The use of Convection-Allowing Models for Severe Weather Forecasting

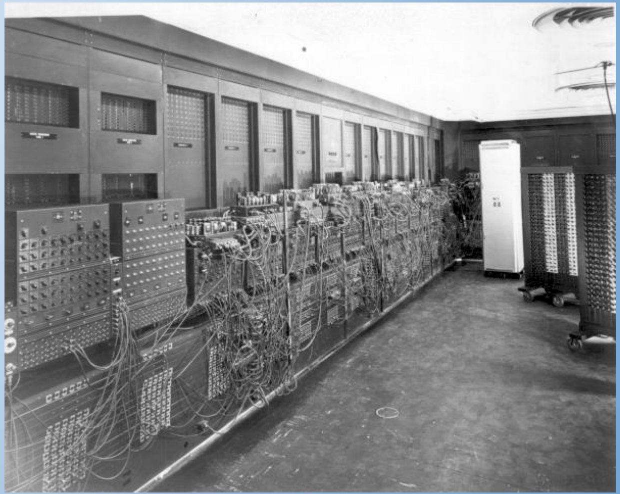
What is Convection-Allowing Model (CAM)?

- CAM means NWP models running at 1-4 km grid spacings so that convection is allowed to explicitly develop and evolve in the model, rather than relying on cumulus parameterization.
- If convective storms are adequately resolved, the model can be called convection-resolving – believed to require sub-km grid spacings.
- If CAM model can accurately predict the initiation and later evolution of convective storms, we will need to rely less on subjective projection based on environmental conditions.

History of Numerical Weather Prediction (NWP)

- NWP began in the 1920s through the efforts of Lewis Richardson, a British scientist, who produced a six-hour forecast by hand for the atmosphere over two points in central Europe, taking at least six weeks to do so, but the forecast was a failure because it was unknown that small enough time step size had to be used to ensure stable time integration.

- NWP wasn't practical until electronic computers were invented that made numerical integration faster than the weather evolution.
- First useful NWP was made in 1950 on ENIAC using a 2D barotropic vorticity equation – can capture large scale Rossby waves
- Operational NWP started in the U.S. in 1955



1st electronic computer ENIAC

History of Numerical Weather Prediction (NWP)

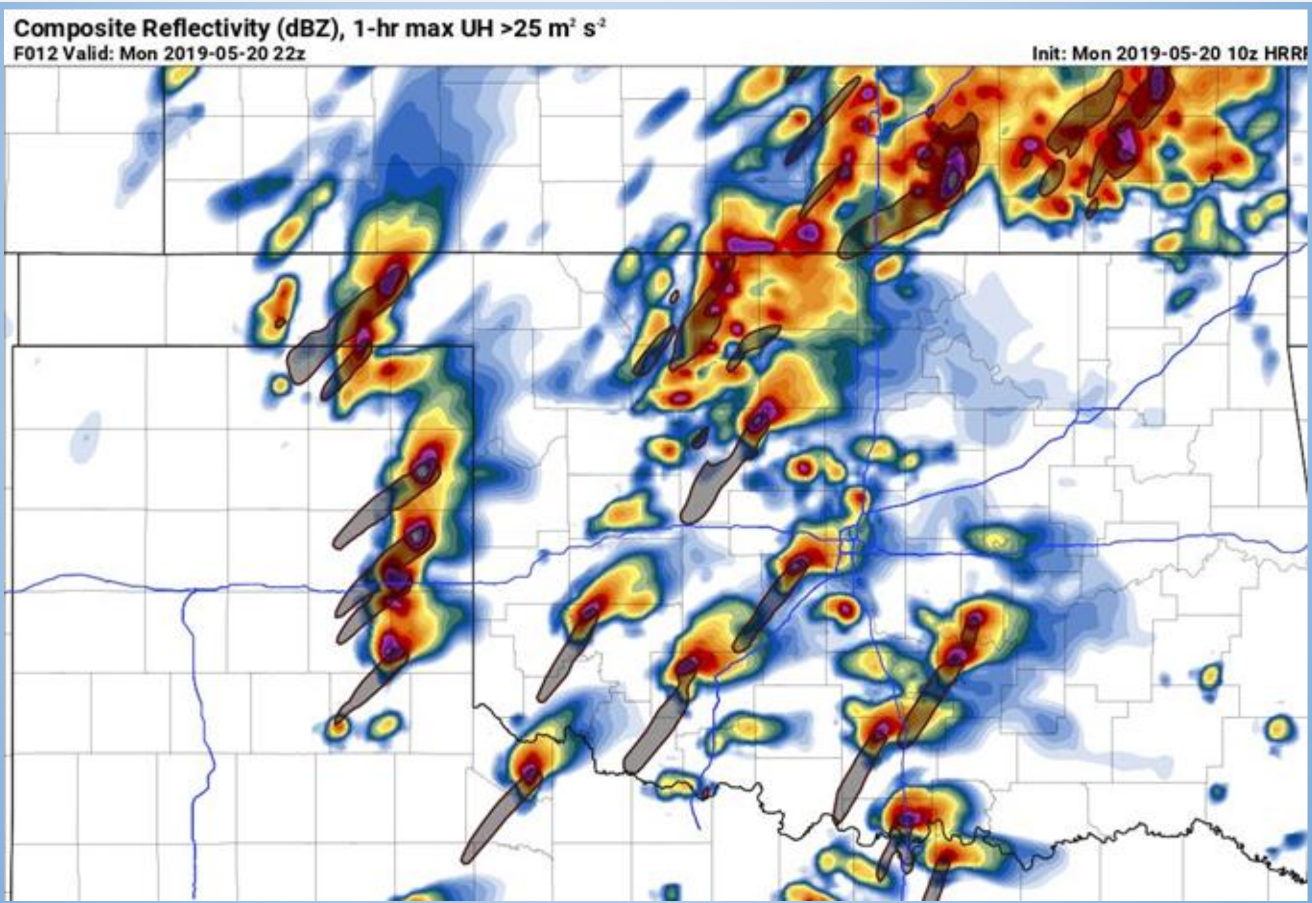
- Earlier NWP models all made the hydrostatic assumptions, with horizontal grid spacings of tens to hundreds of kilometers.
- Vertical velocity is diagnosed, not predicted by vertical momentum equation.
- The horizontal grid spacings of hydrostatic models are too coarse to explicitly revolve/present convective storms. Convection is parameterized with cumulus schemes and only the bulk effects (latent heating, removal of instability, precipitation falling to ground) of convection is modeled.
- To explicitly represent/resolve convection, grid spacings of few km are needed, and vertical velocity (which is directly responsible for convection) should be directly predicted.
- Idealized three-dimensional thunderstorm simulations started in mid-1970's.
    - A lot was learned on supercell storm and squall line dynamics
- Numerical prediction of thunderstorms did not begin until early 1990's.

History of Numerical Weather Prediction (NWP)

- Actually, the Center for Analysis and Prediction of Storms (CAPS) of OU was established as an NSF Science and Technology Center to tackle the exact problem of numerical prediction of thunderstorms.
- “Lilly, D. K., 1990: Numerical prediction of thunderstorms - Has its time come? QJRMS” discusses the vision of convective-scale NWP.
  - Operational WSR-88D radar network, advent of massively parallel supercomputers, advanced data assimilation methods such as 4DVar, development of non-hydrostatic models made it possible.
- Nonhydrostatic mesoscale models they were widely used for research and operational forecasting:
  - Reginal Atmospheric Modeling System (RAMS) of CSU
  - Advanced Regional Prediction System (ARPS) of OU
  - Mesoscale Model version 5 (MM5) of Penn-State/NCAR
  - Weather Research and Forecasting (WRF) model with 2 dynamic cores developed by NCAR and EMC/NCEP
- The two dynamic cores of WRF have been used for regional operational forecasting at NCEP (WRF-ARW for RAP and HRRR, WRF-NMM/NMMB for NAM and NAM hi-res windows, and for hurricane forecasting)
- The next version of regional model, Rapid Refresh Forecasting System (RRFS) will use the FV3 dynamics core, that is already used by GFS.

