Introduction to High-Resolution Atmospheric Modeling

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High resolution?

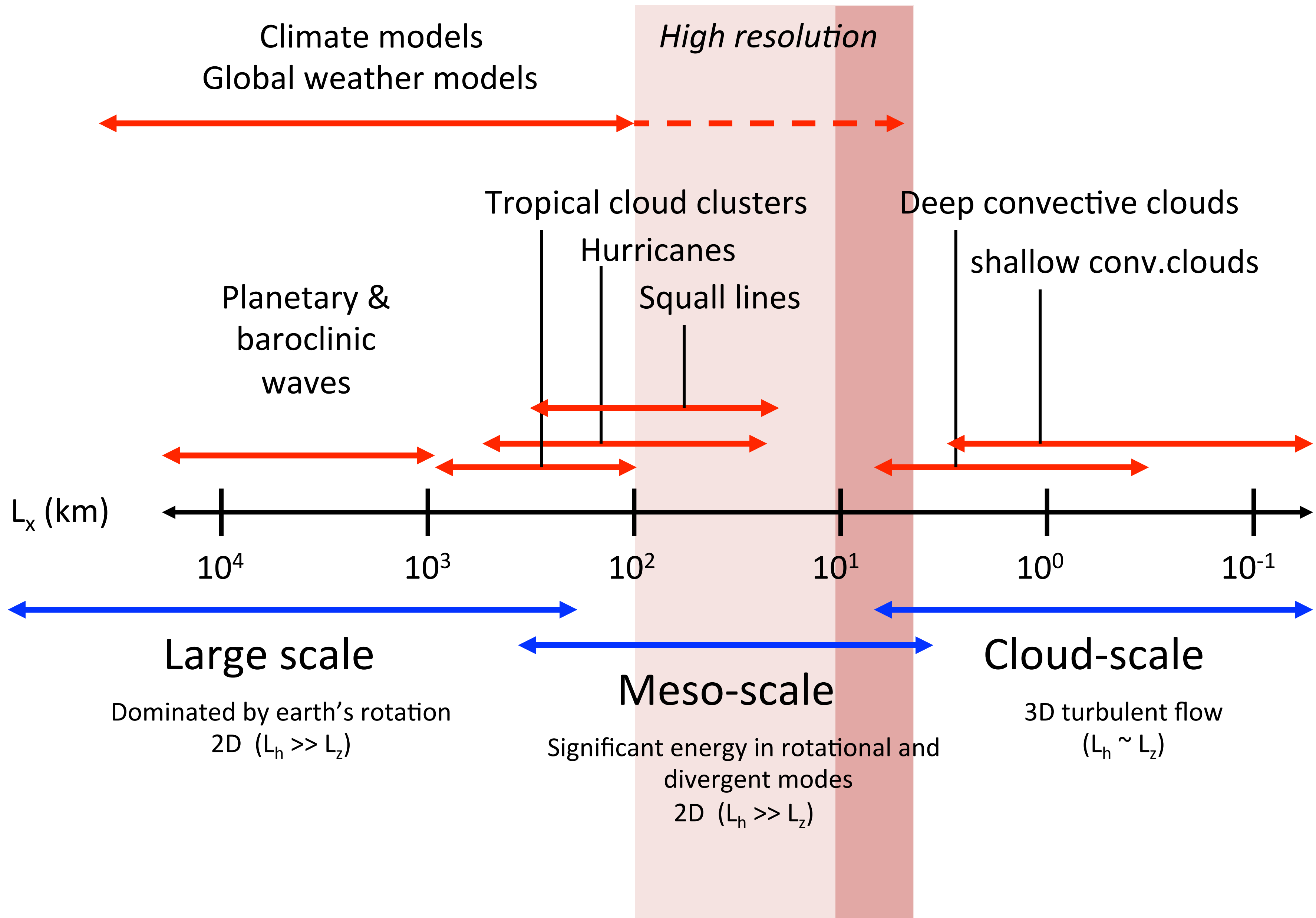
Some history

Convection *resolving* or convection *permitting*?

Squall-lines and supercells

Global model forecast testing

Model/Dynamic Regimes



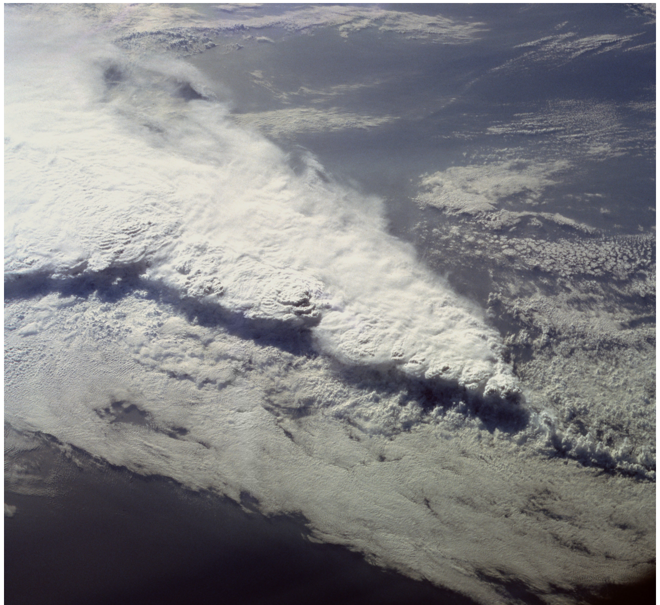
High resolution: Explicit clouds, nonhydrostatic dynamics

Clouds are ubiquitous

Deep convective clouds are responsible for a significant amount of severe weather (high winds, hail, flooding, lightning, etc.)

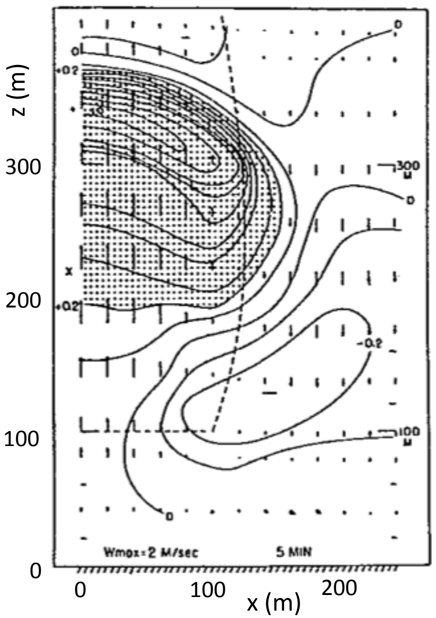
The largest uncertainties in atmospheric weather and climate models involve clouds.


NASA composite image (bluemarblewest)


NASA photo, Florida squall line (view to E-SE)

Some history…
Early 2-D Nonhydrostatic Dry Thermal Simulations

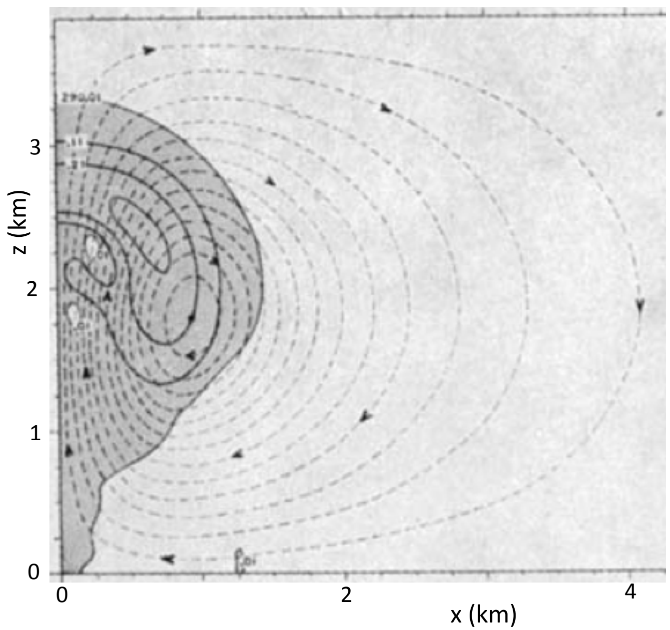
Malkus & Witt, 1959



(32x32), dx = 20 m, 5 min

Incompressible, Boussinesq

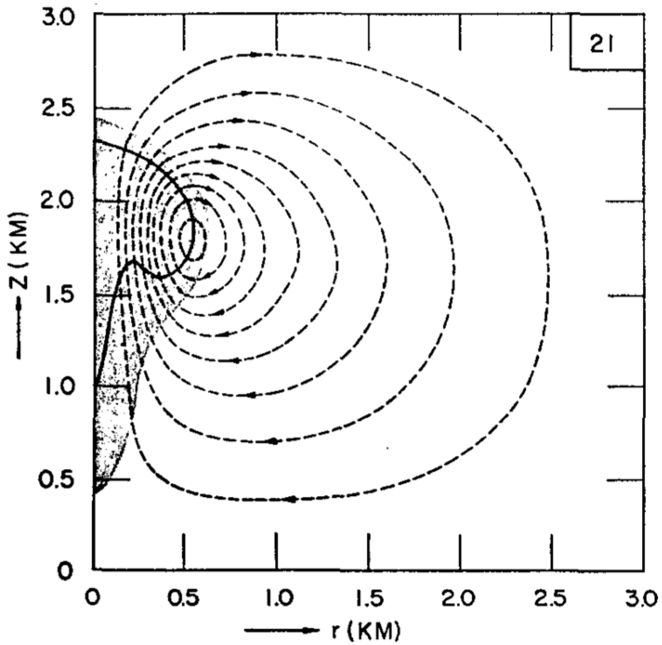
Lilly, Tellus, 1962



(94x31), dx = 125 m, 20 min

Compressible, explicit

Ogura, JAS,1962

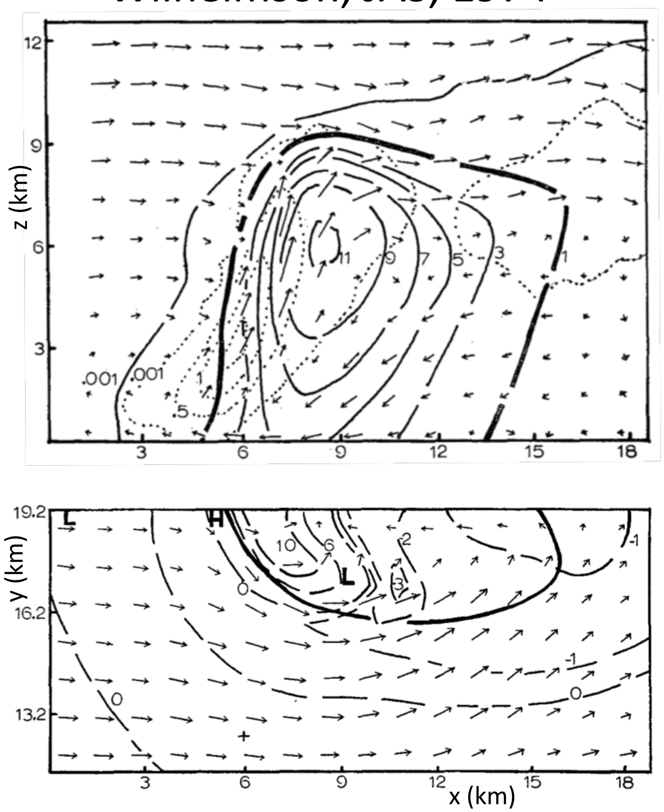


(31x31), dr = 100 m, 21 min

Incompressible, Boussinesq

More history…
1970s - Early 3-D Cloud Models

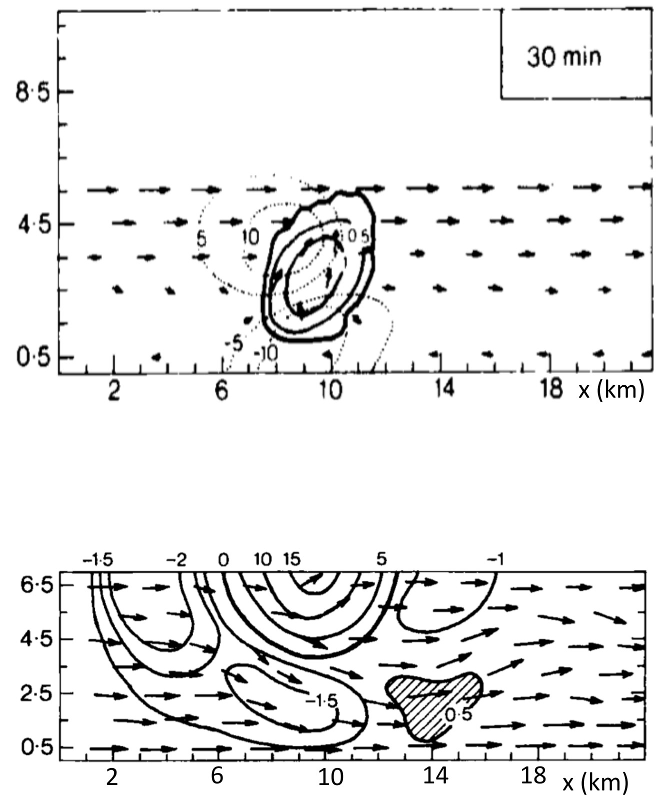
Wilhelmson, JAS, 1974



Cloud and rain water, wind vectors at 45 min

(64x33x25), Anelastic,
d*x* = d*z* = 600 m

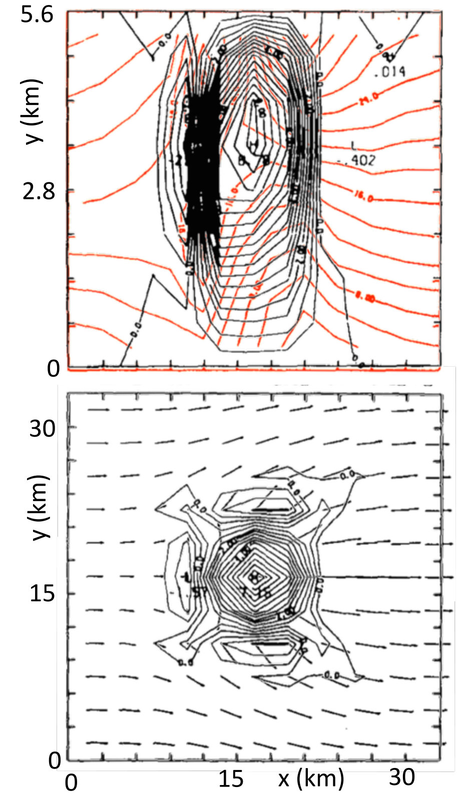
Pastushkov, QJRMS, 1975



Vertical velocity, liquid water, and wind vectors at 30 min

(23x14x12), Anelastic,
d*x* = d*z* = 1 km

Schlesinger, JAS, 1975



Horizontal and vertical velocities at 12.5 min

(11x11x8), Anelastic,
d*x* = 3.2 km, d*z* = 700 m

More history…
Integration of the Nonhydrostatic Equations

Time-step constraints for explicit numerical integration:

Acoustic modes: $\Delta t \le \dfrac{\Delta x}{c_s}, \; \dfrac{\Delta z}{c_s}$

Gravity waves: $\Delta t \le N^{-1}$

Advection: $\Delta t \le \dfrac{\Delta x}{U}, \; \dfrac{\Delta z}{W}$

Dilemma: *Acoustic modes are not of meteorological interest, but may severely constrain explicit time steps.*

