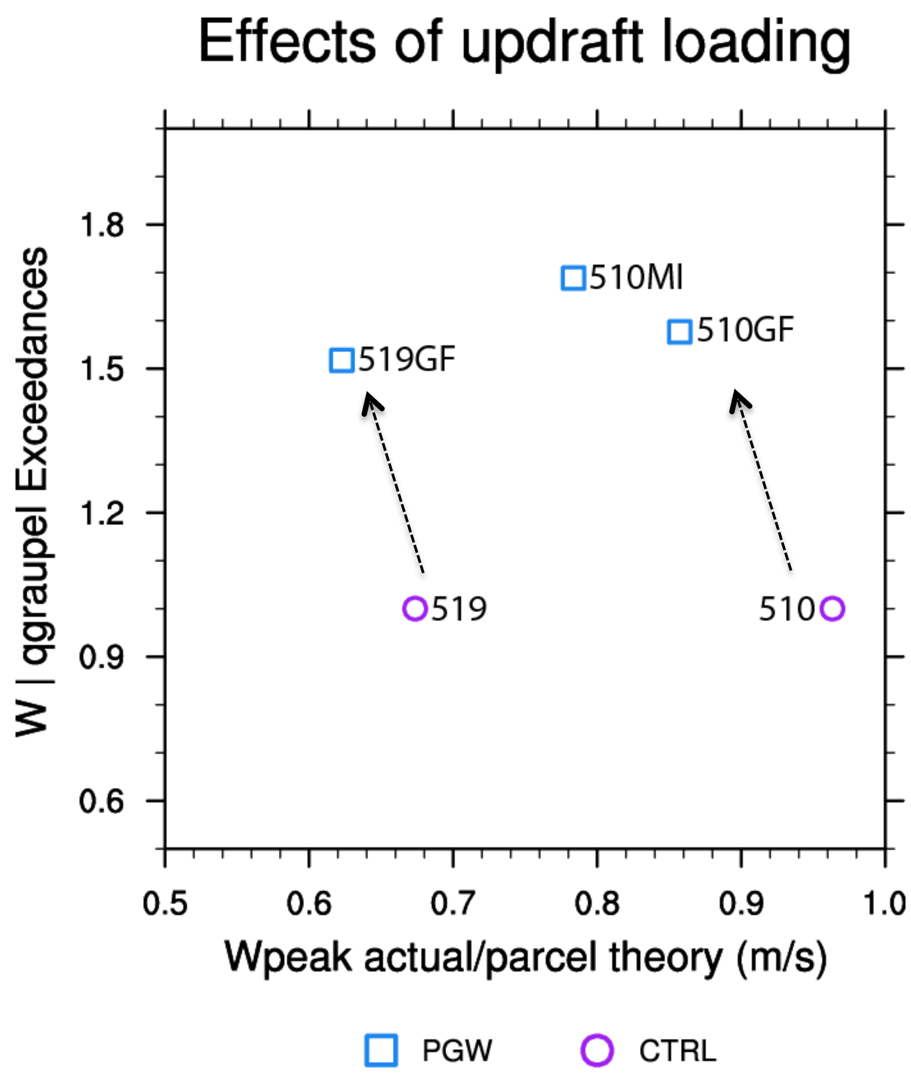
A hypothesis: **the overall moister future environment resulted in more condensate/precipitation within the updrafts, leading to a reduction in buoyancy through increased "precipitation" or "updraft" loading, as represented through:**

$$\frac{dw}{dt} \sim B$$

where *B* is buoyancy, approximated by:

$$B \sim g\left(\frac{\theta_v'}{\overline{\theta}_v} - \underbrace{q_c - q_i - q_r - q_s - q_g}\right)$$

and the *q*'s are condensate mixing ratios. Let's consider the effect of graupel (q_g)...