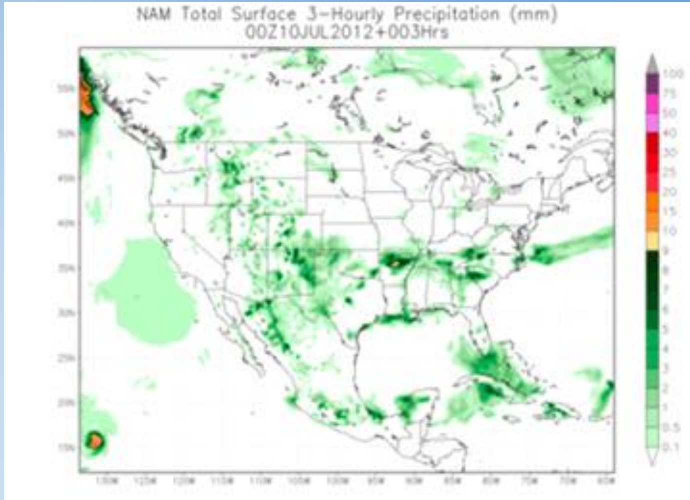
CAMS –Convection-Allowing Models

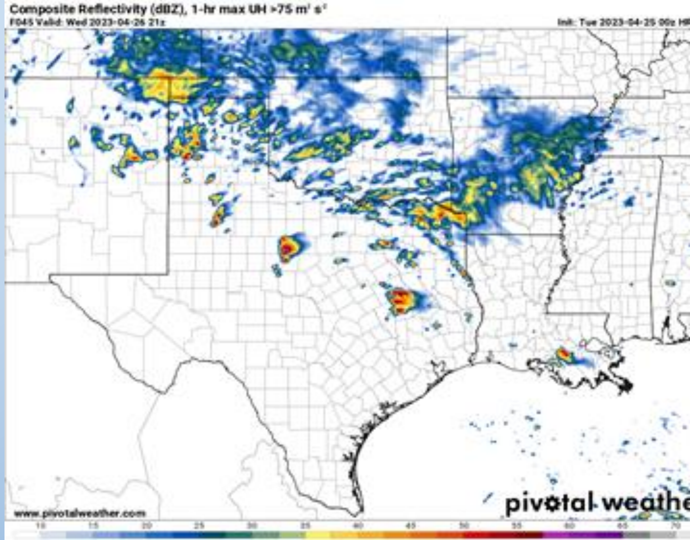
Forecast Applications and their Consequences



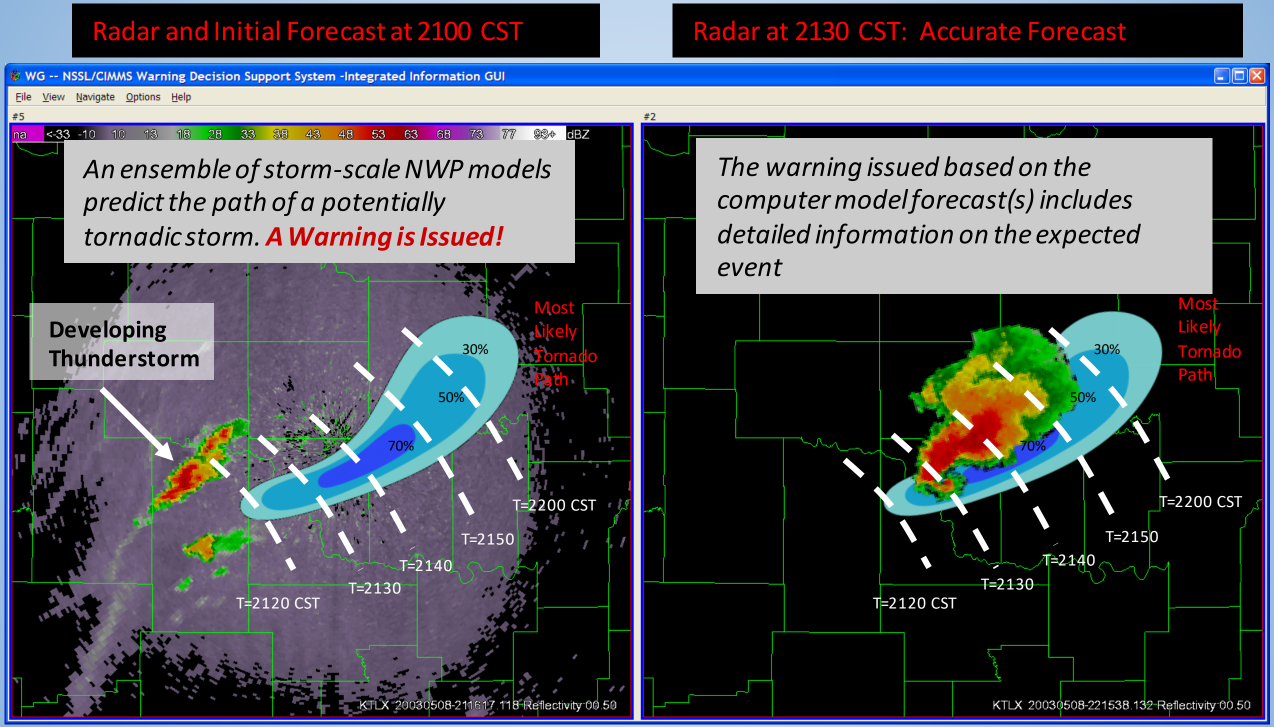
History and background:

- Convection-Allowing or Convection-Permitting Models (CAMS) are high-res NWP models capable of explicitly representing convective scale processes.
  - Small horizontal and vertical grid spacing (1-4 km)
    - Event higher-resolutions qualify as convection-resolving
  - Captures fast evolution of storms.
  - Need to assimilate convective-scale observations
  - CAPS started realtime testing at ~3 km grids in mid-1990's
- First CONUS-scale Experimental CAM (3-4km) forecasts in early 2000s
  - OU CAPS
  - NSSL
  - NCAR
- Operational Models started in the mid 2000s HRRR, NAM Hi-Res windows.
- Still under active research in CAM forecasts, including model improvement, DA and ensemble forecasting.





Vision: Warn-on-Forecast

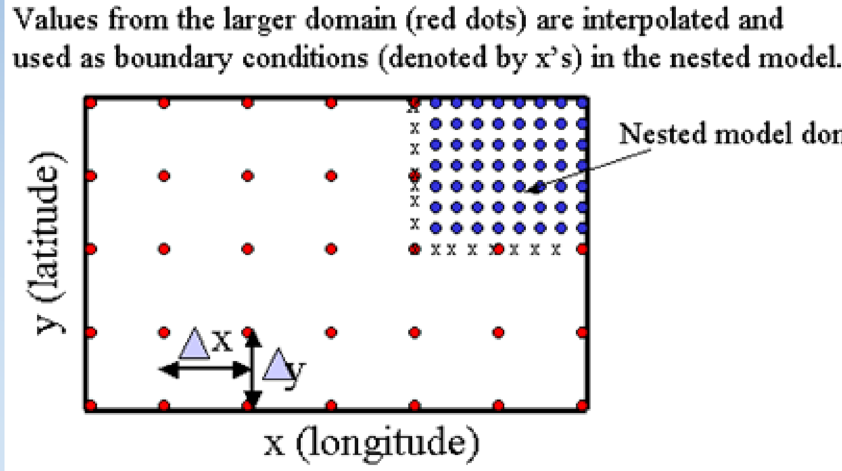


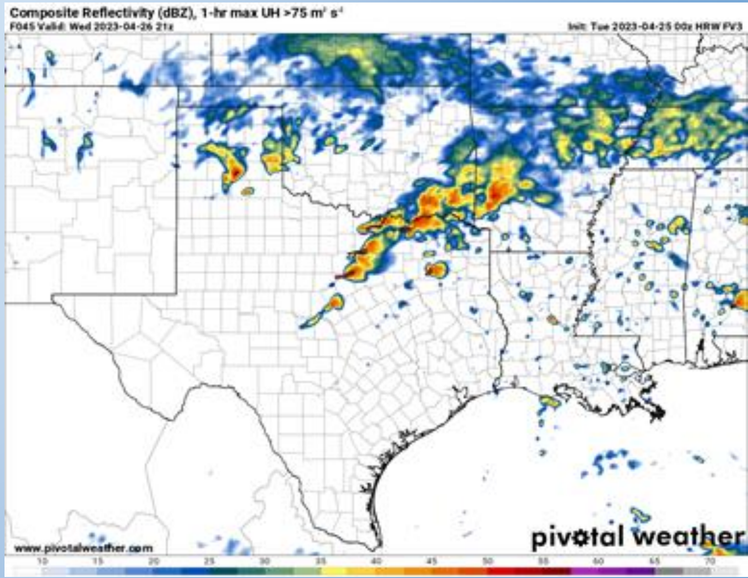
- **More than triple current Tornado Warning lead times**
- **Improved warnings allow enhanced community response**

(Stensrud, Xue and others 2009)

How CAMS Work

- Small Horizontal and Vertical Grid Spacing. Lots of computer power.
- Initial conditions obtained by assimilating high-resolution observations and sometimes radar data frequently, for HRRR at hourly intervals.
- The lateral boundary conditions come from global model forecasts or from a larger-domain regional forecasts (e.g., HRRR from RAP)
- Models are integrated with sub-minute time steps (sometimes a few seconds)
- Output are typically produced at hourly or shorter intervals.
- Special forecast products such as hourly max updraft helicity (UH) fields and radar reflectivity are produced within model or in postprocessing step.
- Common CAM outputs include:
  - Simulated Reflectivity
  - Updraft helicity (UH) – w * vertical vorticity integrated over a depth
  - Precip/Snow accumulation
  - STP, Helicity, low-level vorticity/rotation





Updraft Helicity (UH)