Techniques to Gain Numerical Efficiency in Nonhydrostatic Integrations

- Semi-implicit integration of acoustic/gravity wave modes

$$\frac{\partial \boldsymbol{v}}{\partial t} + c_p\theta\overline{\boldsymbol{\nabla}\pi'}^t = F_{\boldsymbol{v}}$$

$$\frac{\partial \pi'}{\partial t} + \frac{c^2}{c_p\rho\theta^2}\overline{\boldsymbol{\nabla}(\rho\theta\boldsymbol{v})}^t = F_\pi$$

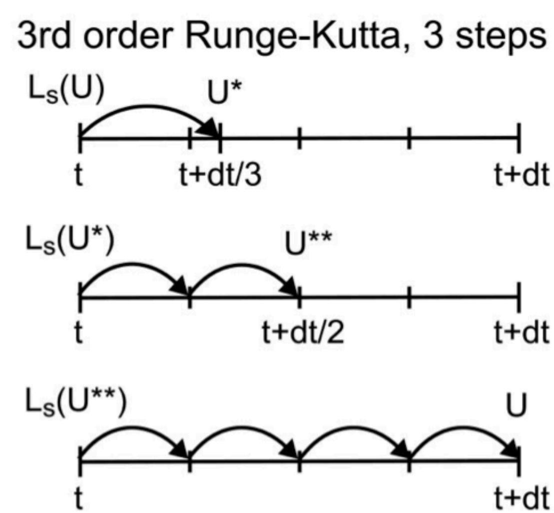
(Tapp & White (1976), Tanguay et al, MC2, MetUM, LM, GRAPES)

- Split explicit, vertically implicit, integration

$$\frac{\partial \boldsymbol{v_h}}{\partial t} + c_p\theta\boldsymbol{\nabla}\pi'^{\tau} = F^t_{\boldsymbol{v}}$$

$$\frac{\partial w}{\partial t} + c_p\theta\overline{\frac{\partial \pi'}{\partial z}}^{\tau} = F^t_w$$

$$\frac{\partial \pi'}{\partial t} + \frac{c^2}{c_p\rho\theta^2}\left\{\boldsymbol{\nabla}(\rho\theta\boldsymbol{v_h})^{\tau+\Delta\tau} + \overline{\frac{\partial \rho\theta w}{\partial z}}^{\tau}\right\} = F^t_\pi$$



(Klemp & Wilhelmson (1978), RAMS, ARPS, COMMAS, MM5, COAMPS, WRF, NICAM)

Techniques to Gain Numerical Efficiency in Nonhydrostatic Integrations

- Horizontally explicit, vertically implicit (HEVI) integration

$$\frac{\partial w}{\partial t} + c_p \theta \overline{\frac{\partial \pi'}{\partial z}}^{\tau} = F_w^t$$

$$\frac{\partial \pi'}{\partial t} + \frac{c^2}{c_p \rho \theta^2} \overline{\frac{\partial \rho \theta w}{\partial z}}^{\tau} = F_\pi^t$$

(NMM, ICON, others)

- Quasi-compressibility approaches

$$\frac{\partial \pi'}{\partial t} + \frac{c_r^2}{c_p \rho \theta^2} \boldsymbol{\nabla}(\rho \theta \boldsymbol{v}) = 0, \qquad c_r < c$$

(Droegemeier & Wilhelmson (1985), Tripoli – NMS)

- Filtered equations to remove acoustic modes

$$\boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$ Boussinesq

$$\boldsymbol{\nabla} \cdot (\bar{\rho} \boldsymbol{v}) = 0$$ Anelastic

$$\boldsymbol{\nabla} \cdot (\bar{\rho} \bar{\theta} \boldsymbol{v}) = H$$ Pseudo-incompressible

$$\frac{\partial \rho_{qs}}{\partial t} + \nabla \cdot (\rho_{qs} \mathbf{V}) = 0$$ Sound-proof

(Schlesinger (1973), Clark, Lipps & Hemler, EULAG, Durran, Arakawa and Konor)

About simulating those clouds…

Convection resolving or *convection permitting*?

Spatial scales of convection

Supercells:

Reference	Type	Characteristic diameter (km) a = avg m = median s = single case	Max diameter (km)
Browning et al. (1976)	in situ and radar	5 (a)	8
Brandes (1981)	radar	11 (s)	—
Nelson (1983)	radar	∼10 (s)	—
Musil et al. (1986)	in situ	14 (s)	—
Kubesh et al. (1988)	in situ and radar	∼8 (s)	—
Dowell and Bluestein (2002)	radar	8 (s)	—

Midlatitude continental (excluding supercells):

Reference	Type	Characteristic diameter (km) a = avg m = median s = single case	Max diameter (km)
Byers and Braham (1949)	in situ	∼4	
Kyle et al. (1976)	in situ	2.8 (m)	4.6
Heymsfield and Hjelmfelt (1981)	in situ	4 (m)	6
Musil et al. (1991)	in situ	3 (a)	15
Yuter and Houze (1995)	radar	∼3 (m)	8

Spatial scales of convection

Tropical cyclones:

Reference	Type	Characteristic diameter (km) a = avg m = median s = single case	Max diameter (km)
Jorgensen et al. (1985)	in situ	1.2 (m)	7
Black et al. (1996)	radar	1 (m)	9
Eastin et al. (2005) - rainbands	in situ	1.5 (m)	3.0
Eastin et al. (2005) - eyewalls	in situ	2.0 (m)	4.0

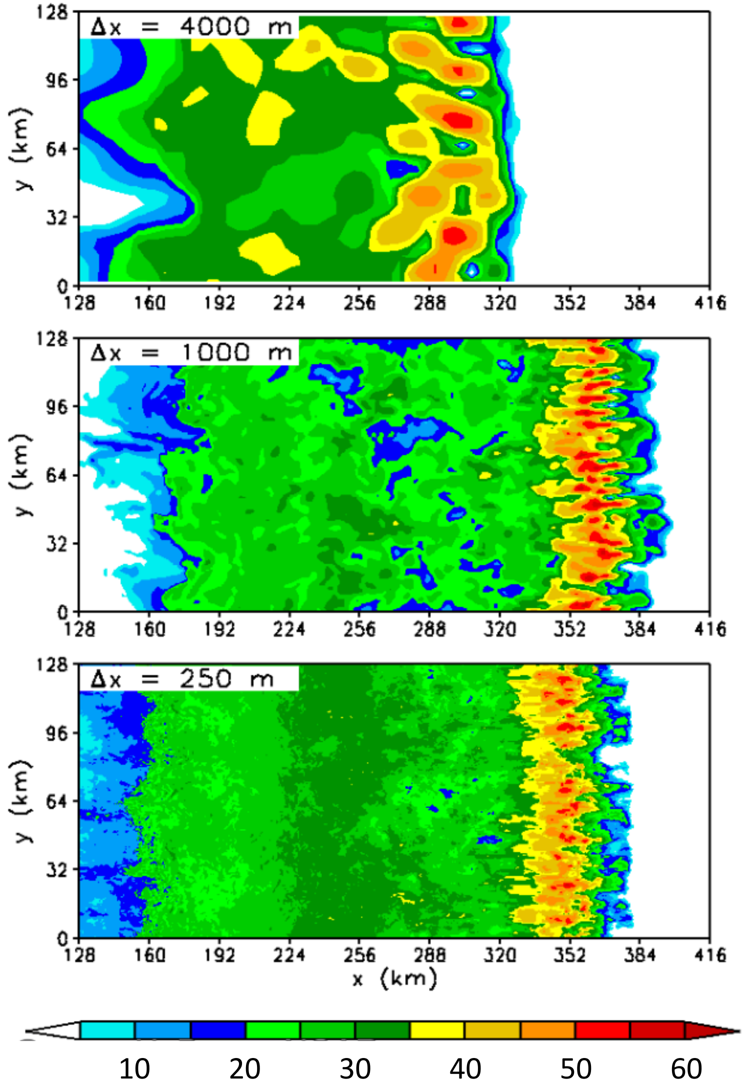
Tropical convection (mostly maritime) (excluding tropical cyclones):

Reference	Type	Characteristic diameter (km) a = avg m = median s = single case	Max diameter (km)
LeMone and Zipser (1980)	in situ	0.9 (m)	6
Warner and McNamara (1984)	in situ	1.4 (m)	15
Jorgensen and LeMone (1989)	in situ	< 1 (m)	8
Lucas et al. (1994)	in situ	1.0 (m)	4
Igau et al. (1999)	in situ	0.8 (m)	4
Anderson et al. (2005)	in situ	1 (m)	3

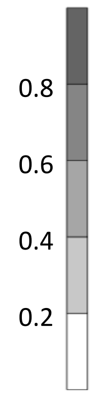
Large (> 2 km) updrafts are "exceedingly rare"

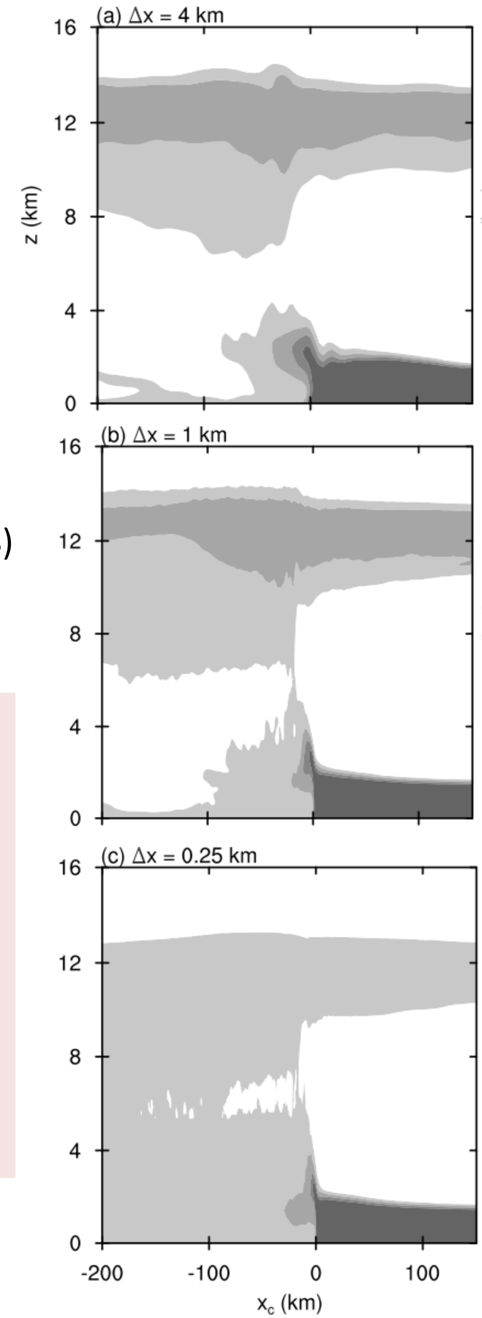
Results from idealized convective simulations

Composite reflectivity (dBZ), 6 hours
Periodic squall lines, George Bryan (2008)



Line-averaged
passive tracer
T = 6 hours
Periodic squall lines,
Bryan and Morrison (2008)





What do the simulations tell us?

At dx O(km):

(1) Cells are not resolved.
(2) Not enough low and mid-level detrainment.
(3) Too much upper-level detrainment.

Rain-Rate at the Surface

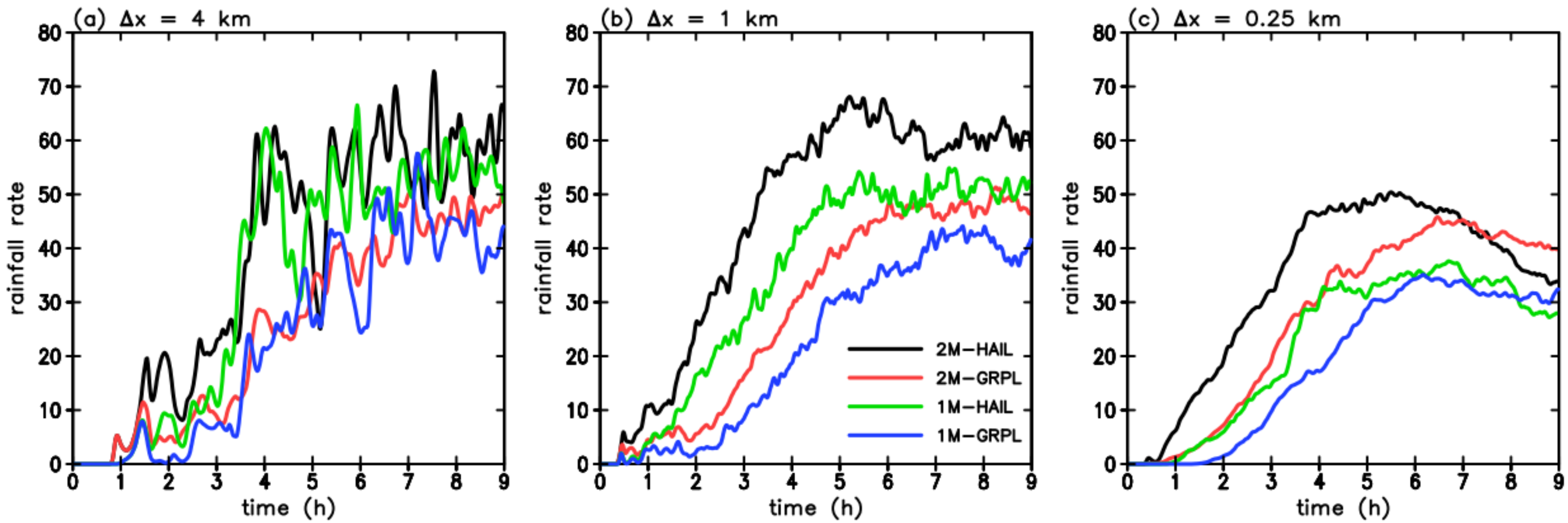
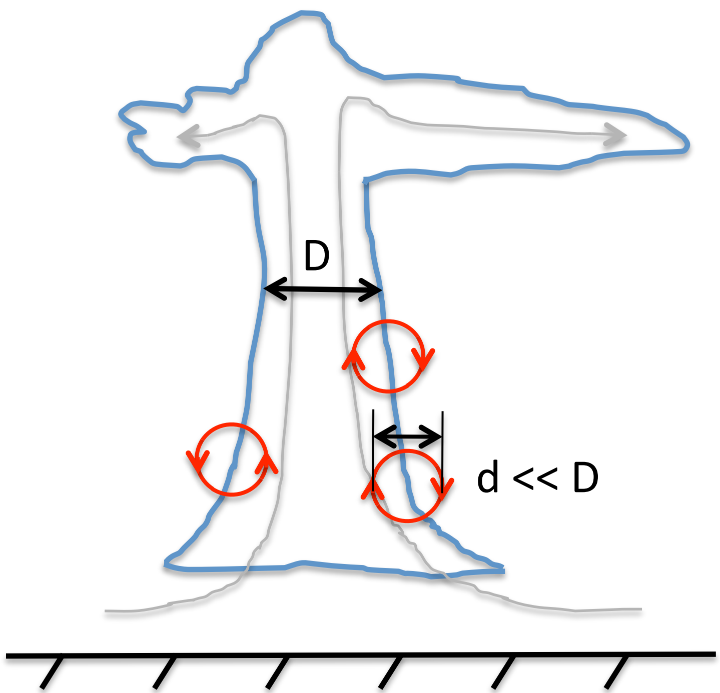


FIG. 4. Time-series of domain-total rainfall rate ($\times 10^6$ kg s^{-1}) for (a) $\Delta x = 4$ km, (b) $\Delta x = 1$ km, and (c) $\Delta x = 0.25$ km. The different microphysical setups are in different colors, as indicated by the legend.