Relatively <u>more</u> graupel in PGW updrafts

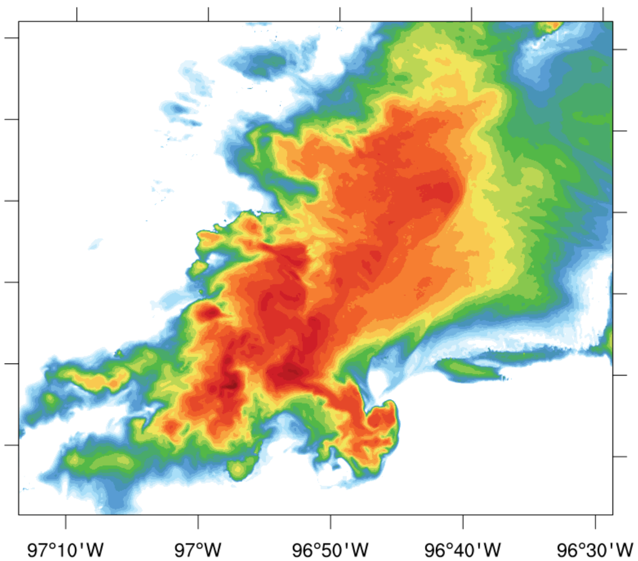
Loading proxy: Exceedances of *w* > 25 m/s and q_g >.005 kg/kg at *z* = 5 km

(PGW experiments normalized by CTRL value)

What about tornado intensity under PGW?

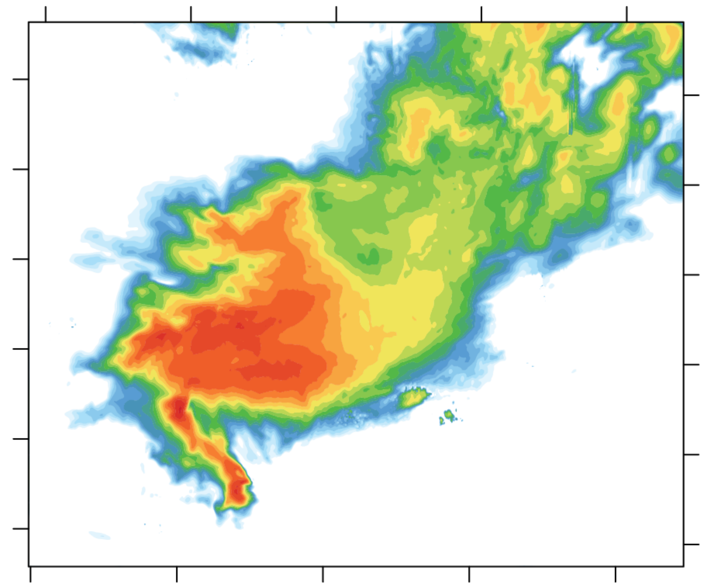
The suggestion based on peak vertical vorticity (and updraft helicity) is the possibility of stronger tornadoes in some of the experiments. Two simulations performed with 111-m grid spacings support this.

Control



$\varsigma_{max} = 0.35\ s^{-1}$

GFDL-PGW



$\varsigma_{max} = 0.38\ s^{-1}$

Let's end with some answers:

- ***Will the supercells of yesterday and today be the squall lines of tomorrow?***
  - For this limited sample, the answer is no. In these significant events, the reduction of vertical wind shear (in two of the CMIP5 members) was insufficient to cause a change in the convective mode.
  - However, for other events at the margins, a mode change is possible.

Let's end with some answers:

- ***Will the supercells of yesterday and today be more intense in the tomorrow?***
  - The answer depends on whether the supercell storm can even form. But if they can, they will generally have stronger updrafts. The strength will not, however, be in proportion to the projected higher levels of CAPE under PGW.

