Numerical Simulation of a Tornadogenic Supercell

Leigh Orf
Assistant Professor of Meteorology
Central Michigan University
Mount Pleasant, MI

Overview

- What motivates my research
- Computational challenges of billion grid zone simulations
- Background information on supercells
- Current research focus:
  - Descending Reflectivity Cores (DRC's)
  - Tornadogenesis

What motivates my work

- It is my belief that, in general, meteorologists are not running their models at high enough resolution for the phenomena being studied (e.g., Bryan et al 2003)
- There are unsolved problems in meteorology which ***require*** (among other things) the most powerful computers in existence. This motivates the computer geek in me.
- We do not understand why tornadoes do (and do not) form within supercells. This motivates the meteorologist in me.

Current focus

- Microscale structure of supercell thunderstorms (with Matt Gilmore, UIUC)
  - Descending Reflectivity Cores (DRC's)
  - Tornadogenesis
- Microburst outflows applied to wind-loading on structures (with William Lin, U of W. Ontario)
- Creating a data management and visualization framework for Terabyte and Petabyte sized problems

Computational requirements of the supercell tornadogenesis problem

- Need to contain supercell plus its surrounding environment *while resolving tornado-scale flow*
- Typical supercell horizontal scale (as defined by reflectivity echoes): ~ 50 km
- Typical tornado horizontal scale: ~ 100 m
- Even 50 meter grid spacing is not enough to resolve flow scales important to tornadogenesis

1 billion grid points, 10 trillion bytes

- 2400x2400x200 = 1.15 billion
- 120 km x 120 km x 20 km at 50 m horizontal grid spacing
- Multiply by ~30 arrays, each holding 4-byte floating point data. This is your memory requirement (about 600 GB in practice)
- Storage requirement: Dropping *lossy* history file data every 5 model seconds for 2 hour integration: 10 TB
  - High temporal resolution required for understanding transient, rapidly developing phenomena (and smooth visualization/trajectory analysis)

How is this done?

- Massively parallel architectures with a lot of storage
- A well-written MPI model designed for this architecture
- Split the job over many processors
  - Biggest run thus far: 2400x2400x100 over 320 processors. Took 94 wallclock hours for 2 model hours.
- History file data stored in pieces rather than in 1 file
  - Each computational node writes its own piece of the domain to disk
  - Post-processing software handles this distributed file format
  - `http://hdftools.sourceforge.net`

Tilting at windmills?

"The study of tornadogenesis in a fully three-dimensional model with moist physics and turbulence is a complex task. Some investigators believed that even if a tornado were generated in a three-dimensional supercell simulation, the flow would be so turbulent and complex that one would not be able to understand the physics of the flow[1]"