Bryan and Morrison (2011)

Resolving Atmospheric Convection



Updraft diameter: D

D: Severe convection - 5-8 km
Typical midlatitude cells - 2-4 km
Tropical cells - 1-2 km
Shallow convection - 0.1-1 km

Eddies responsible for entrainment/detrainment: diameter d << D

Mesh spacing needed to resolve turbulent eddies: h << d, D

Resolutions needed to resolve deep convection: h ~ O(100 m)

Resolutions needed to resolve shallow convection: h ~ O(10 m)

About simulating those clouds…

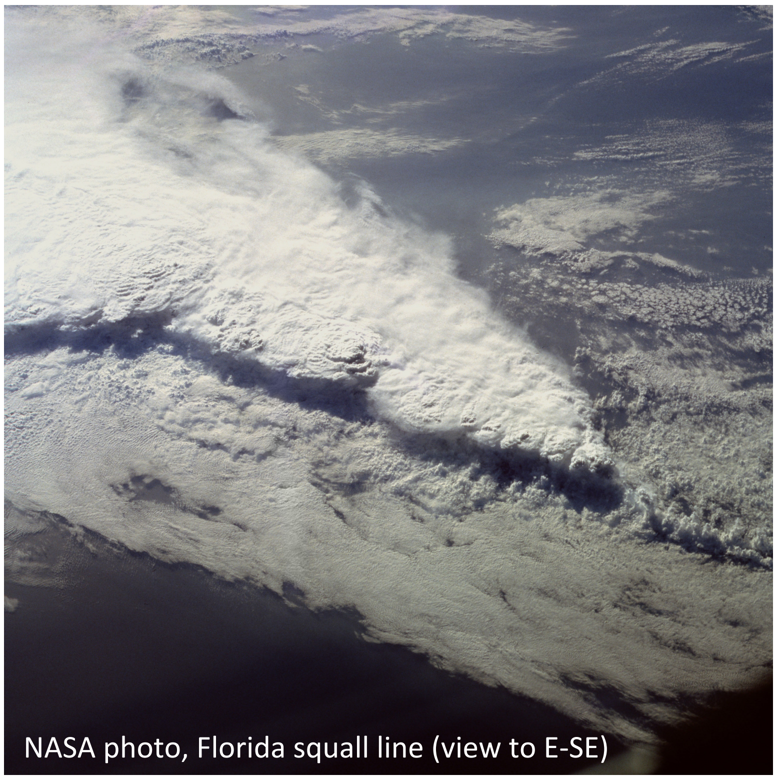
Convection resolving or
convection permitting?

All of our production applications (climate, NWP) are *convection permitting.*

We are *parameterizing* convective clouds with large laminar plumes.

What are we asking our models to do in convection-permitting mode?

Unstable convection



Cloud systems:
squall lines, cloud clusters, etc.

Large individual storms:
Supercell thunderstorms

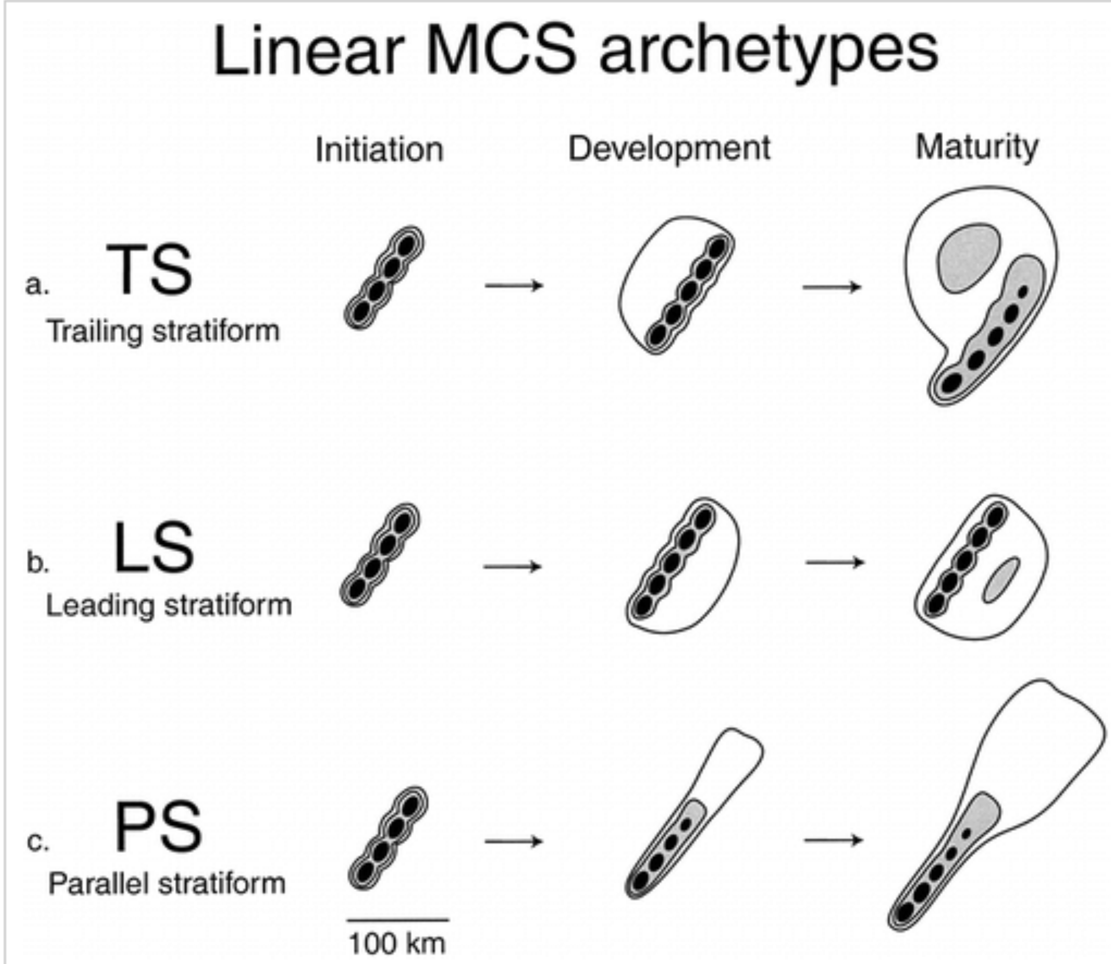
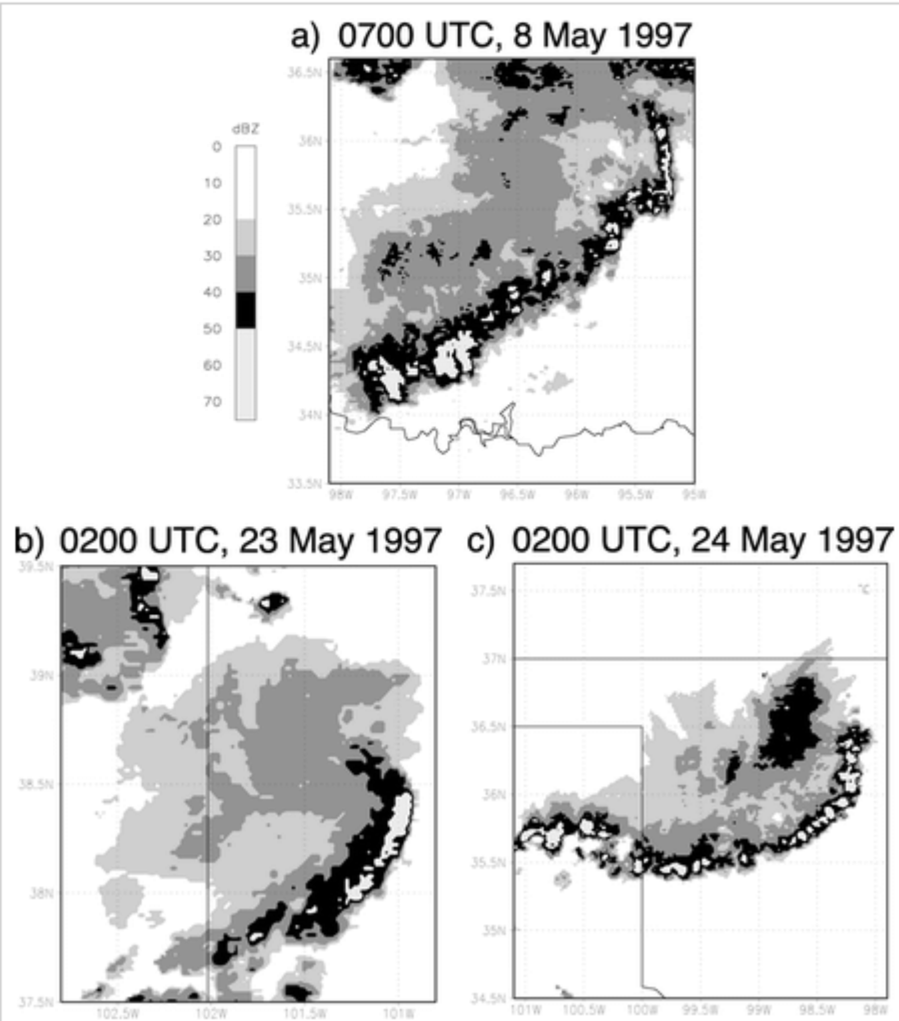


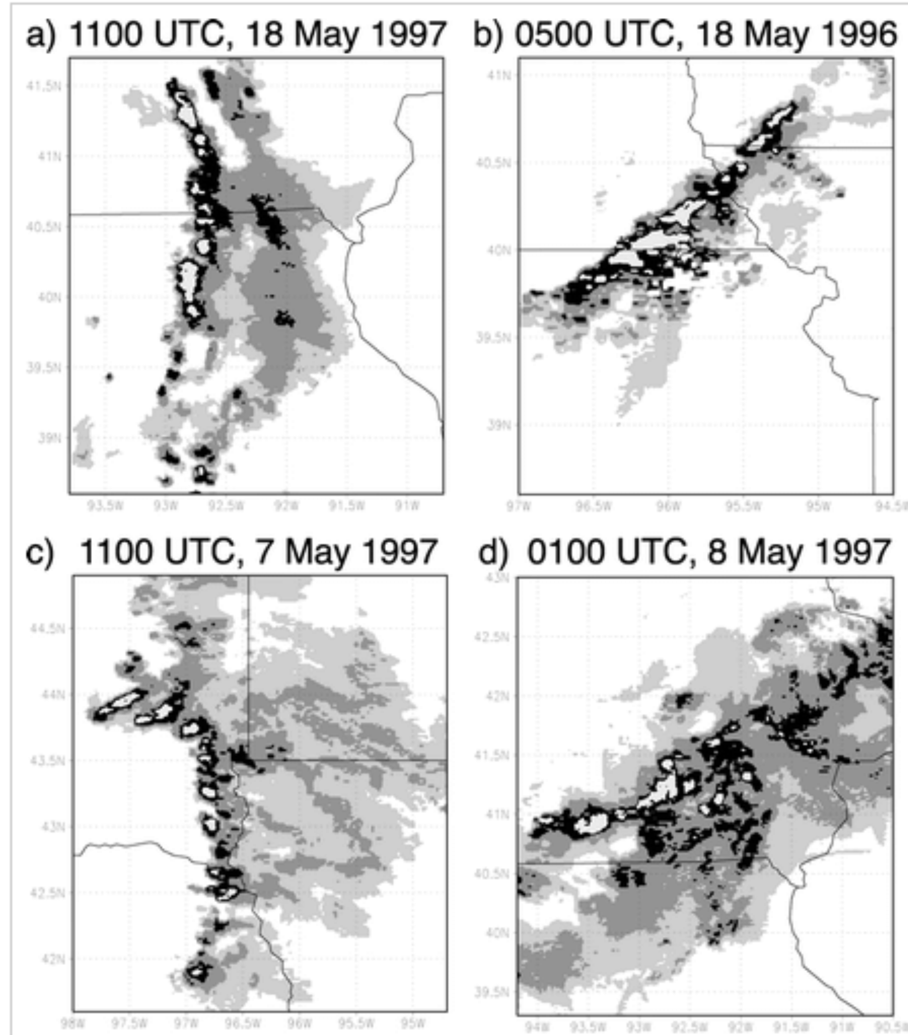
Fig. 4. Schematic reflectivity drawing of idealized life cycles for three linear MCS archetypes: (a) TS, (b) LS, and (c) PS. Approximate time intervals between phases: for TS 3–4 h; for LS 2–3 h; for PS 2–3 h. Levels of shading roughly correspond to 20, 40, and 50 dB*Z*.

Parker and Johnson, MWR, 2000

Trailing stratiform squall lines



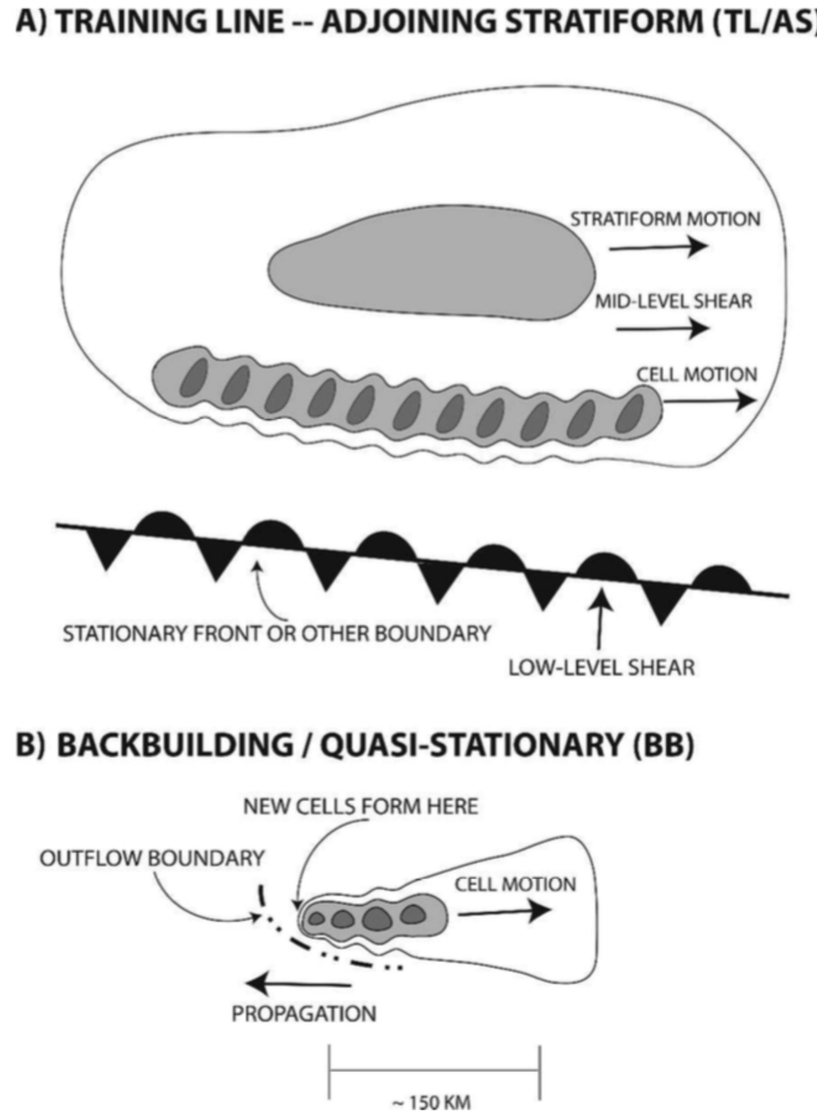
Leading stratiform squall lines



Parker and Johnson, MWR, 2000

Schumacher and Johnson, MWR, 2005
Extreme-Rain-Producing
Mesoscale Convective Systems

FIG. 3. Schematic diagram of the radar-observed features of the (a) TL/AS and (b) BB patterns of extreme-rain-producing MCSs. Contours (and shading) represent approximate radar reflectivity values of 20, 40, and 50 dBZ. In (a), the low-level and midlevel shear arrows refer to the shear in the surface-to-925-hPa and 925–500-hPa layers, respectively, as discussed in section 4. The dash–dot line in (b) represents an outflow boundary; such boundaries were observed in many of the BB MCS cases. The length scale at the bottom is approximate and can vary substantially, especially for BB systems, depending on the number of mature convective cells present at a given time.