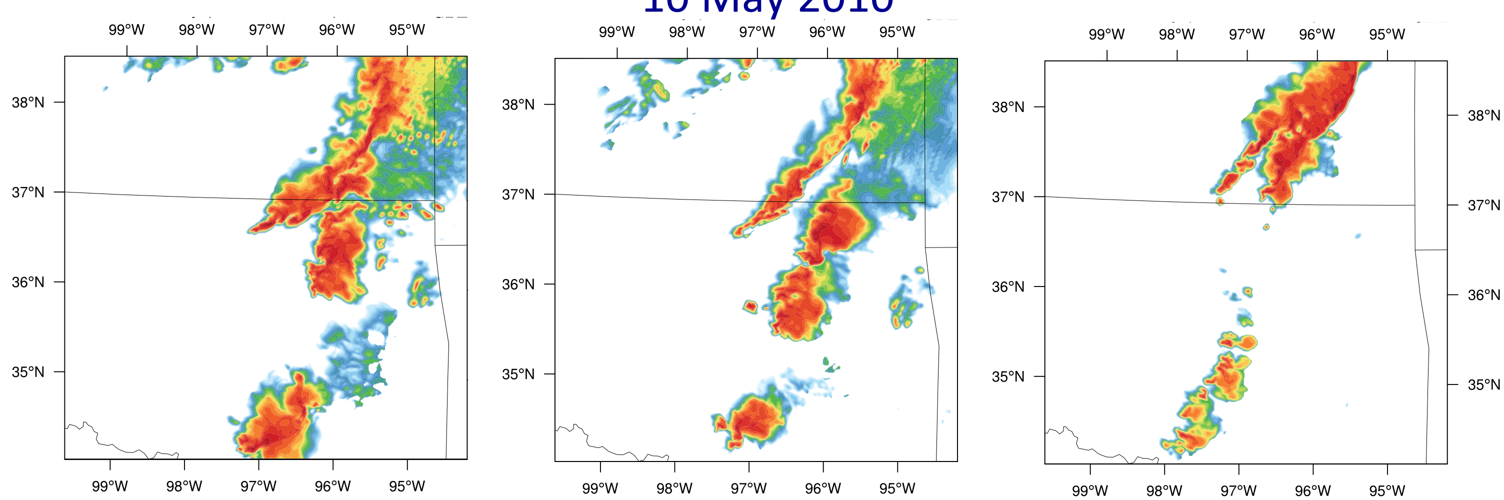
Let's end with some answers:

- ***Will the tornadoes of yesterday and today be more intense in the future?***
  - The answer depends on whether the tornadic storm can even form. But if they can, these experiments suggest that higher future intensity is possible, but it's certainly not a robust result: only 2 of the 9 primary PGW simulations resulted in higher vertical vorticity (stronger rotation).

Let’s end with some answers:

- ***Were the (tornadic) supercells of yesterday and today caused by climate change?***
  - For this oft-asked question, the answer is that we now have a methodology for such attribution work!

10 May 2010



Control+[1890-1990] Control Control+[2090-1990]