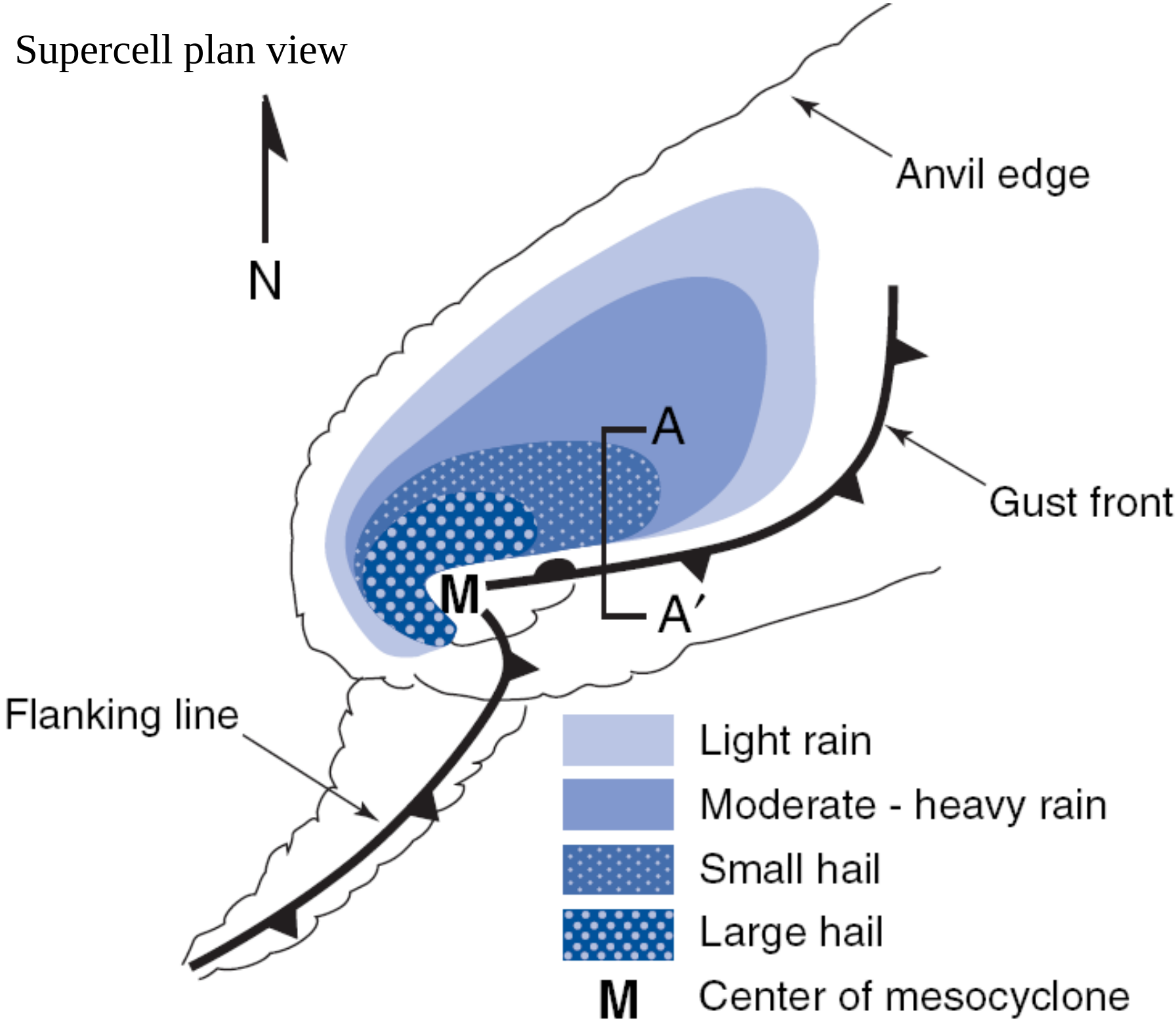
[1]This statement was made by a prominent senior research scientist to the second author (Wicker) while he was pursuing his Ph.D. research on tornadogenesis!