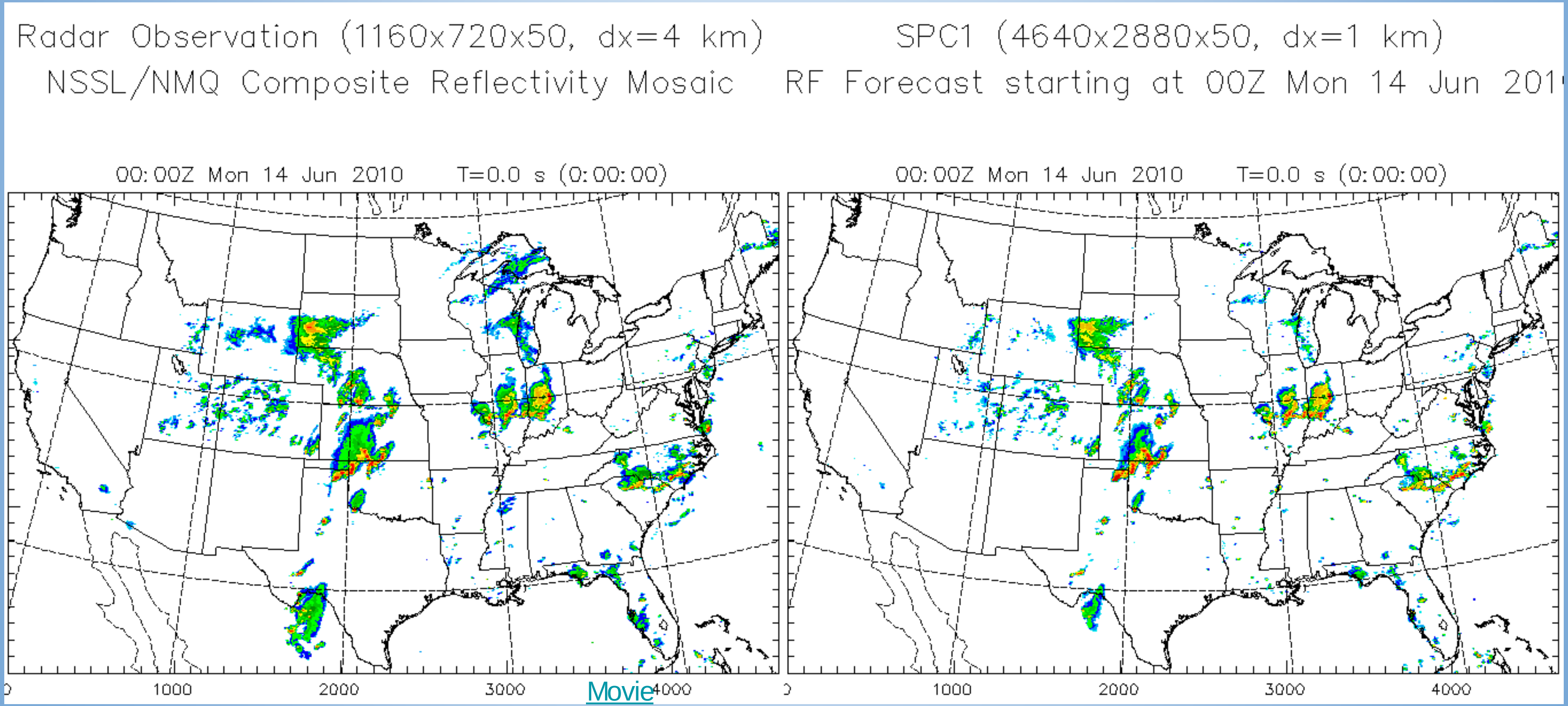
$$UH = \int_{z_b}^{z_t} w\zeta dz$$

- For mid-level UH, used 1-6 km depth
- For low-level UH, used 0-2 km depth
- Look for positive values of UH, mid-level UH maximum accompanied by a low-level UH max

- UH tracks have been shown to be one of the best forecast products/indicators for severe weather including tornado and hail

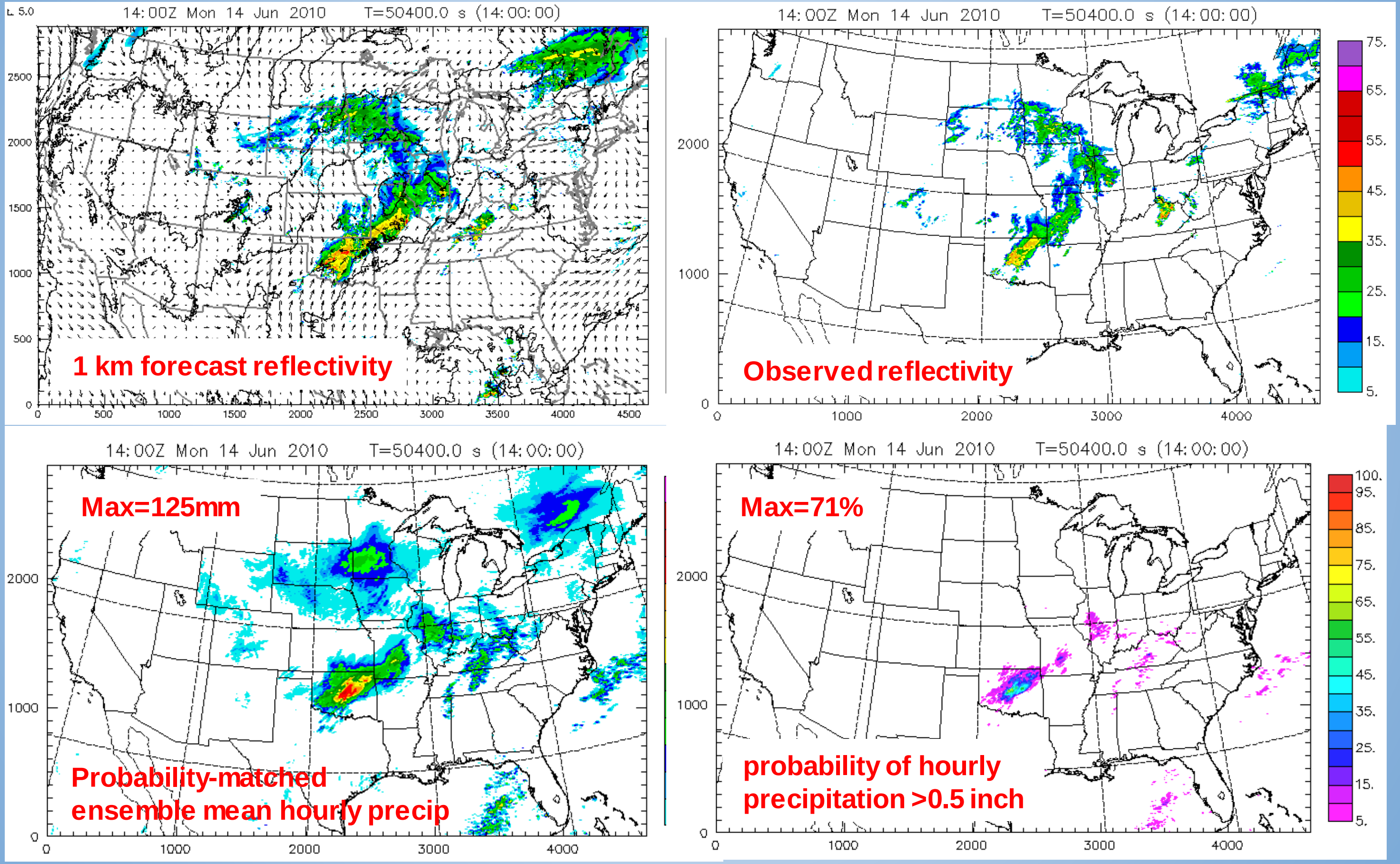
June 14, 2010 – Oklahoma City Flooding Case

Radar reflectivity observation | 1 km CAPS realtime forecast using WRF



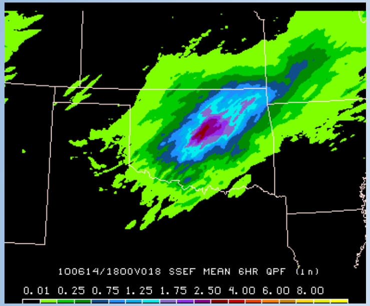
Movie

June 14, 2010 – OKC Flooding Case

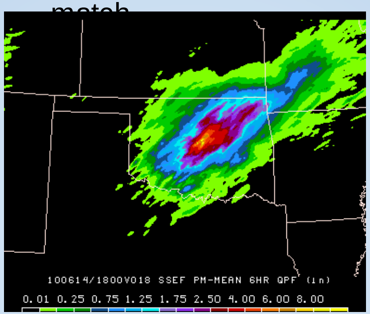


12–18Z accumulated precipitation: 18h (June 14, 2010 – OKC Flood Day)