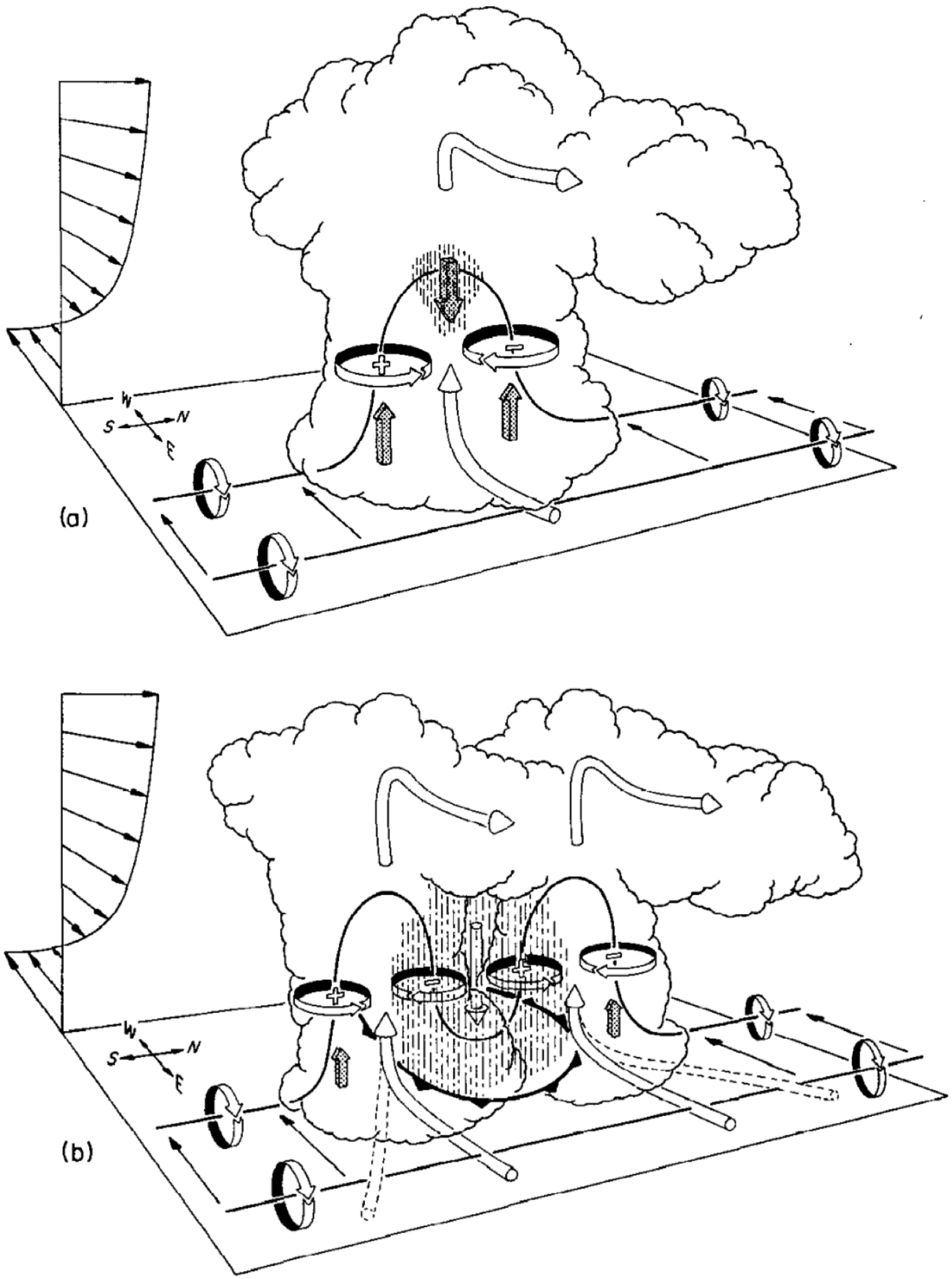
Supercells: 219 papers with “supercell” in title or abstract in AMS journal search.

Many and perhaps most have a modeling component.

Idealized supercell simulations starting in the early 1970s.

LP supercell, courtesy Roger Hill

Supercell thunderstorm, courtesy Lou Wicker

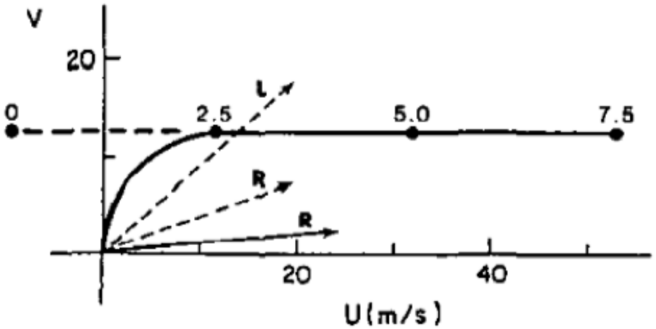


Splitting supercell

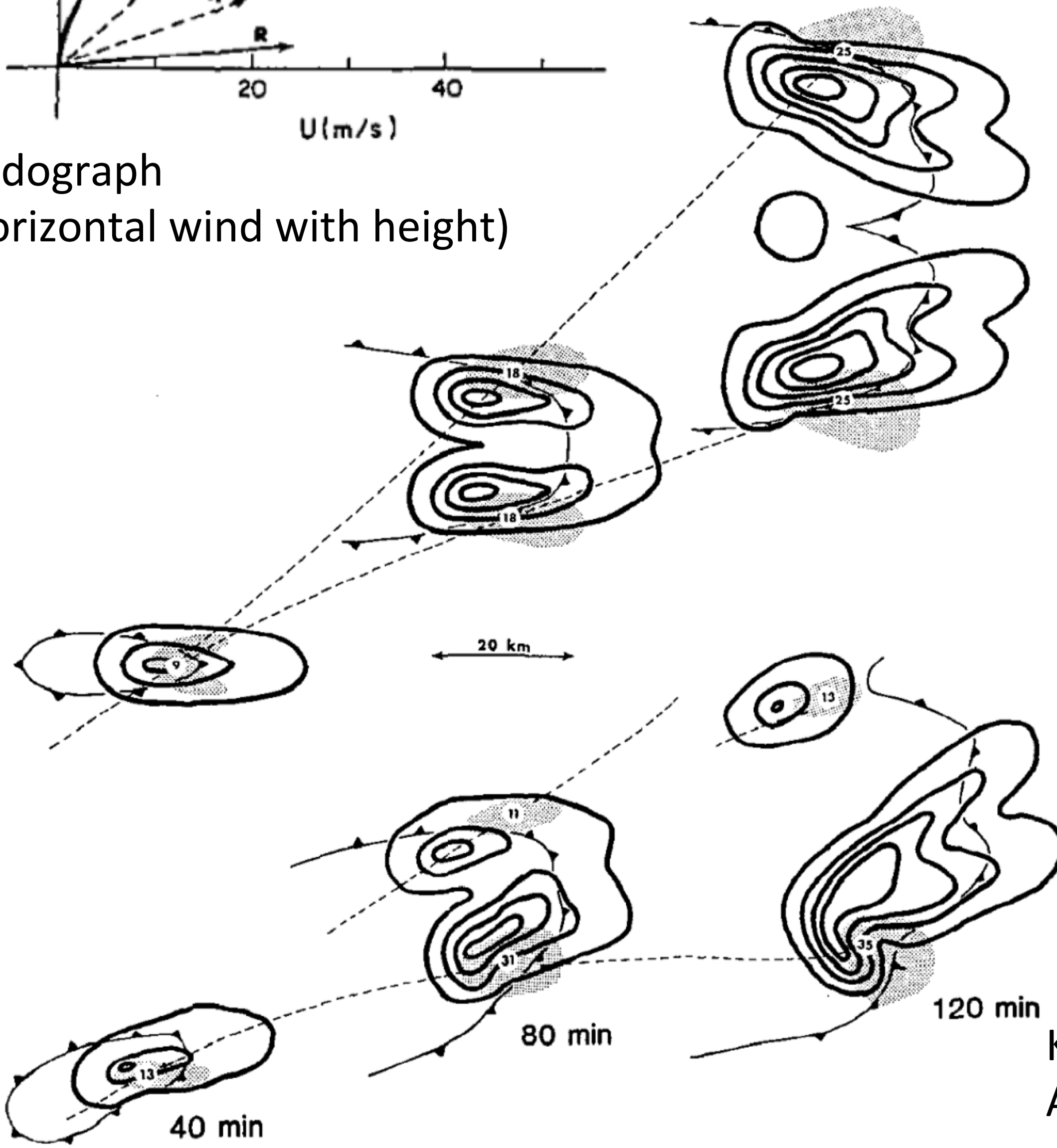
The initial rain core is what drives the splitting. Horizontal vorticity and its tilting is integral to splitting process and subsequent evolution of the storms.

Klemp, 1987,
Annual Review of Fluid Mechanics

Splitting supercells



Hodograph
(horizontal wind with height)



Straight-line hodograph (top) produce symmetric splitting storms.

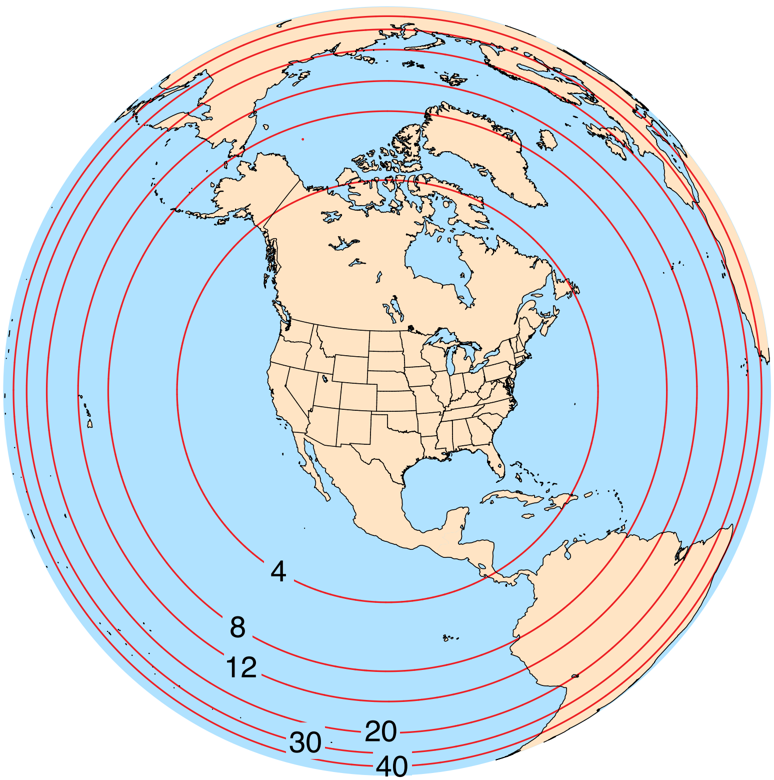
Clockwise curvature hodograph (bottom) favoring the right mover.

2.5 km reflectivity (lines)
Updrafts (shaded)

Klemp, 1987,
Annual Review of Fluid Mechanics

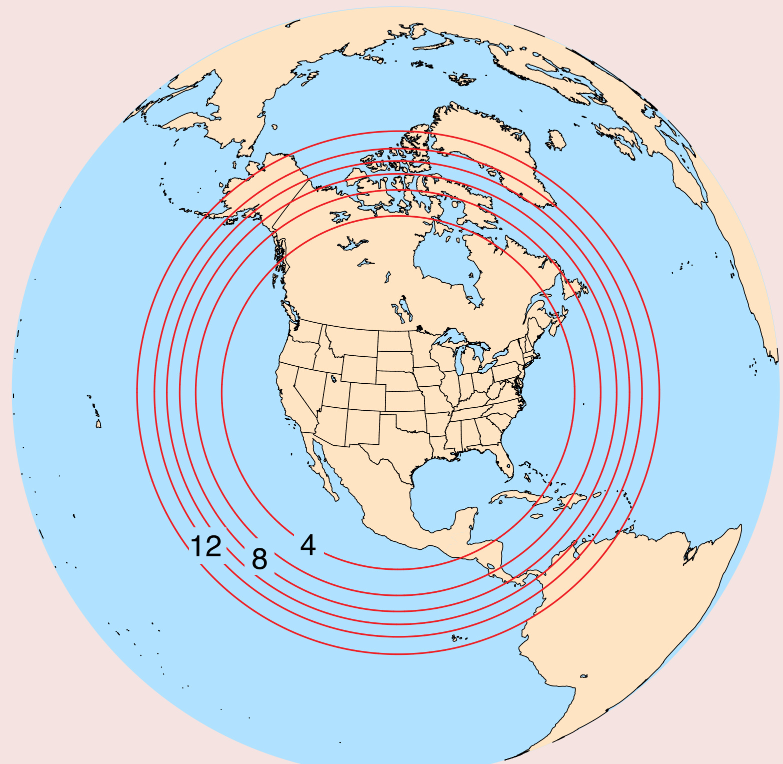
MPAS
Model for Prediction Across Scales

HWT Spring Experiment
5-day forecasts, 50 – 3 km mesh
1-31 May 2015



3-50 km mesh, Δx contours 4, 8, 12, 20, 30, 40
approximately 6.85 million cells
68% have < 4 km spacing

(1) PECAN field campaign
3-day forecasts
7 June – 15 July 2015
(2) HWT Spring Experiment
1-31 May 2016, 5-day forecasts



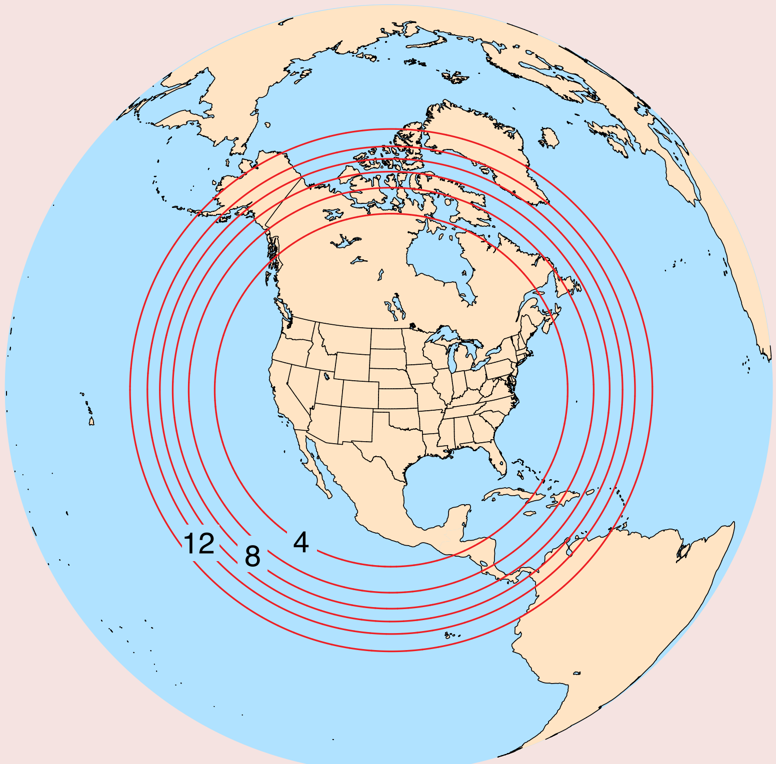
3-15 km mesh, Δx contours
approximately 6.5 million cells
50% have < 4 km spacing

MPAS
Model for Prediction Across Scales

MPAS Physics:

- WSM6 cloud microphysics (2015)
  (Thompson microphysics 2016)
- Grell-Freitas convection scheme
  (scale-aware)
- Monin-Obukhov surface layer
- MYNN PBL
- Noah land-surface
- RRTMG lw and sw.