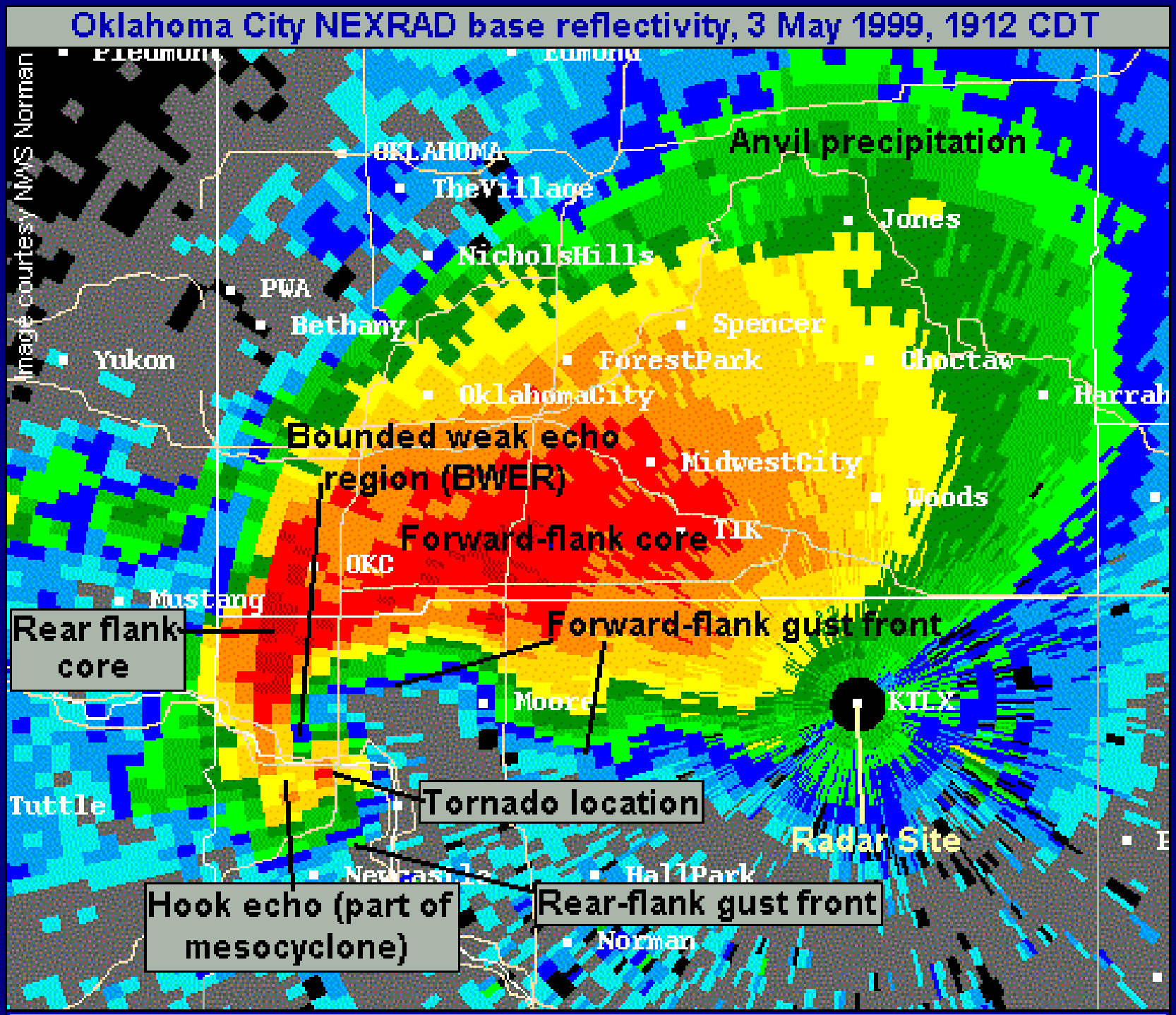
Wilhelmson and Wicker (2001). "Numerical Modeling of Severe Local Storms" *Severe Convective Storms monograph*