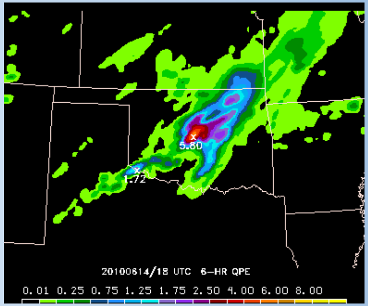
SSEF mean



CAPS SSEF Prob match

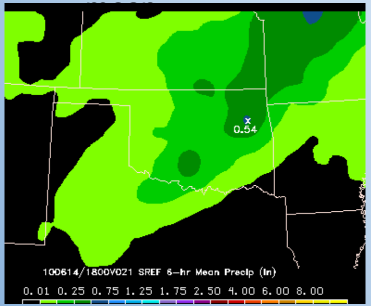


QPE

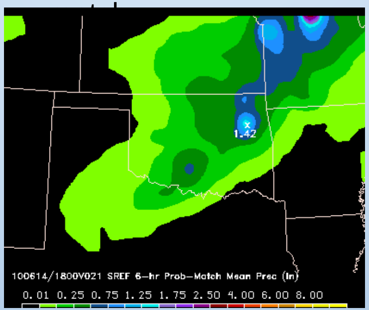


NWS Operational Fcsts

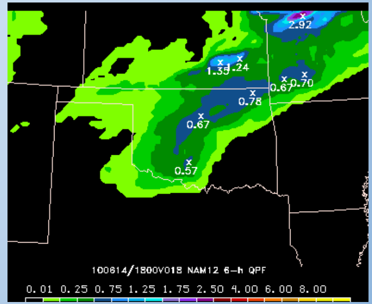
NCEP SREF mean



NCEP SREF Prob match



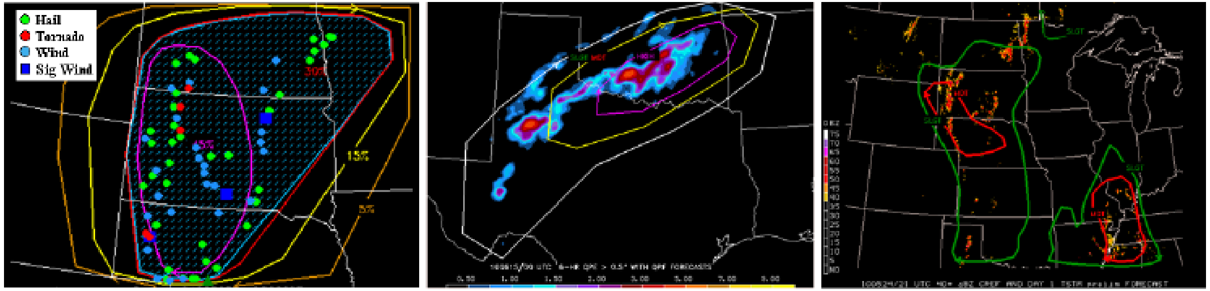
NCEP 12 NAM



Experimental Forecast Products Produced and Evaluated during HWT Spring Experiments

Probabilistic Forecasts for Severe, QPF (>0.5 inch/6h) and Aviation Weather (Z>40dBZ) and Verifying Weather

a) Severe component outlook | b) QPF component outlook | c) Aviation component outlook



PRELIM Severe Day-1 Forecast Valid: 24/2000 - 25/0000 UTC

QPF for 6-hr accumulated precipitation Valid: 0615/0000 UTC

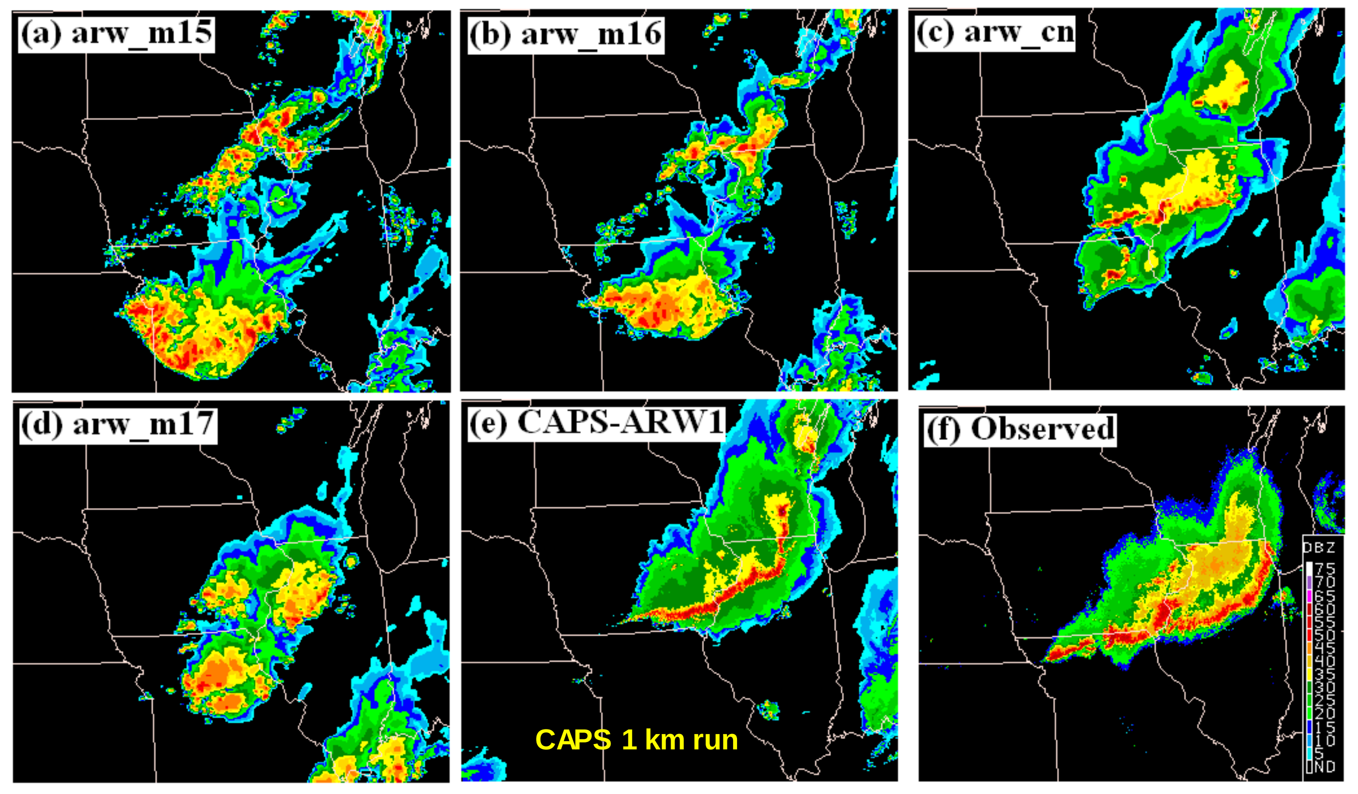
Aviation forecast for 40 dBZ reflectivity Valid: 0524/2100 UTC

d) Severe Component Discussion for 24 May 2010

THE HI-RES GUIDANCE INDICATED TWO CORRIDORS OF SEVERE WEATHER POTENTIAL...ONE ALONG THE EASTWARD SURGING COLD FRONT OVER THE CENTRAL HIGH PLAINS, AND THE SECOND ALONG THE WARM FRONT AND IN THE VICINITY OF THE LIFTING SURFACE LOW OVER THE NORTHERN PLAINS. THE STORMS ALIGN FAIRLY WELL WITH THE OBSERVED PLACEMENT OF SURFACE FEATURES. A SECOND AREA OF STORMS ALSO DEVELOPS IN HI-RES GUIDANCE OVER EASTERN SD/NEB. WE ARE UNCERTAIN WHETHER THESE STORMS WILL BE REAL FEATURES IN THE ATMOSPHERE GIVEN A LACK OF LOW-LEVEL FORCING...THOUGH AN UPPER DISTURBANCE OBSERVED IN WV IMAGERY WILL APPROACH THAT REGION AND COULD PROVIDE A FAVORABLE ZONE OF ASCENT FOR STORM INITIATION. REFLECTIVITY STRUCTURES NEAR AND EAST OF THE LIFTING SURFACE LOW OVER SD/ND SHOW POSSIBLE SUPERCELL STORM TYPES, WHICH IS CONFIRMED IN HOURLY MAX UPDRAFT HELICITY. THESE STRUCTURES ARE IN LINE WITH FAVORABLE SHEAR/INSTABILITY PARAMETERS INDICATED IN 40KM OPERATIONAL NAM AND CURRENT SURFACE OA DATA. VERTICALLY INTEGRATED GRAUPEL FROM HI-RES GUIDANCE IS LARGE IN MAGNITUDE AND WIDESPREAD ACROSS THE FORECAST AREA DOMAIN, AND WIND SIGNATURES ARE DEPICTED AS WELL. THE LARGE VALUES OF UD-HELICITY ALONG WITH HAIL/WIND SIGNATURES INDICATE THAT A FEW HIGHER-END STORMS MAY BE POSSIBLE (WHICH WE ALSO DETERMINED BASED ON OBSERVED FEATURES AS WELL AS OPERATIONAL MODEL GUIDANCE)...WHICH GIVES US CONFIDENCE IN FORECASTING A SIG-SVR HATCHED AREA. OVERALL, WIDESPREAD CONVECTION IS FORECAST BY HI-RES GUIDANCE, WHICH WE BELIEVE IS LIKELY GIVEN THE STRONG FORCING ASSOCIATED WITH THE APPROACHING UPPER TROUGH OVERSPREADING A LARGE AREA OF HIGH INSTABILITY/MOISTURE.