(1) PECAN field campaign
3-day forecasts
7 June – 15 July 2015
(2) HWT Spring Experiment
1-31 May 2016, 5-day forecasts



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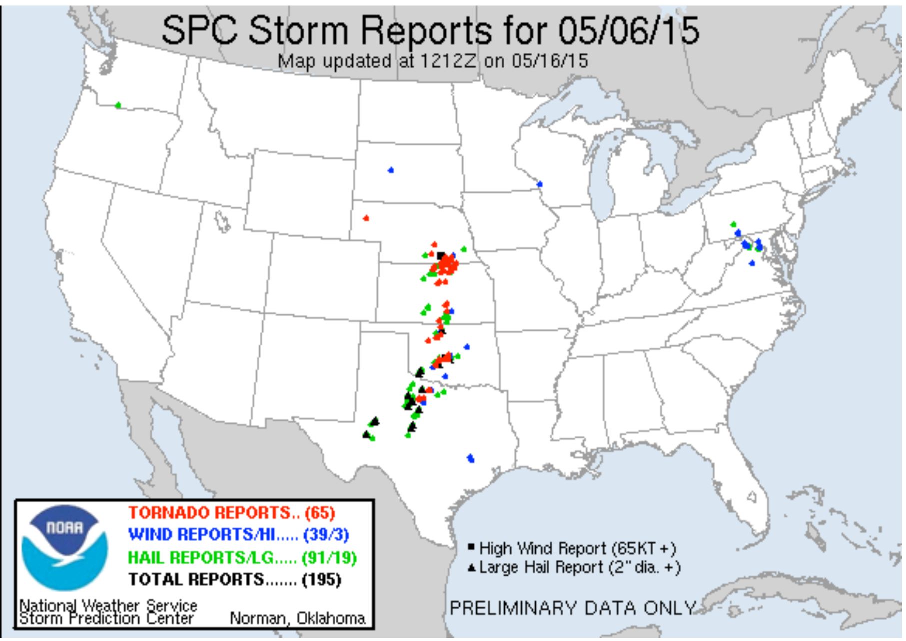
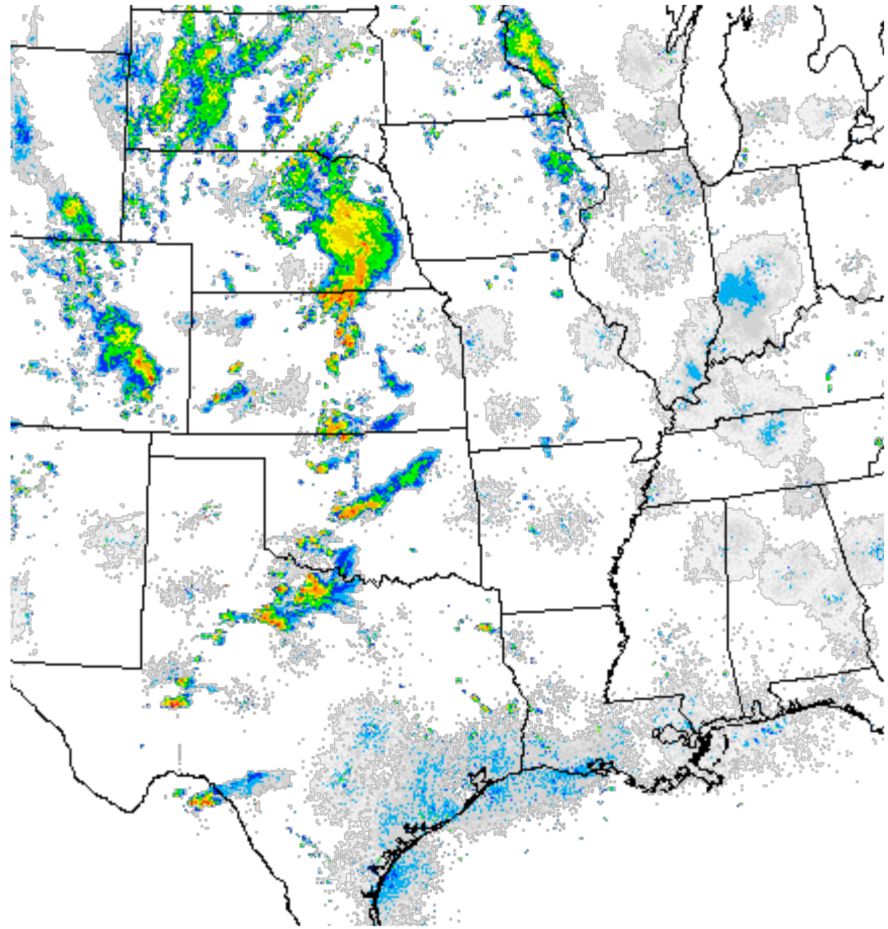
MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed Spring Experiment 2015

Forecasts Results from MPAS



Reflectivity, NOAA SPC archive
valid 2015-05-07 00 UTC



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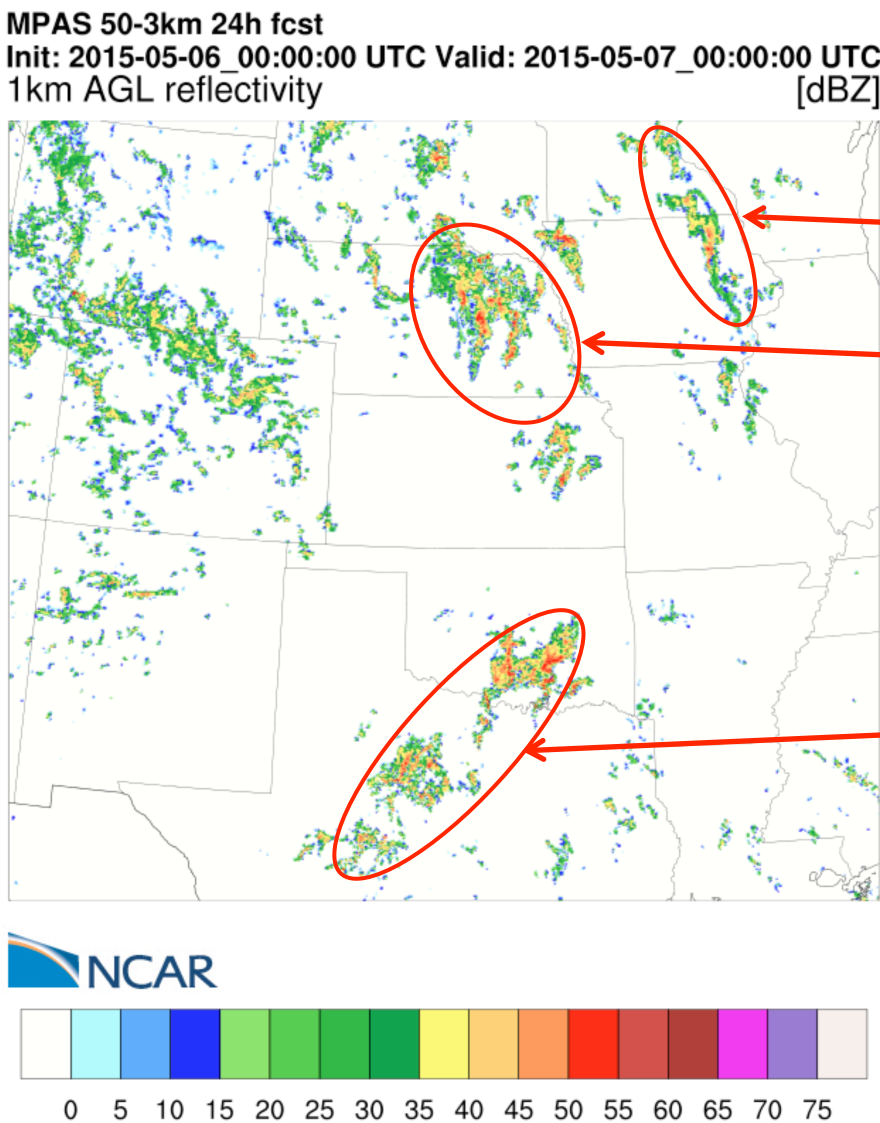
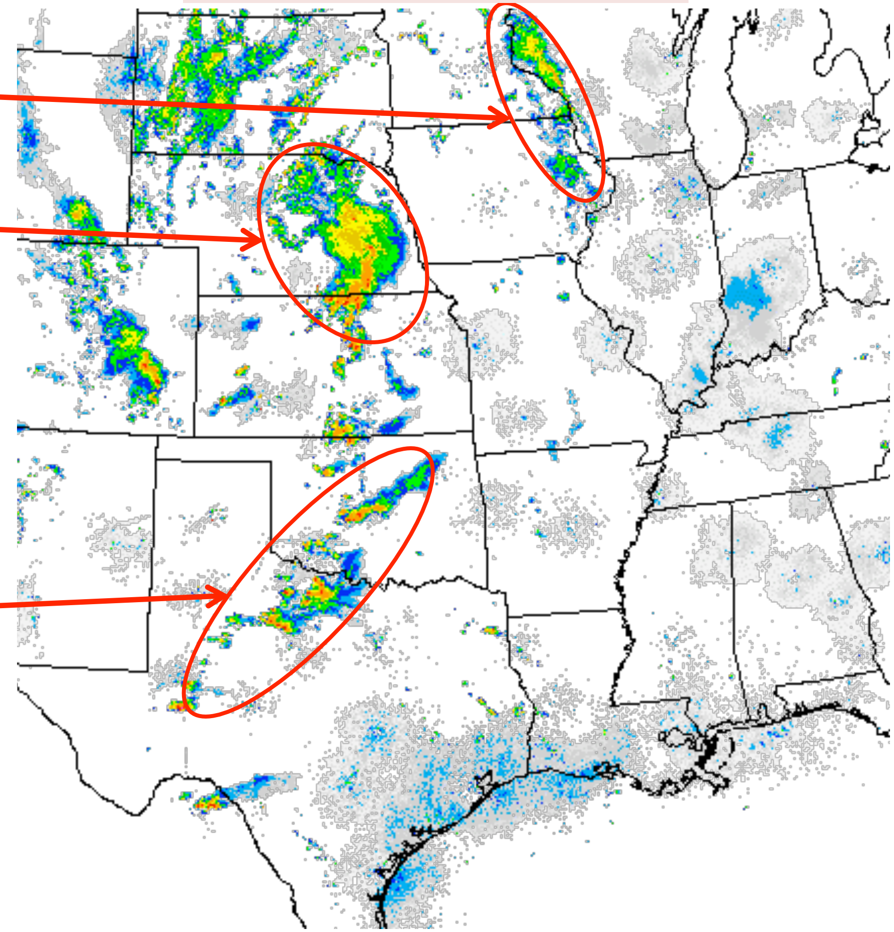
Model for Prediction Across Scales

Hazardous Weather Testbed Spring Experiment 2015
Forecasts Results from MPAS



Reflectivity, NOAA SPC archive valid 2015-05-07 00 UTC



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Spring Experiment 2015
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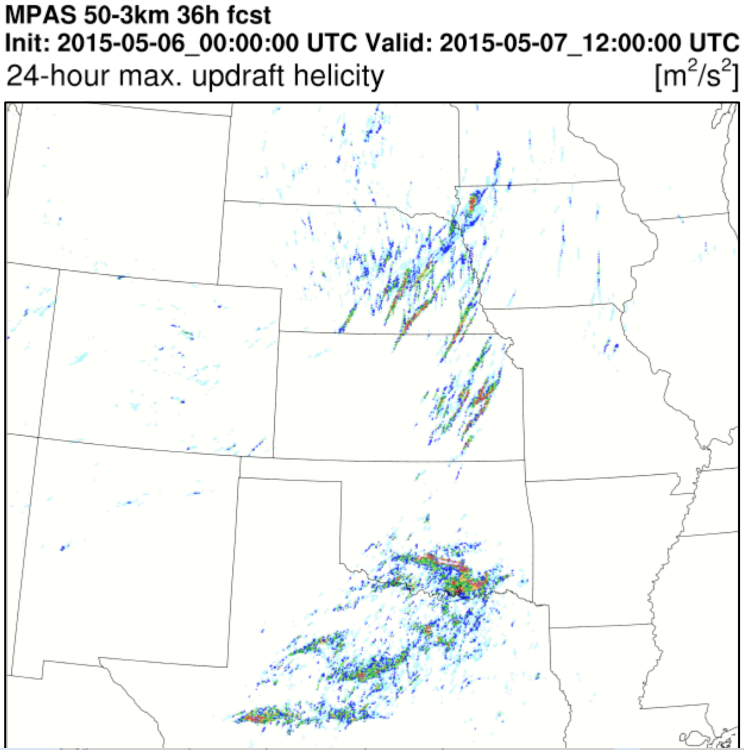
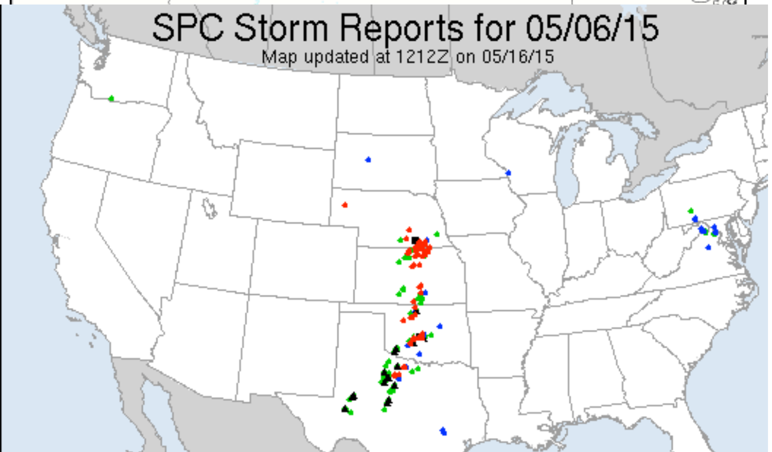