Supercell thunderstorms

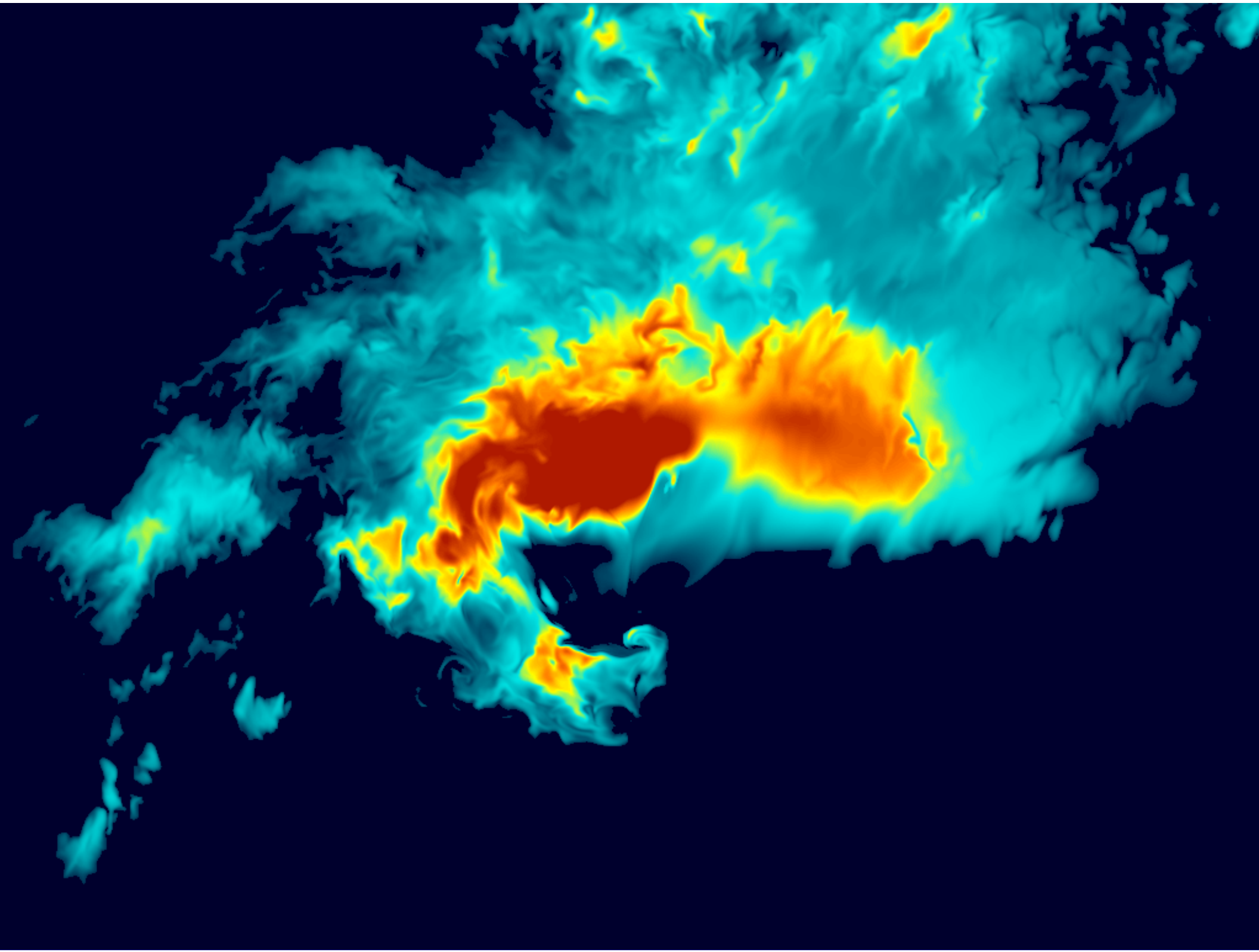
- Long lived
- Rotating updraft (mesocyclone)
- Produce strongest tornadoes
- Favorable environmental conditions:
  - Very unstable atmosphere (large values of CAPE)
  - Large amounts of wind shear throughout troposphere