(Clark et al. 2012 BAMS)

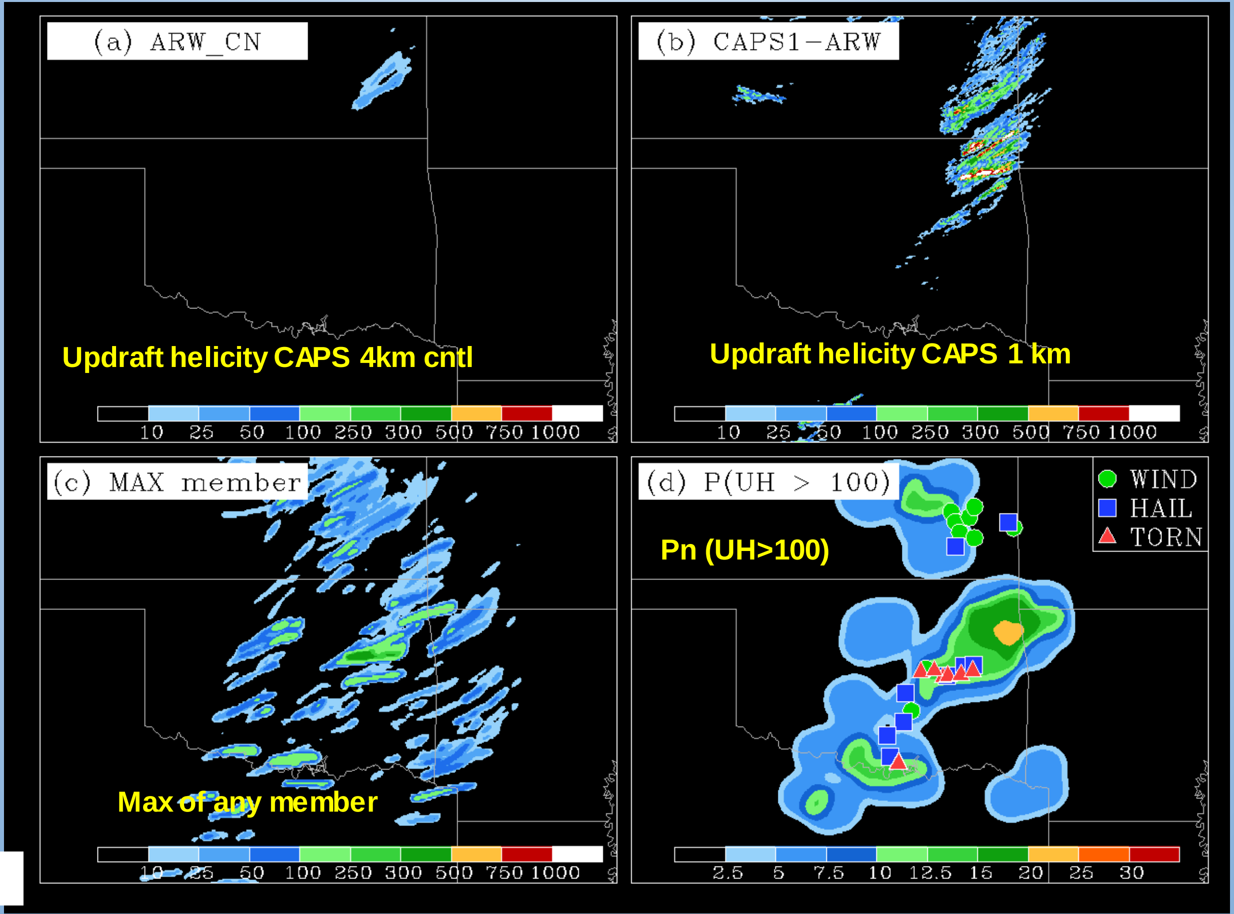
Products – Simulated Reflectivity



(Clark et al. 2012 BAMS)

Hourly Maximum Updraft Helicity (t=25h)

24h forecast Valid at 00-01 UTC May 11, 2010.



(Clark et al. 2012 BAMS)

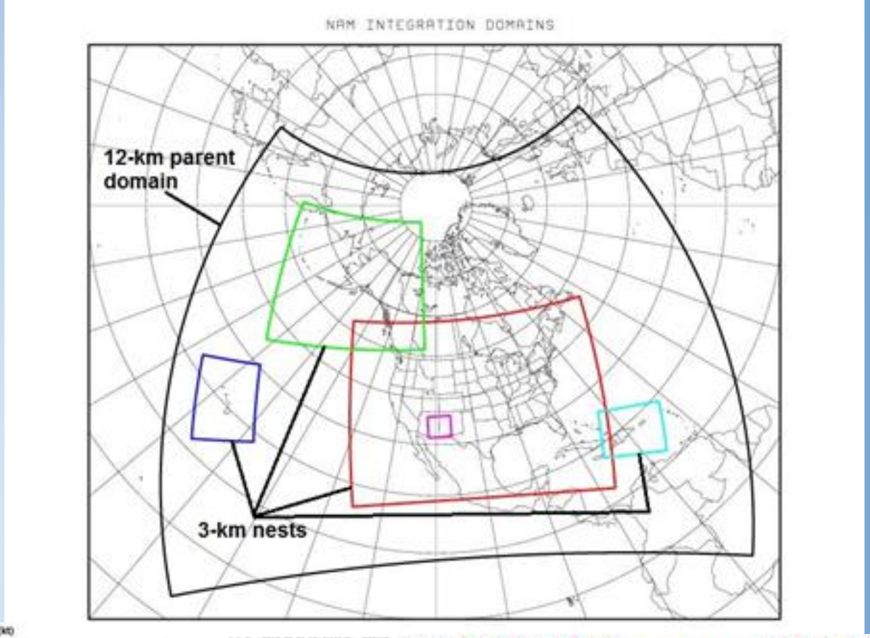
Current CAMS: WRF

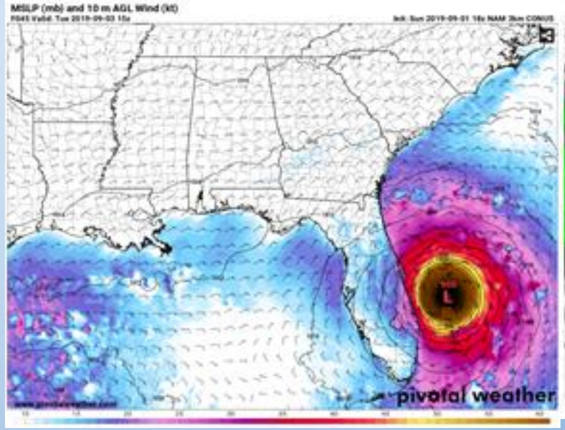
- Weather Research and Forecasting model (WRF)
  - One of the most well known and important CAM/model frameworks.
  - “A state of the art mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications.”
  - Developed by NCAR in the mid 2000s - it is widely used.
- Multiple Flavors with own Biases
  - NSSL (cool and moist PBL)
  - ARW (Formerly EMC) (Dry and overmixing)
  - NNMB (Moist Boundary layer Buoyancy too high)
- Variable grid spacing and microphysics schemes.
- Multiple cores and schemes allow for dispersive ensembles.

	WRF-EMC	WRF-NSSL
Horiz. Grid (km)	4.0	4.0
Vertical Levels	35	35
PBL/Turb. Param.	MYJ	MYJ
Microphys. Param	Ferrier	WSM6
Radiation (SW/LW)	GFDL/GFDL	Dudhia/RRTM
Initial Conditions	32 km NAM	40 km NAM
Dynamic Core	NMM	ARW

Current CAMS: NAM Nest

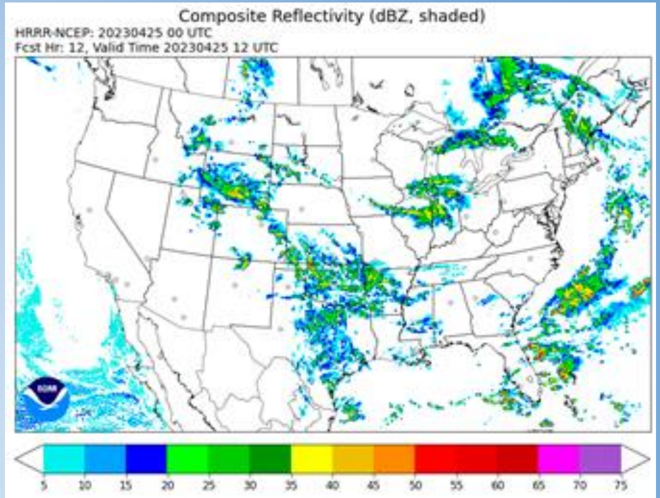
- Nested North American Model (NAM Nest/NAM 3/4k)
  - Nested subgrid version of the North American Model.
  - 12 km NAM for used boundary conditions
  - 1 km nested fire-weather domain
- Hybrid Ensemble 3DVAR data assimilation scheme.
- Known Biases:
  - Cool and moist bias often found at the surface with overdone buoyancy.
  - Cold pool overdevelopment can lead to erroneous convection, rapid upscale growth or lack of storms entirely.
  - **<u>Significantly Overdeepens TCs</u>**