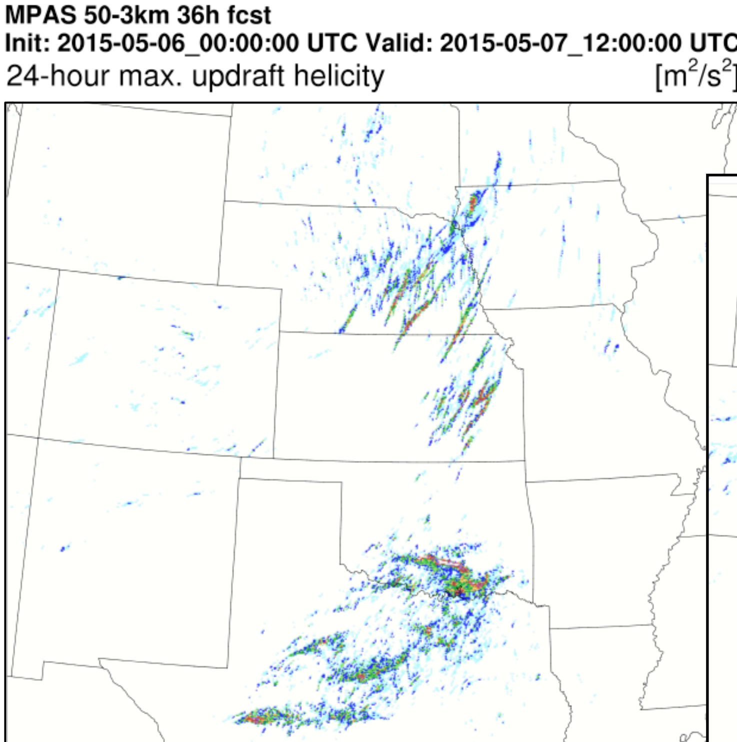


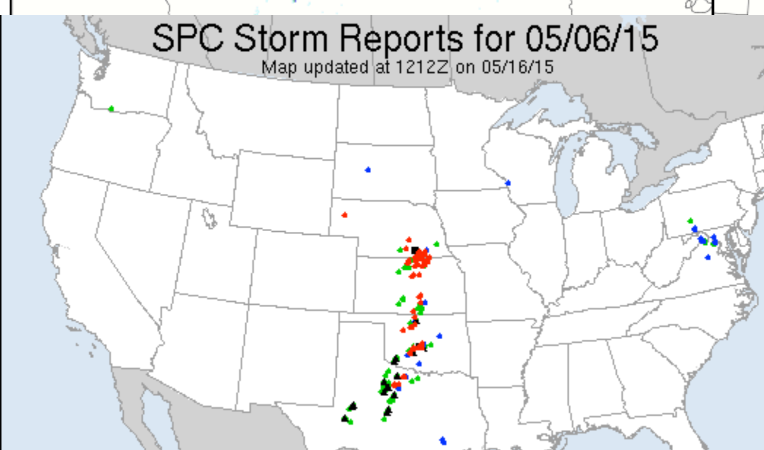
$$\text{Helicity} = V \cdot \zeta_{rel}$$

$$\begin{aligned} \text{Updraft helicity} &= w \cdot \zeta_{rel} \\ &= w \times \text{vertical relative vorticity} \end{aligned}$$

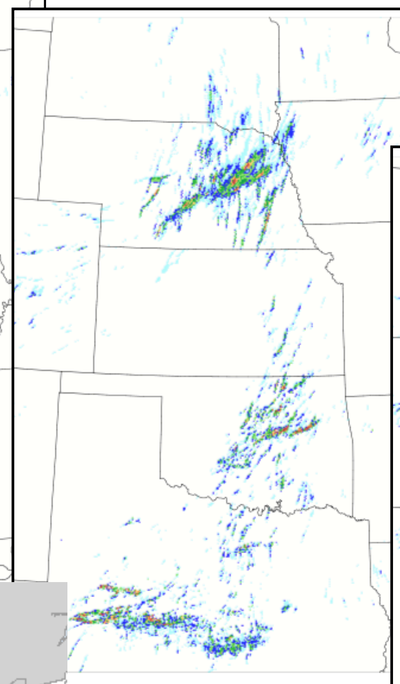
Hazardous Weather Testbed Spring Experiment 2015
Forecasts Results from MPAS

MPAS
Model for Prediction Across Scales

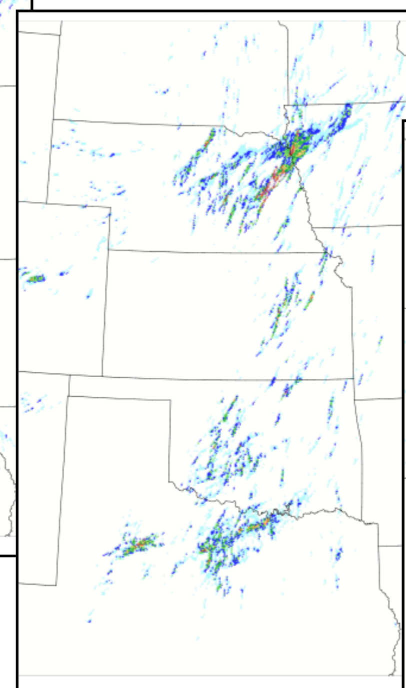




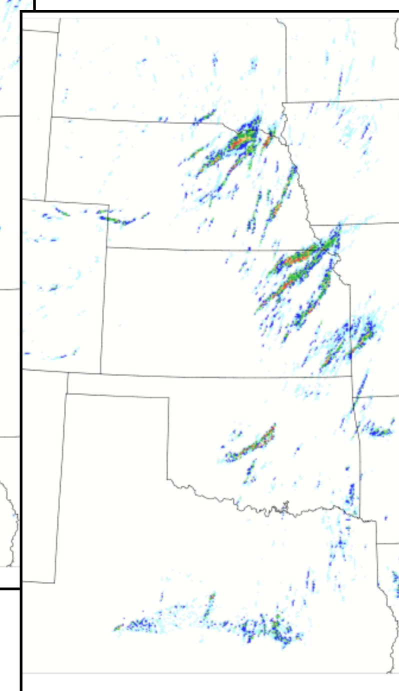
60h forecast



84h forecast



108h forecast

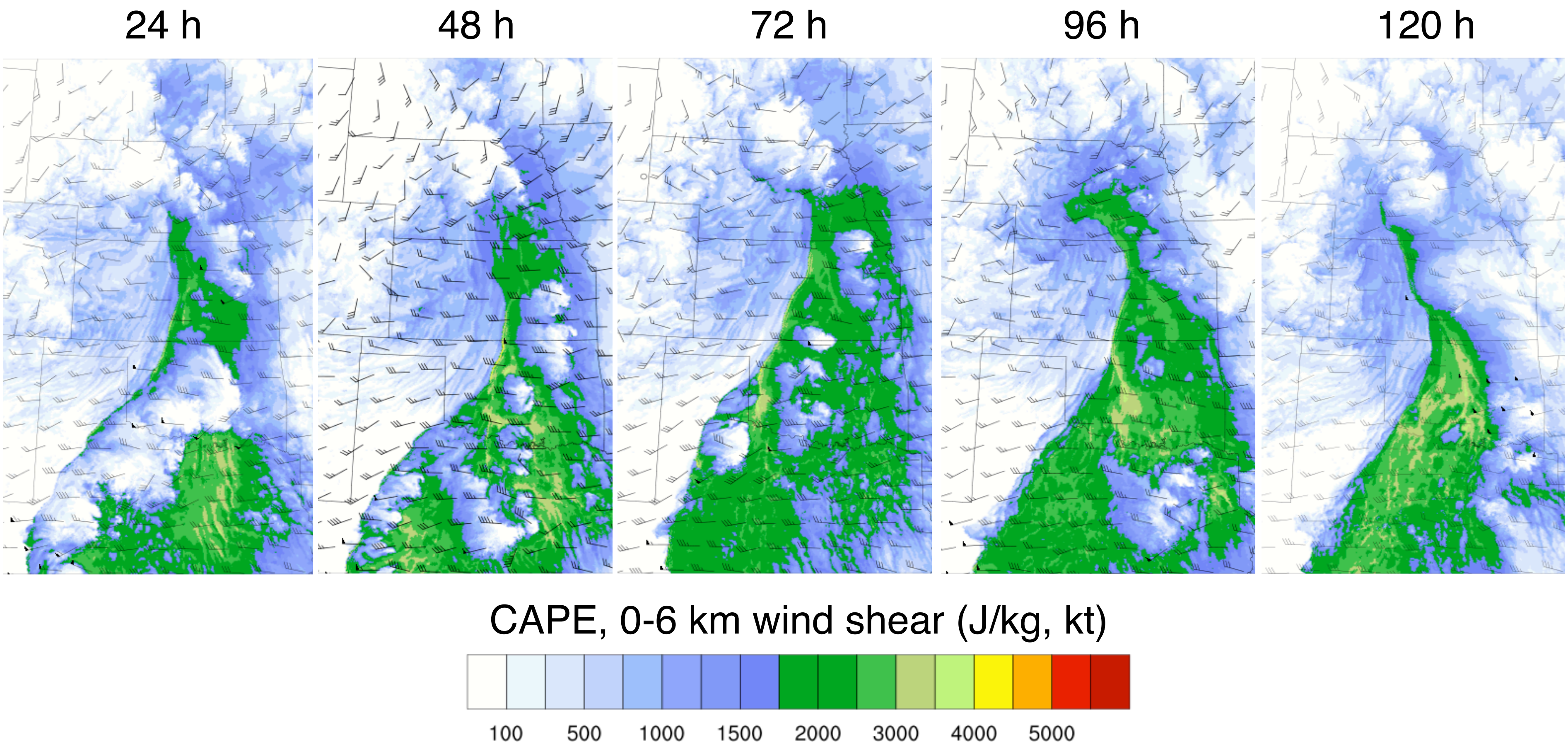


MPAS

Model for Prediction Across Scales

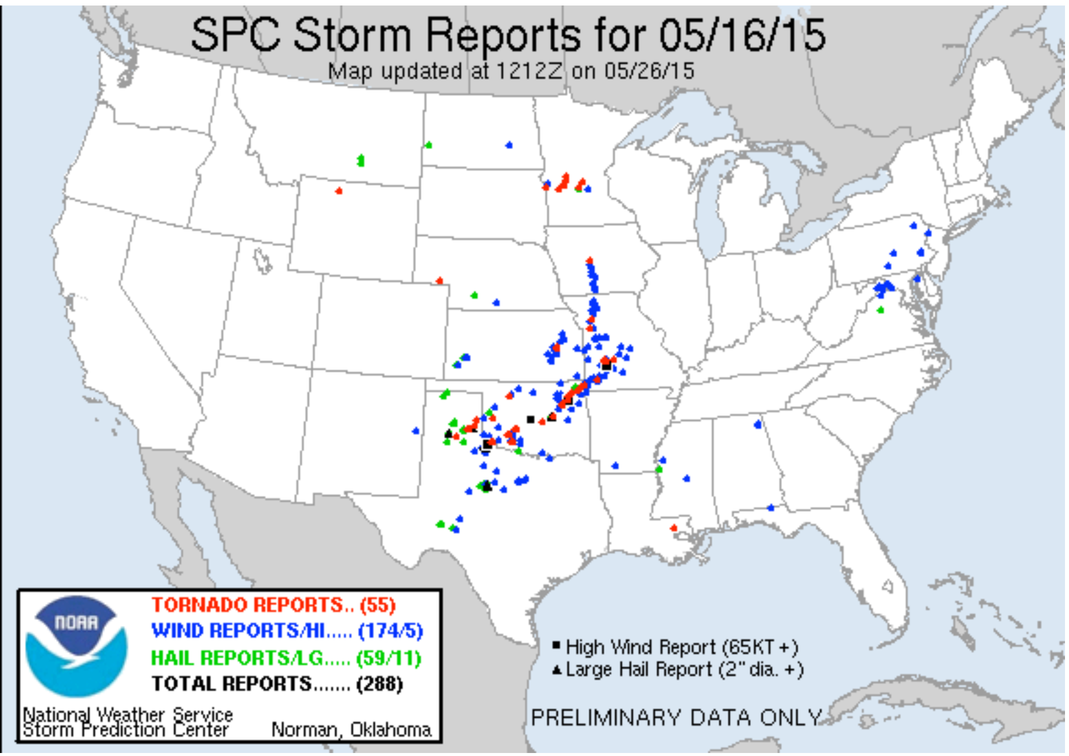
Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS

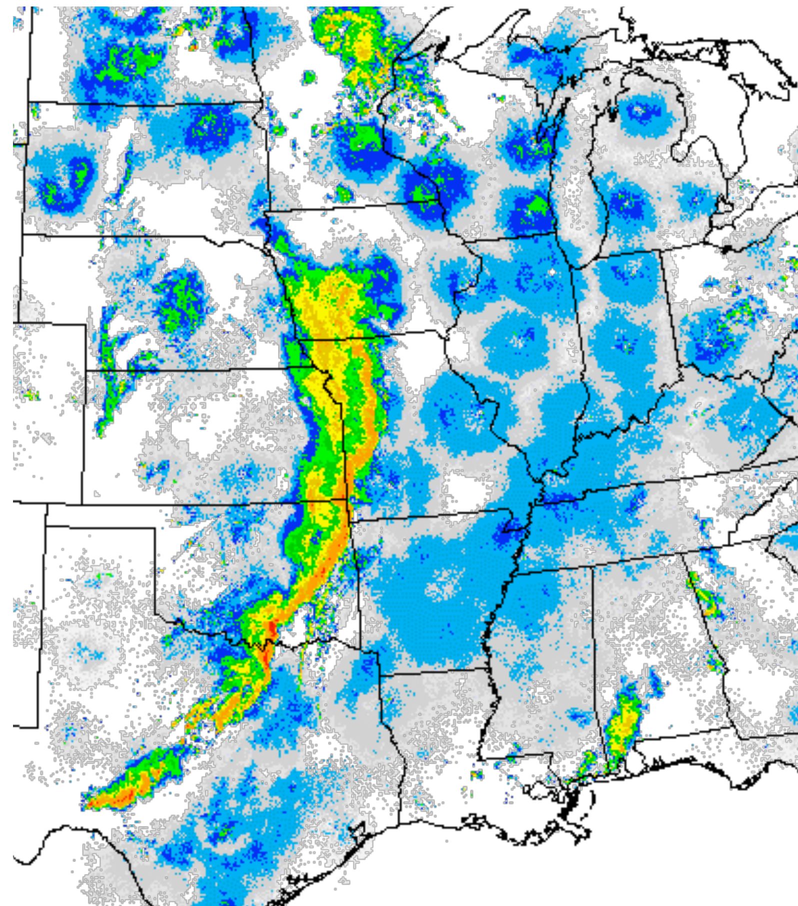
Forecasts valid 2015-05-7 00 UTC



Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS

Reflectivity, NOAA SPC archive
valid 2015-05-17 06 UTC





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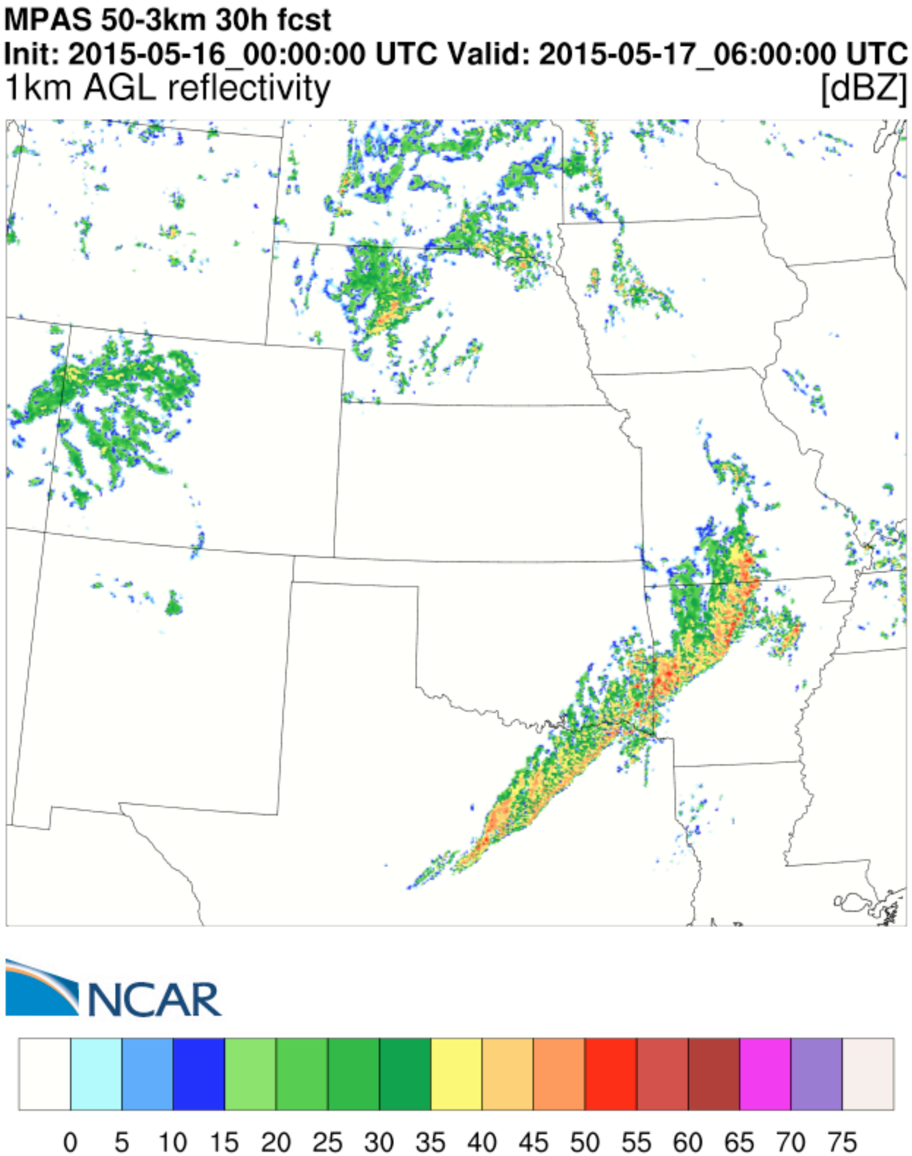

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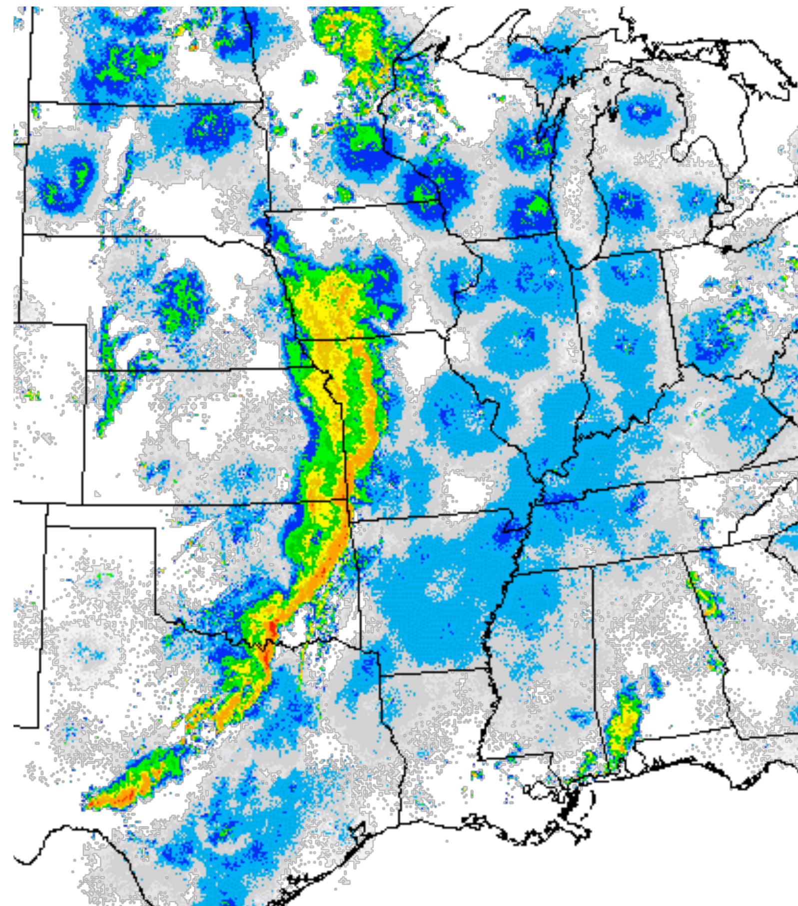

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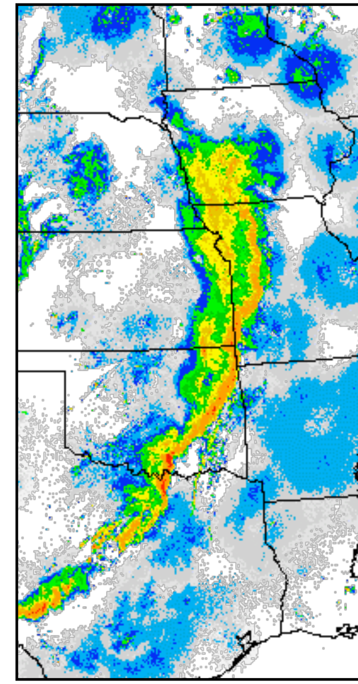
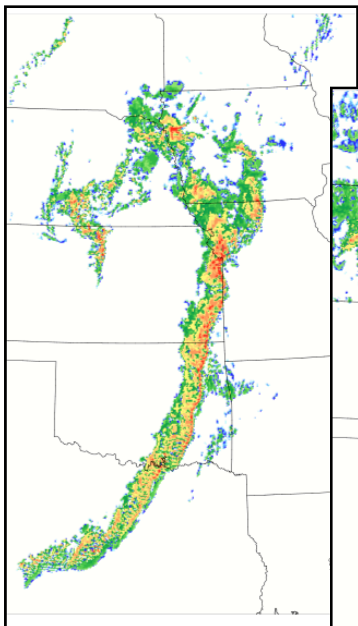
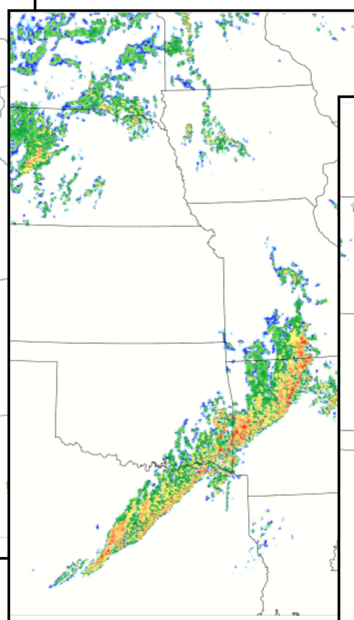