Supercell plan view



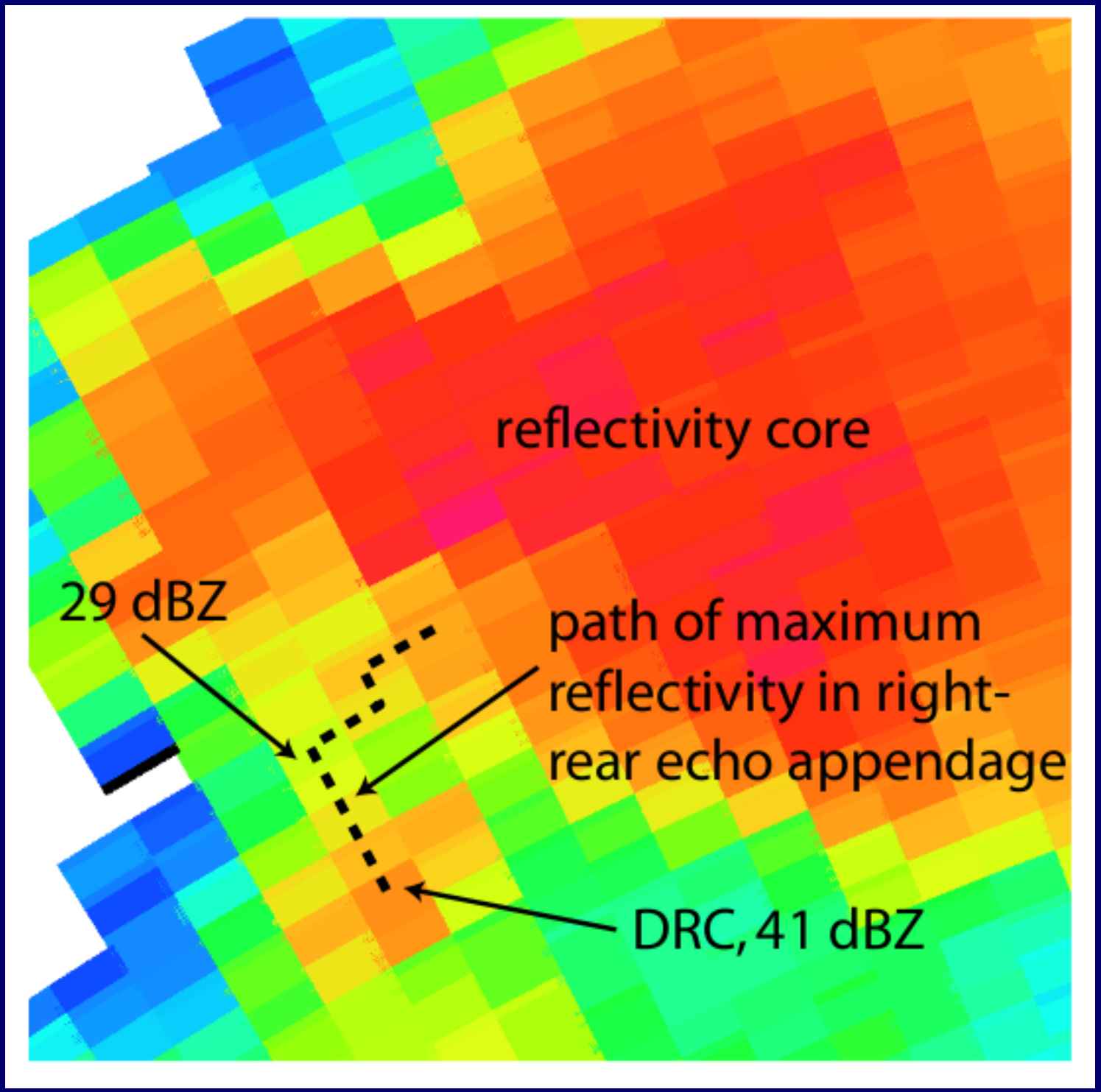


RADAR DEPICTION OF A CLASSIC SUPERCELL CONTAINING A VIOLENT TORNADO

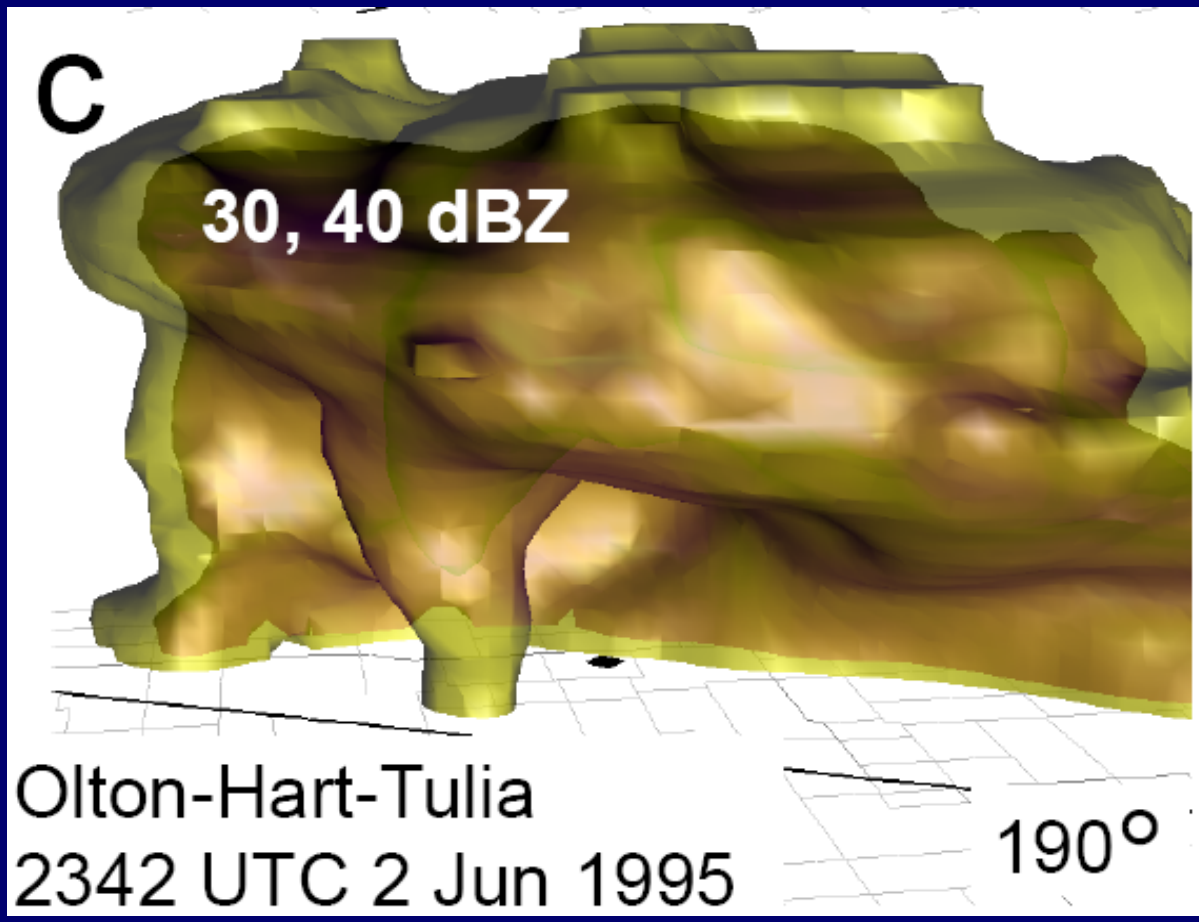


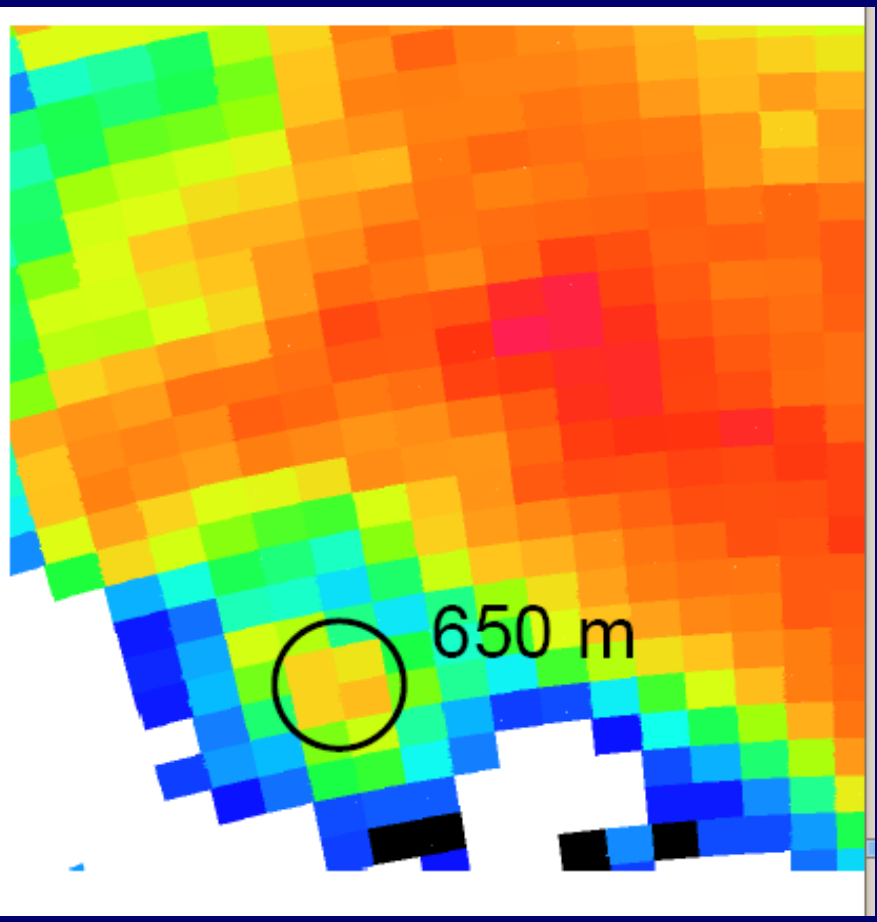
Descending Reflectivity Cores

- 2 June 1995: Texas panhandle outbreak captured by VORTEX
- Reflectivity signature found in tornadic storms from this event dubbed Descending Reflectivity Core (DRC)
- Rasmussen, E., J. M. Straka, M. S. Gilmore and R. Davies-Jones (2006) "A Preliminary Survey of Rear-Flank Descending Reflectivity Cores in Supercell Storms" *Weather and Forecasting* **(in press)**