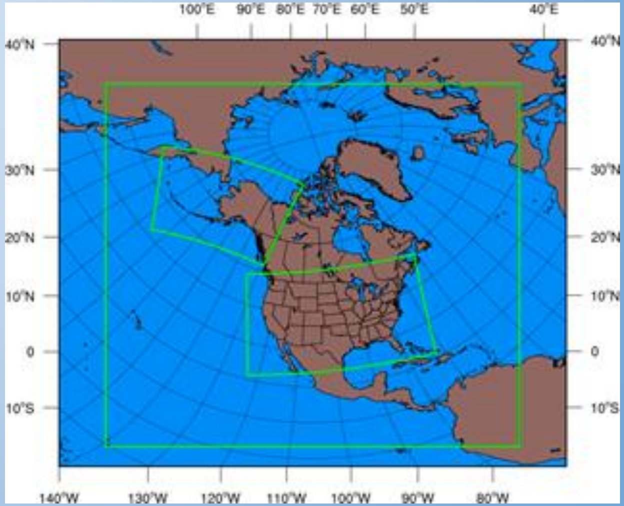




Current CAMS HRRR

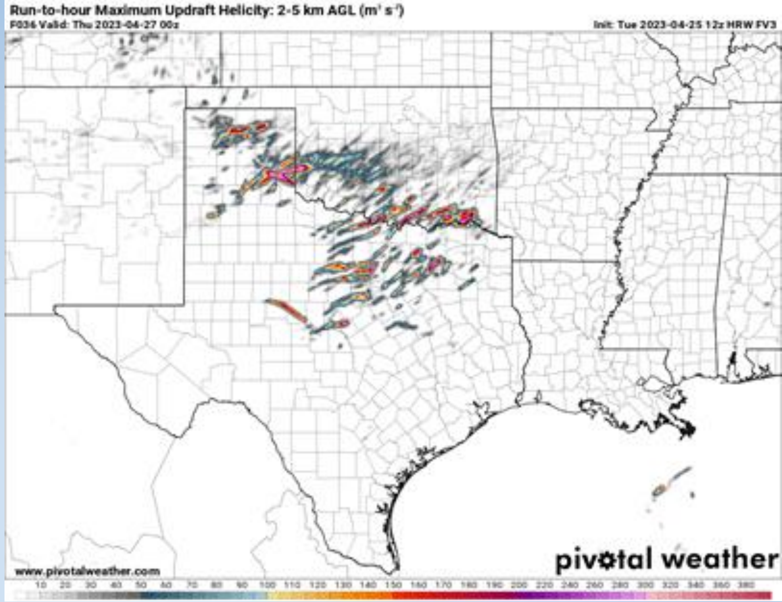
- High Resolution Rapid Refresh developed by EMC 30th of Sept 2014. Also has an ensemble version HRRR(E)
- Will be replaced by FV3-based RRFS in 2025.
- 3 km Rapid Updating (hourly and 15 minute)
- RAP 13km forecasts as boundary conditions and assimilates radar data using EnVar.
- Thompson microphysics and MYNN PBL scheme
- Known Biases include:
    - Significant over mixing bias in warm season boundary layers
        - Pushes dryline too far east
        - Lowers dew points and buoyancy.
    - Overdevelopment of surface cold pools
        - Upscale growth too fast.
    - Fails to produce convection in weak forcing cases.

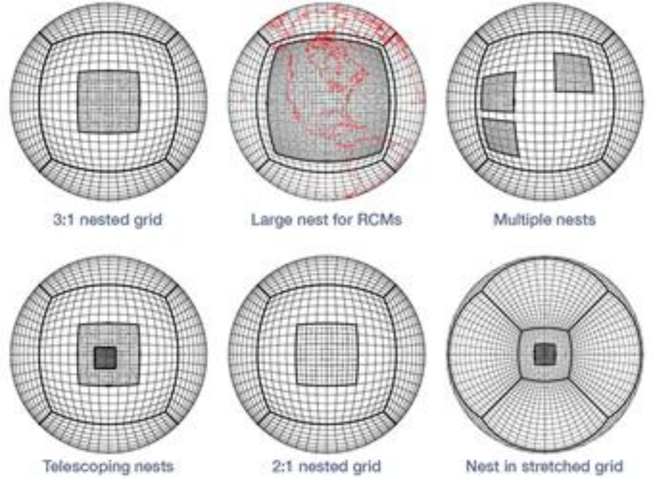




Current CAMS: Hi-Res FV3

- High Resolution Finite Volume Cubed-Sphere dynamical core (FV3)
- Part of NOAA's next generation unified forecasting system (UFS)
- Same dynamical core as the GFS used to provide boundary conditions.
- EnVar-EnKF combination for data assimilation.
- Known Biases:
  - Overmixing and dry bias
  - Lower buoyancy
  - Over convective within weak forcing.
  - Much higher updraft helicity due to grid spacing and calculations
- Can handle certain boundary layer cases better than other models with a “middle ground”



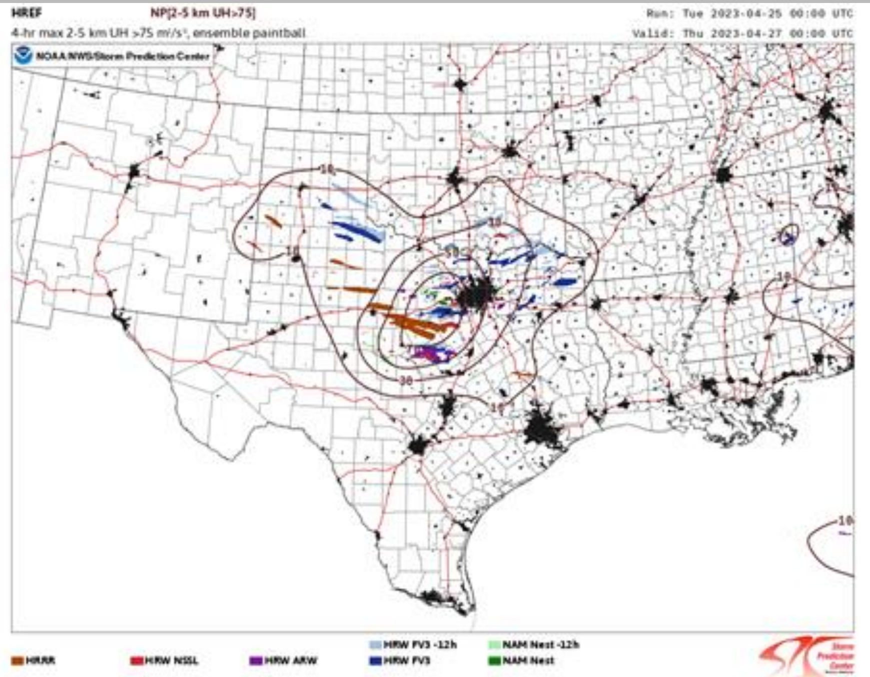


CAM Ensembles: HREF

- High Resolution Ensemble Forecast System
- Began in the mid 2010s as the Storm Scale Ensemble of Opportunity (SSEO) at SPC.
- HREF is a 48 hour 10 member ensemble of operation convection allowing models.
  - 5 Model cores
  - 5 time lagged members
- Produces a number of different hourly max and ensemble products.
- Serves as a good basis for nearly all types of forecasts.

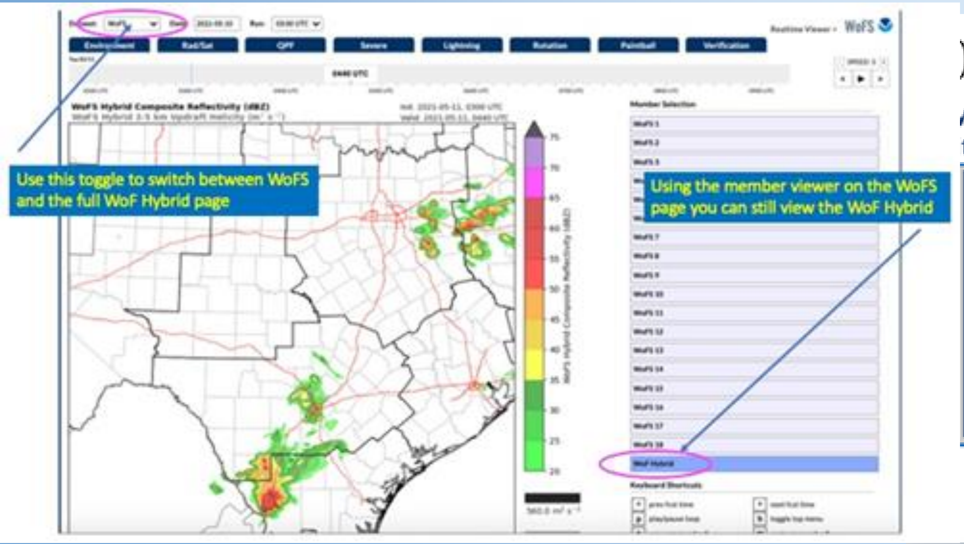
Configuration period: 2021-05-11 through present

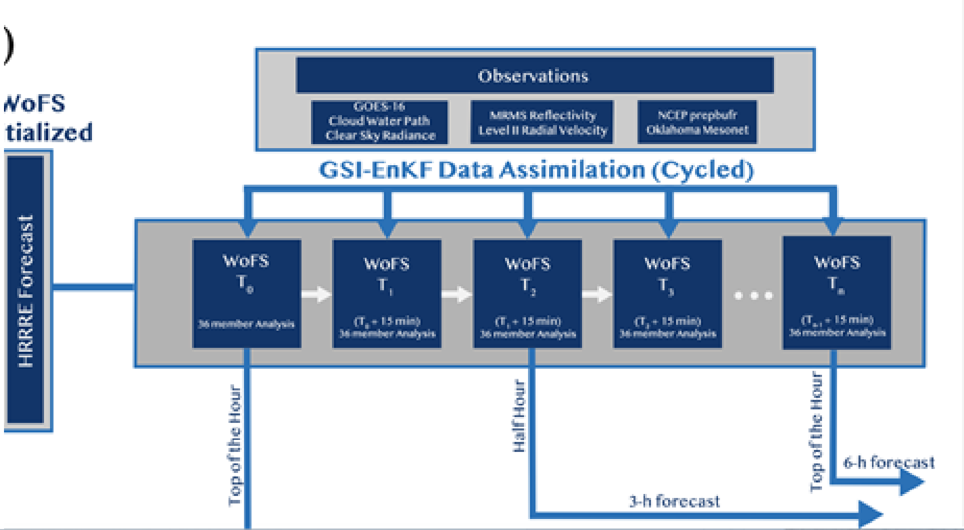
Member	ICs	LBCs	Microphysics	PBL	dx (km)	Vert. levels	Included in HREF hours
HRRR	RAP -1h	RAP -1h	Thompson	MYNN	3.0	50	0 - 36
HRRR -6h	RAP -1h	RAP -1h	Thompson	MYNN	3.0	50	0 - 30
HRW ARW	RAP	GFS -6h	WSM6	YSU	3.2	50	0 - 48
HRW ARW -12h	RAP	GFS -6h	WSM6	YSU	3.2	50	0 - 36
HRW FV3	GFS -6h	GFS -6h	GFDL	GFS EDMF	3.0	60	0 - 60
HRW FV3 -12h	GFS -6h	GFS -6h	GFDL	GFS EDMF	3.0	60	0 - 48
HRW NSSL	NAM	NAM -6h	WSM6	MYJ	3.2	40	0 - 48
HRW NSSL -12h	NAM	NAM -6h	WSM6	MYJ	3.2	40	0 - 36
NAM CONUS Nest	NAM	NAM	Ferrier-Aligo	MYJ	3.0	60	0 - 48
NAM CONUS Nest -12h	NAM	NAM	Ferrier-Aligo	MYJ	3.0	60	0 - 48