Reflectivity
NOAA SPC archive
2015-05-17 06 UTC

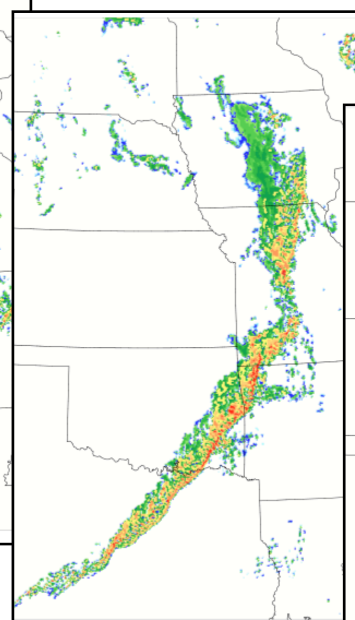
6 h forecast



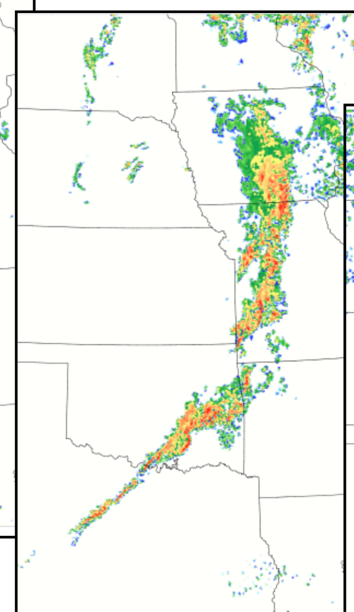
30 h forecast



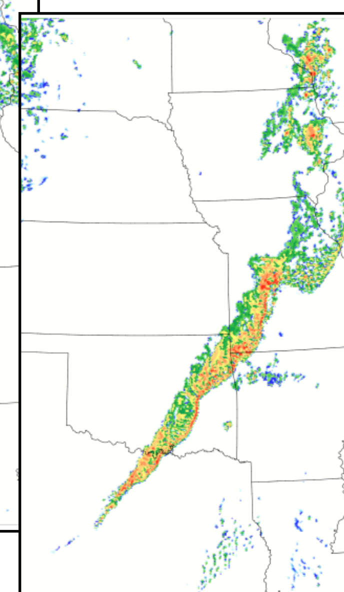
54 h forecast



78 h forecast



102 h forecast

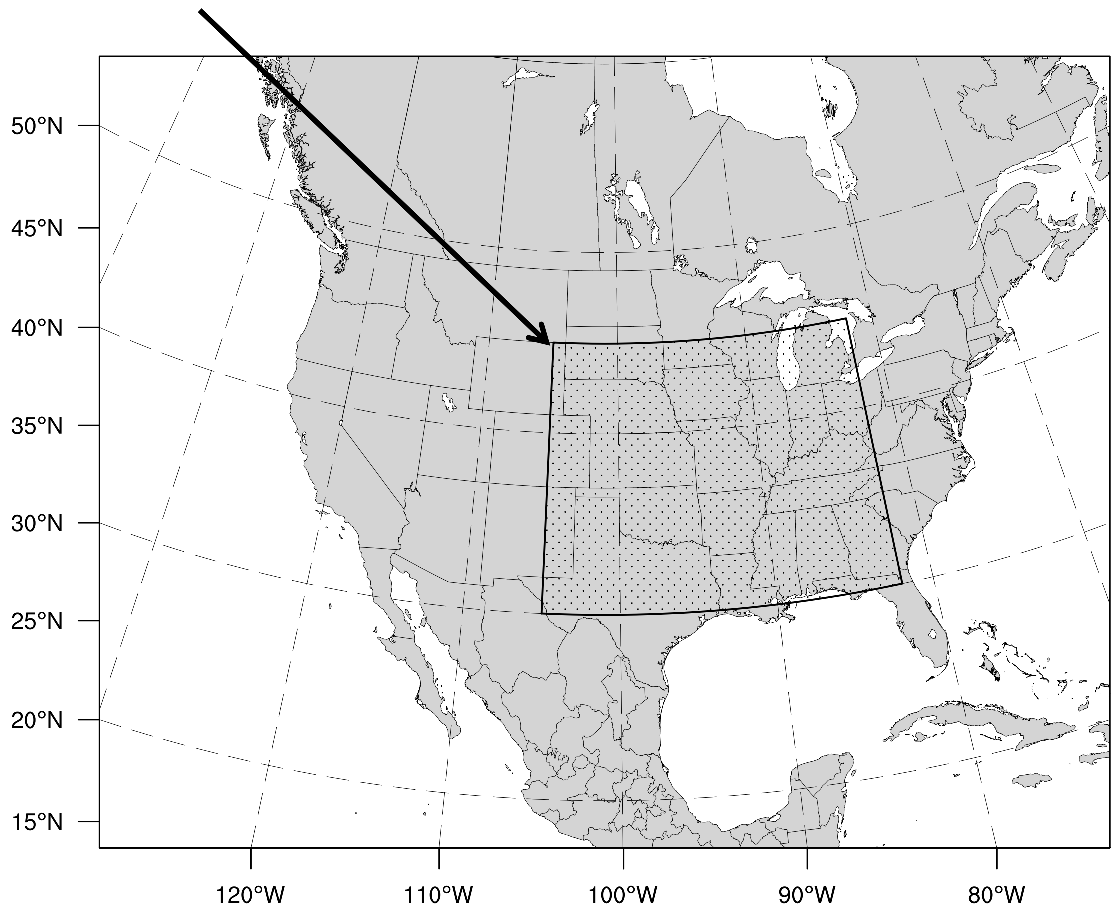


1 km AGL reflectivity
Forecasts valid 2015-05-17 6 UTC

Hazardous Weather Testbed Spring Experiment 2015

Verification against ST4 precipitation analyses

Verification region

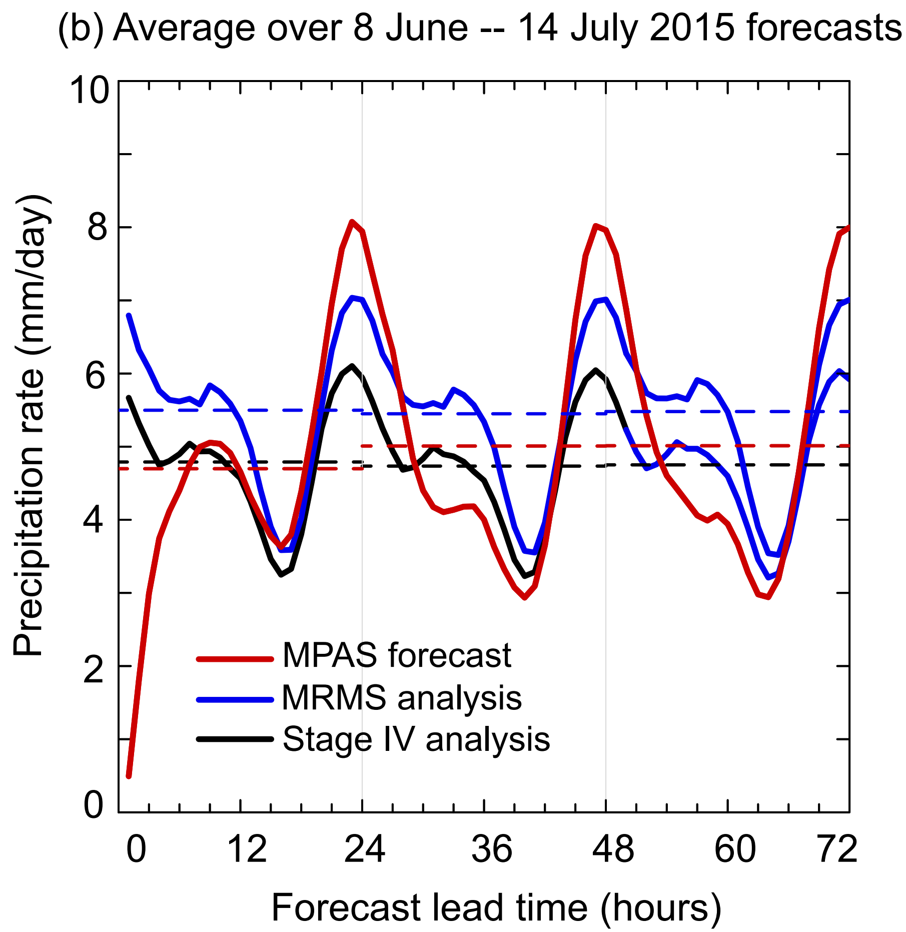


MPAS
Model for Prediction Across Scales

Verification against ST4 and MRMS analyses

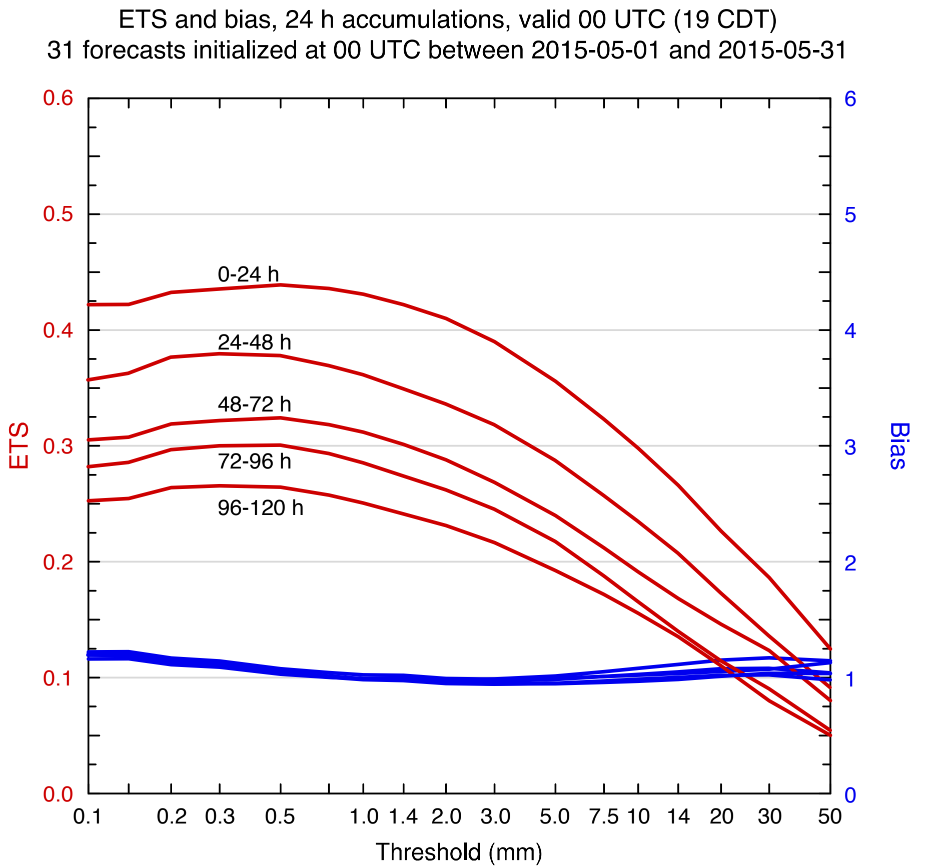
- Timing of diurnal precipitation maxima and minima is very good.
- Significant over-estimation of diurnal precipitation maxima.
- Significant underestimation of diurnal precipitation minima.
- Over (under) estimation does not improve over time.

- Daily average precipitation (dashed lines) shows a small positive bias early, decreasing over time.



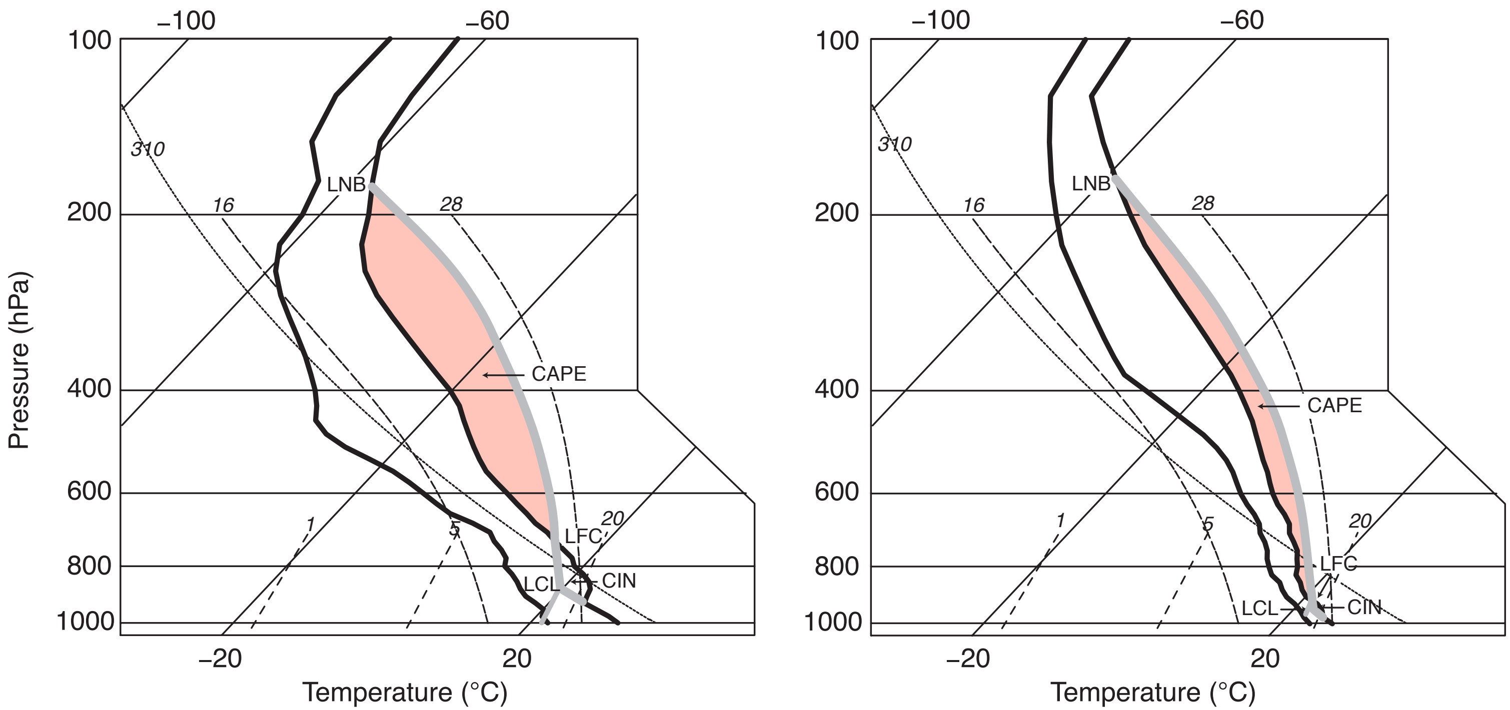
MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed
Spring Experiment 2015
Verification against ST4 precipitation analyses



24 h accumulations

Midlatitude and Tropical Deep Convection



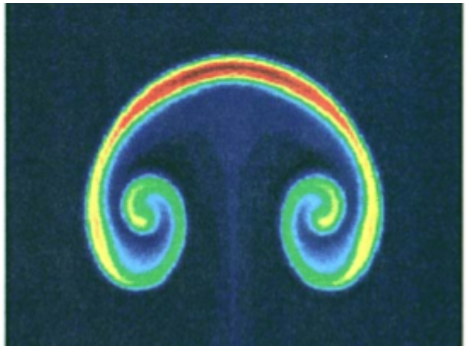
Skew T – log P diagrams for conditionally unstable
(left) warm-season continental midlatitude and (right) oceanic tropical
environments.

Tropical convection is more difficult to simulate than midlatitude convection

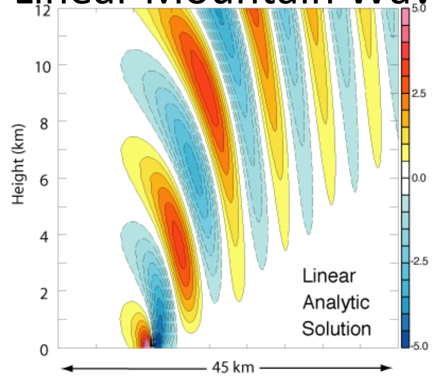
Adapted from Trier, S.B., 2003: Convective storms: Convective initiation.
Encyclopedia of Atmospheric Sciences, Academic Press, 560-569; Figure 1.

Nonhydrostatic Idealized Test Cases

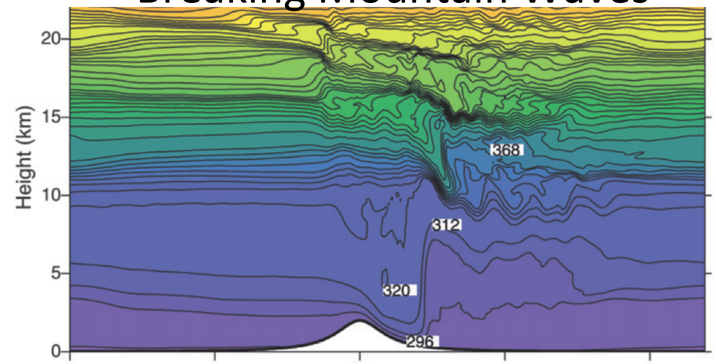
Warm Thermal



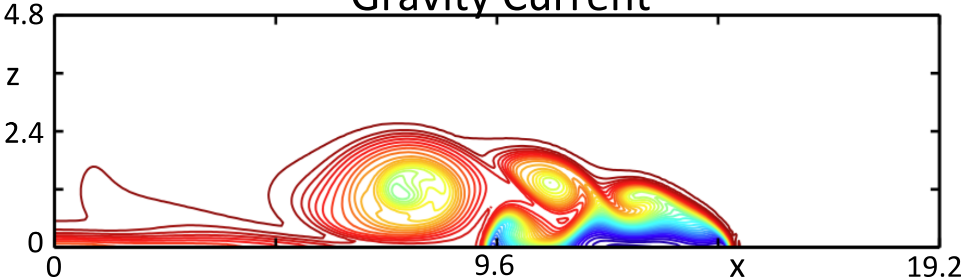
Linear Mountain Wave



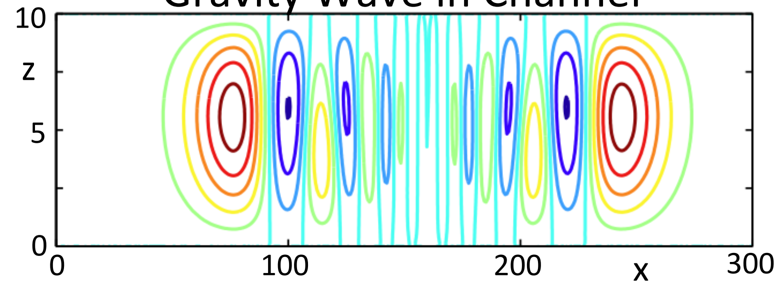
Breaking Mountain Waves



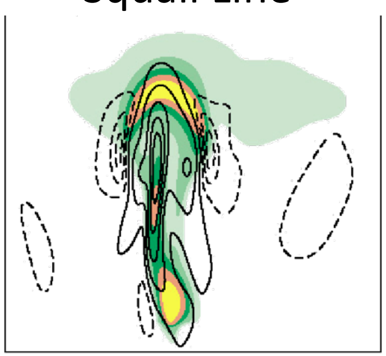
Gravity Current



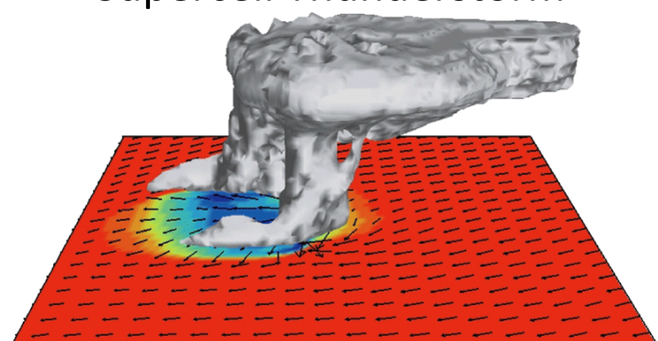
Gravity Wave in Channel



Squall LIne



Supercell Thunderstorm



Good test-case characteristics:

- Easy to configure and analyze
- Require minimal model physics
- Known solution (analytic or converged)
- Discriminating test for some aspect of the numerics

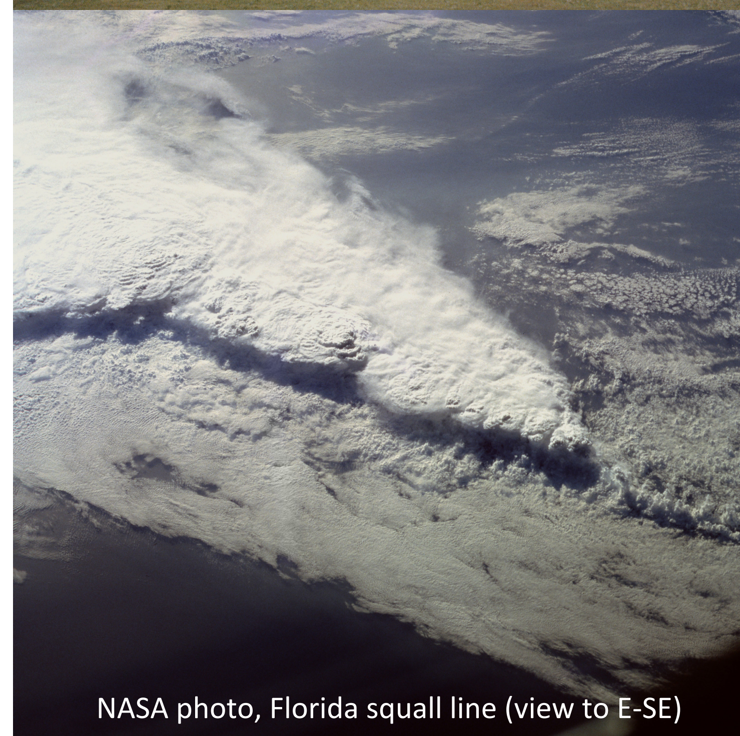
Final comments:

Deep moist convection testing is critical for evaluating nonhydrostatic cores.

Global convection-permitting simulations are costly.

- Some alternatives:
  - Variable-resolution
  - Nesting
  - Limited-area version of global model
  - 3D Cartesian plane version of the global model
  - 2D (x,z) version of the global model

DCMIP test cases are only a starting point for model testing.



NASA photo, Florida squall line (view to E-SE)