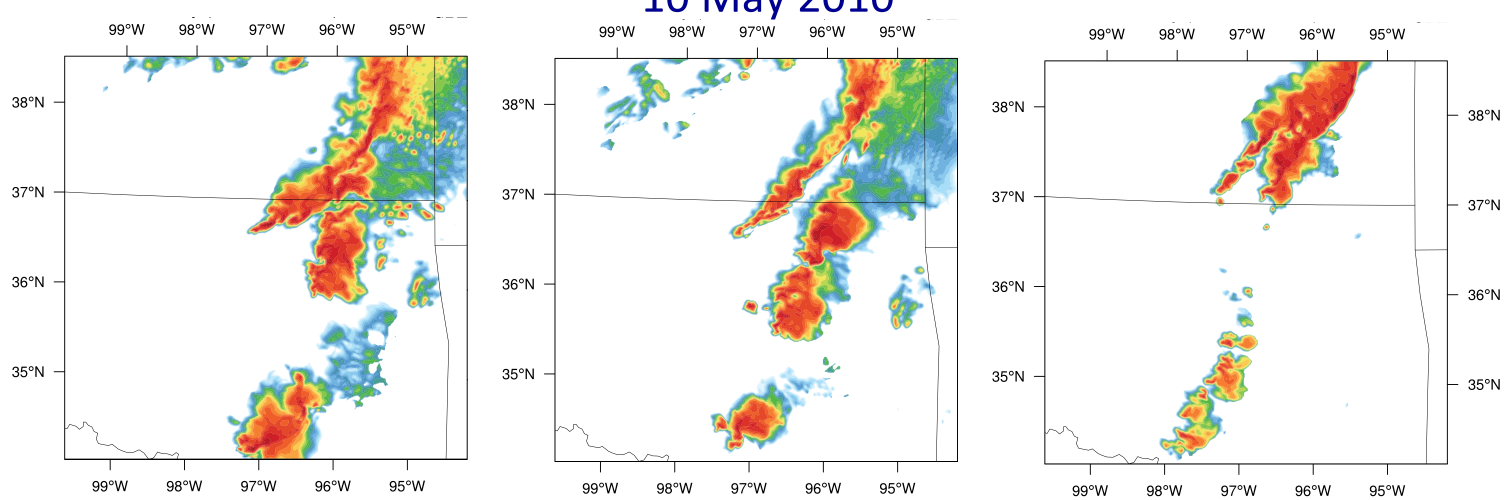
Future direction: Attribution

- The only change to the procedure is the calculation of the Δ's, e.g.,

$$\Delta T = \overline{T(x,y,z)}_{C19th} - \overline{T(x,y,z)}_{C20th}$$

where both the 19th and 20th Century information are from historical runs of GCMs

10 May 2010

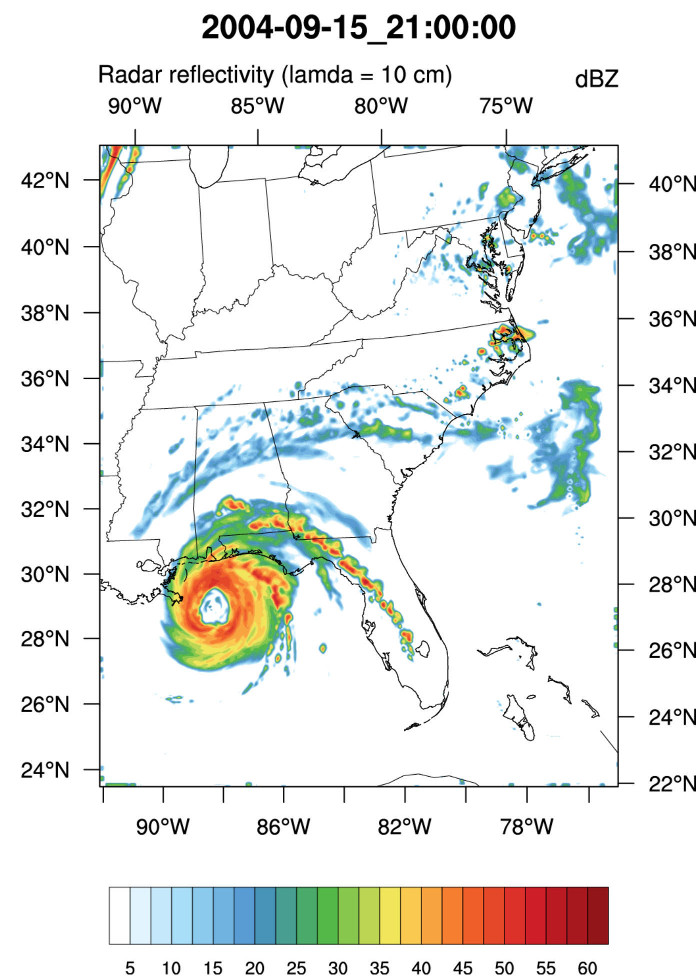


Courtesy: Geoff Marion

Control+[1890-1990] Control Control+[2090-1990]

Future direction: Tropical-cyclone induced tornadoes

- Specific question here is whether a prolific tornado-generator like Hurricane Ivan (2004) will become even more hazardous in a future climate



Courtesy: Dereka Carroll-Smith

Questions?

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