CAM Ensembles: WOFS

- WARN On Forecast System (WOFS) is an experimental CAM ensemble run by NSSL.
- Runs during the Spring Forecast Experiment Hazardous Weather Testbed (HWT) and on certain extra days.
- 3 km ensemble forecasts
- High Spatial and temporal frequency (hourly and 15 min runs out to 6 hours)





Common CAM Problems

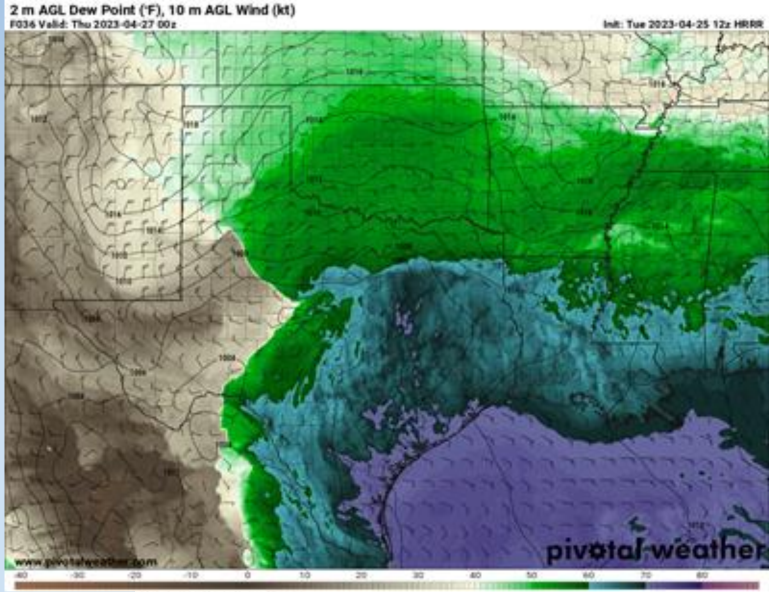
"All models are wrong, but some are useful."

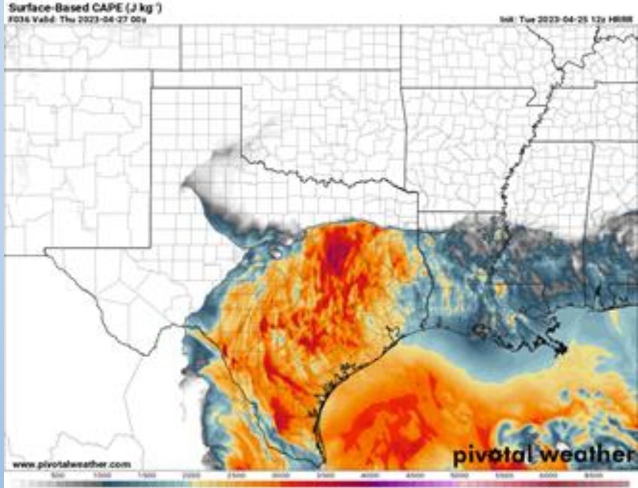
-George EP Box

- Depend on correct boundary condition and data assimilation. Subject to the same caveats as all NWP with some extra.
  - Missing radar or satellite data
  - Improper assimilation of surface conditions between synoptic observations.
- "Spin Up Time"
  - Models can take an hour or more to "catch on" to evolving forecasts, if no convective scale data are assimilated.
- Weak forcing can be difficult to initiate storms in the model.
  - Very common along drylines.
  - Inverse is true for strong forcing along cold fronts or other boundaries. Models develop too many storms or rapid upscale growth can happen

How to use CAMS: Environment

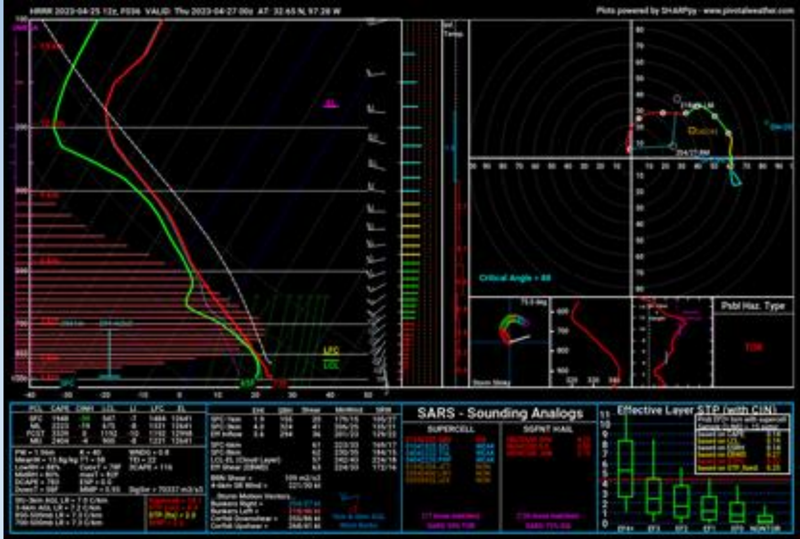
- Cams can provide useful information when interrogating small but potential favorable environments for severe weather.
- They can also provide greater resolution and more information in cases where regional or global model (much more coarse) spacing misses important attributes.
    - Near outflow boundaries.
    - Complex terrain.
    - Ongoing convection.
    - Land ocean interfaces
- Compare how models initialize but also check back as they can “catch up” if run frequently.

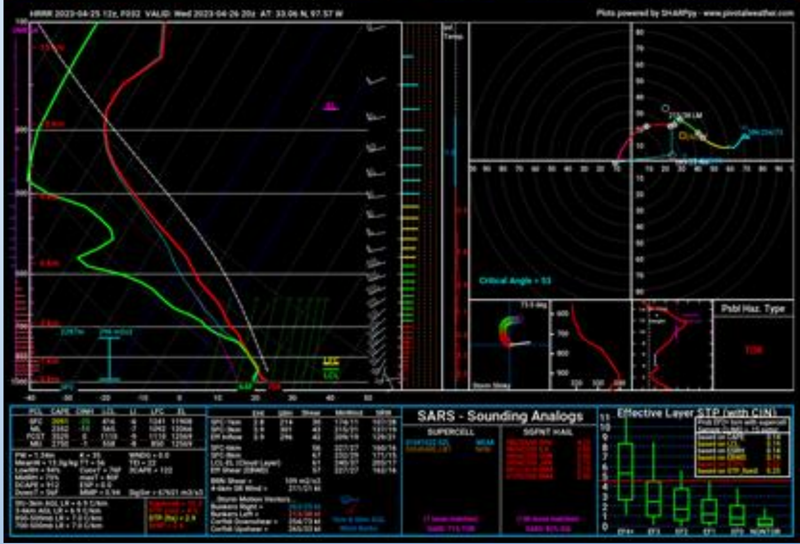




How to use CAMS: Soundings

- Soundings are a great way to visualize pre-convective environment using CAMS.
- Tighter grid spacing (Horizontal and vertical) allows more useful sounding locations with less interpolation.
- Often can catch subtle features such as shortwave troughs with weak forcing for warm season storms.
- **CAUTION**
    - Best practice is to only use for pre-convective environment.
    - Soundings can be “contaminated” by ongoing storms resulting in unrealistic environment.
    - Compare and modify soundings to real world observations as much as possible.



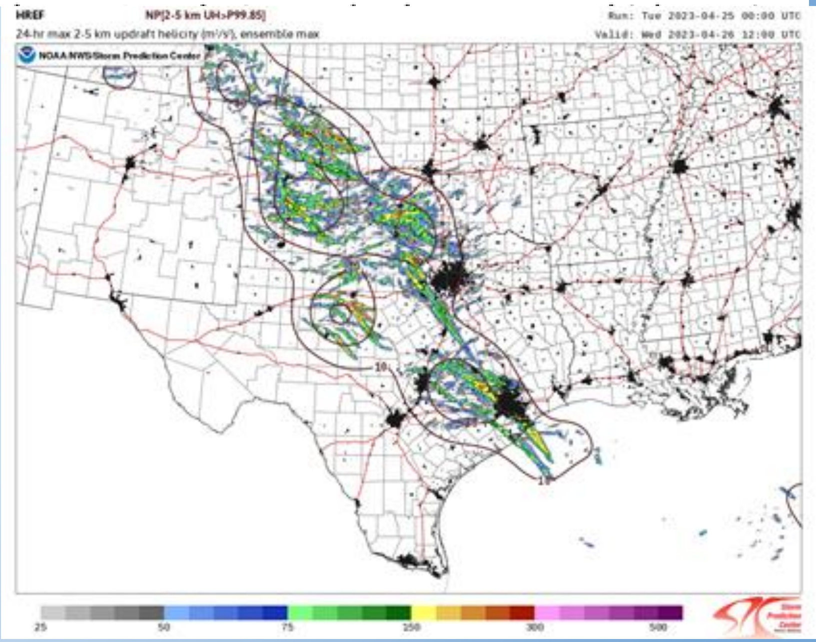


How to use CAMS: Hourly Output

- Summation of output over 1-24 hours.
  - Updraft helicity
  - Updraft velocity
  - Simulated reflectivity
  - Max Wind gust
- Can be very useful for quick estimation of storm intensity.
  - Severe weather is correlated with higher updraft helicity but with many caveats.
- **<u>Caution:</u>**
  - Updraft helicity is usually estimated at 2-5 km (mid-levels) tells you nothing about potential storms low-level updraft or tornadoes only supercells.
  - Can be elevated above the surface with more of a hail threat
  - Looks cool and scary

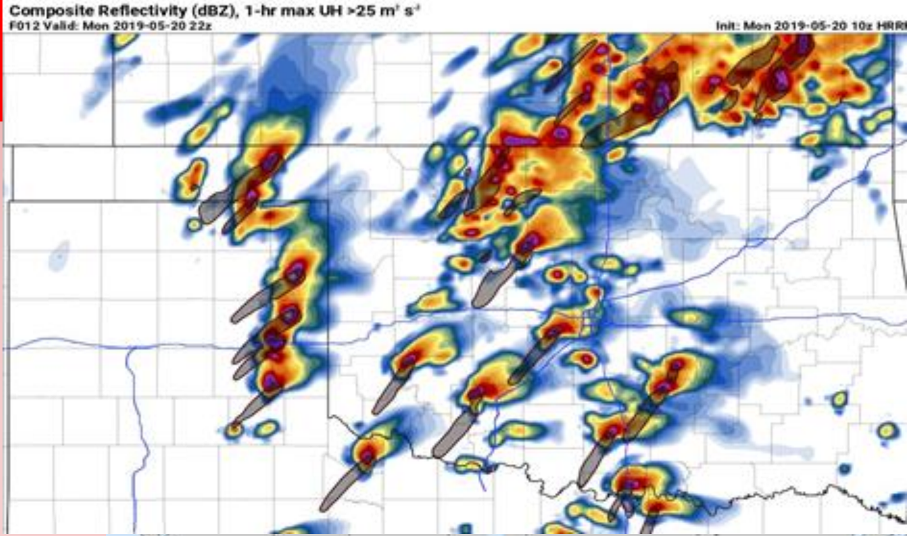
Updraft helicity (UH) is commonly used as a forecast parameter to identify rotating updrafts (Kain, et al., 2008). It is defined as:

$$UH = \int_{z1}^{z2} w \, \zeta \, dz$$

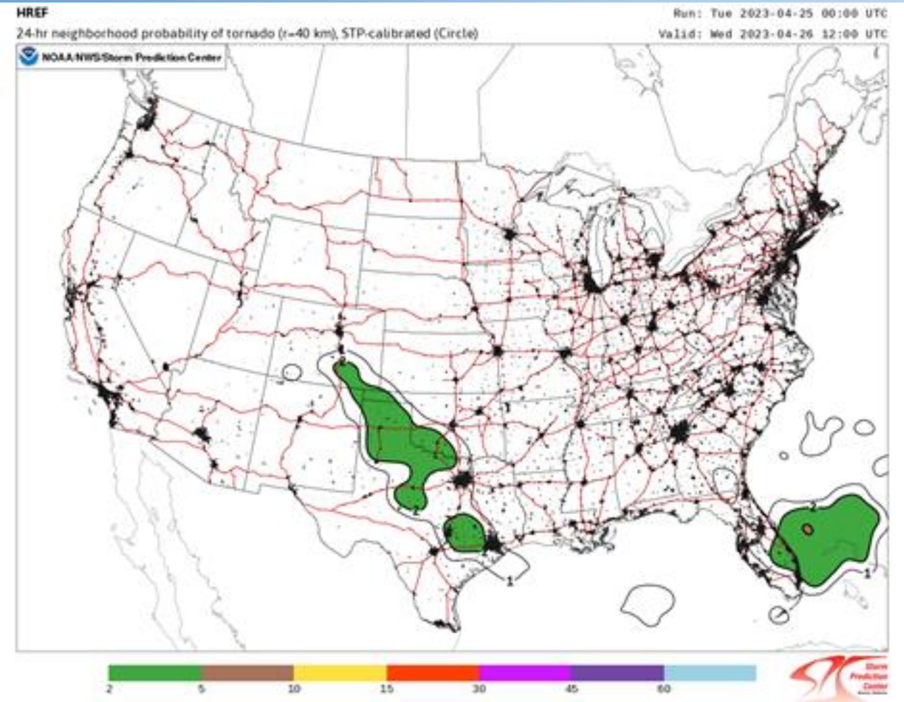


How **NOT** to use CAMS

- The higher resolution the model the more realistic it can appear. It's tempting to implicitly trust CAM output, but that is rarely how the atmosphere works.
- Avoid looking only at CAMS, know the background state of the atmosphere from observations.
- Don't "cherry pick" by looking at one or two flashy parameters or output from one or two models.
  - Ensembles can give you a much better idea of the range of outcomes.
- Do not rely on CAM output as the root of your forecast and know their biases.



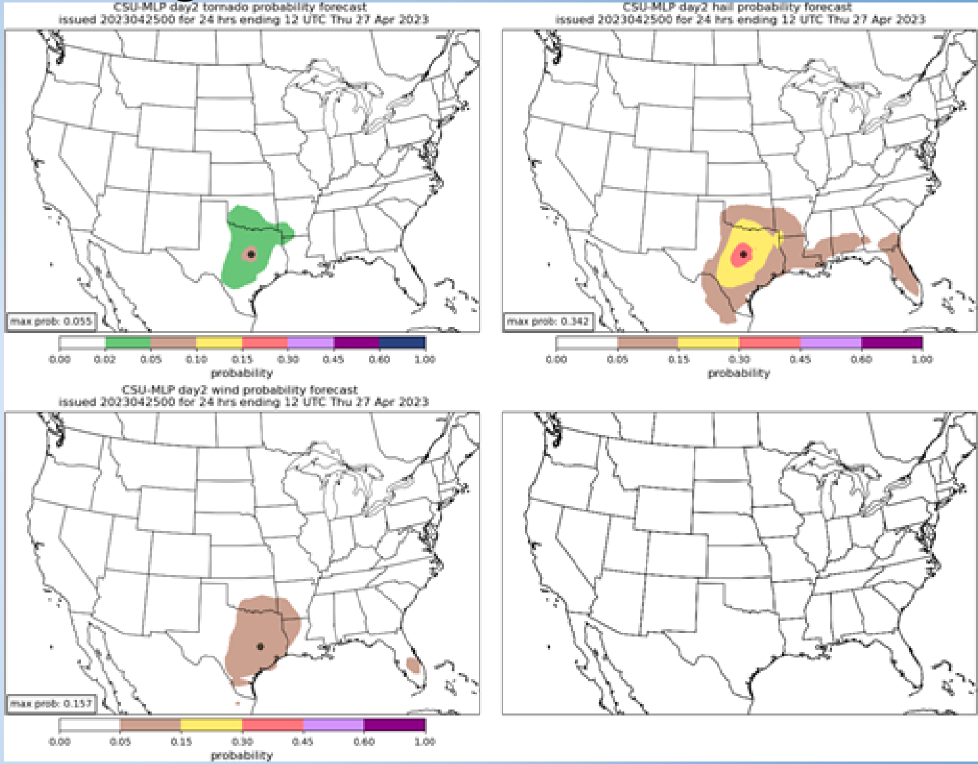
CAMS Extras: Post Processed Calibrated Guidance



- Relatively new area of research focusing on applying statistical models to CAM output.
- Can create probability distributions for events when correlated with storm reports.
- Often look very close to human forecasts.
- Use caution when interpreting them as the same biases with CAMS apply to the output.

The future of CAMS: Machine learning Guidance

- Calibrated guidance using machine learning and storm reports.
- Output often looks very similar to human forecasts but can differ a great deal.
- Not well understood given the complexity of machine learning.
- Do not always rely on the same predictors humans use to make their forecasts.
- Subject to many biases
- Emerging area of research, likely the next big thing in modeling.



Now let's look at the Cams for Today!

- Split up into groups of 2 or 3 and start looking at each different model.
  - HRRR
  - FV3
  - NAM3k
  - NSSL WRF
- Come up with a forecast based on your model.
  - How does it behave compared to your thoughts about what will happen.
  - Is it similar to other forecasts?
  - Big differences?

- https://www.spc.noaa.gov/exper/href/

http://wxwatcher.us/map/outlook/