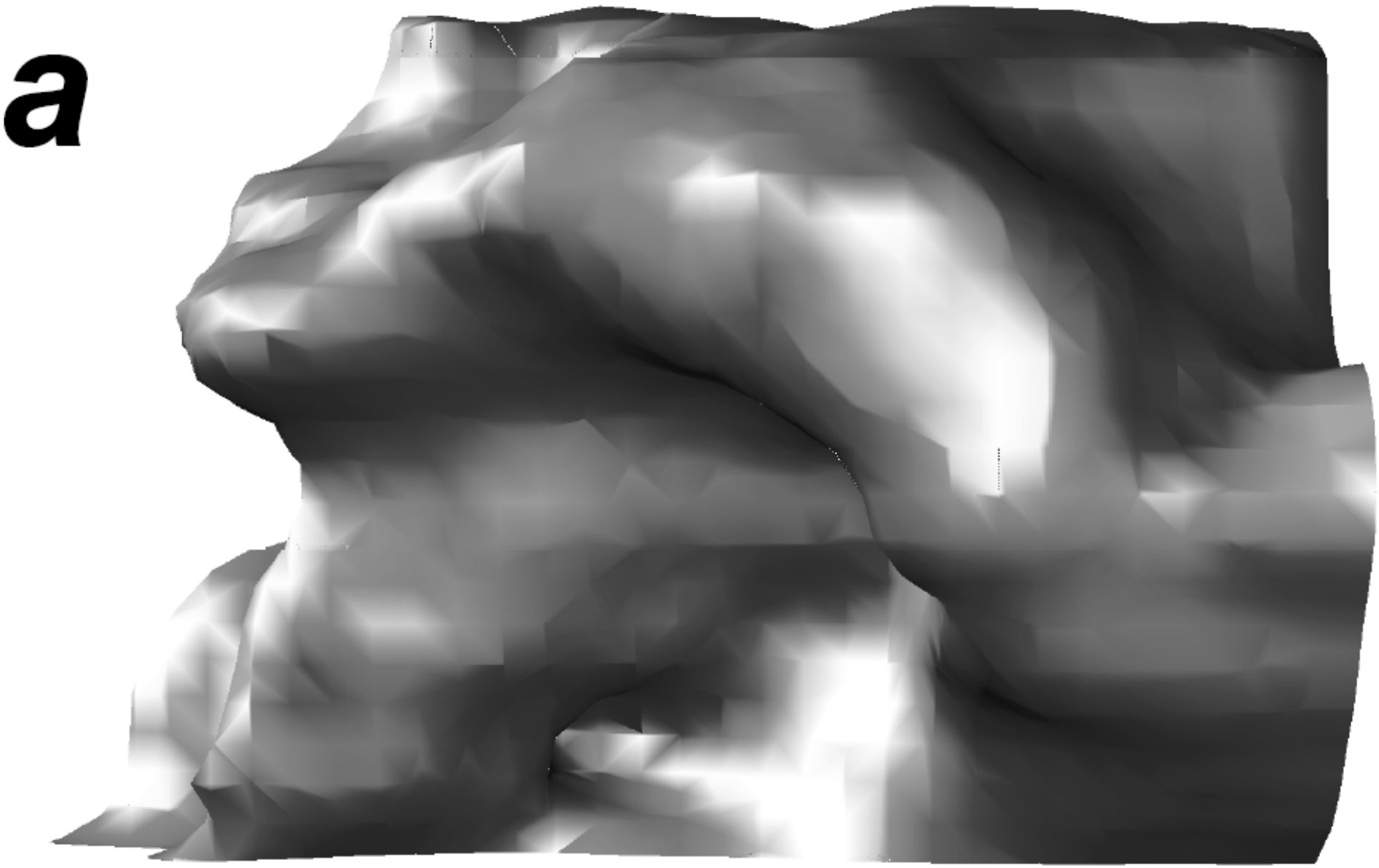

reflectivity core
29 dBZ
path of maximum
reflectivity in right-
rear echo appendage
DRC, 41 dBZ

DRC isosurface + reflectivity

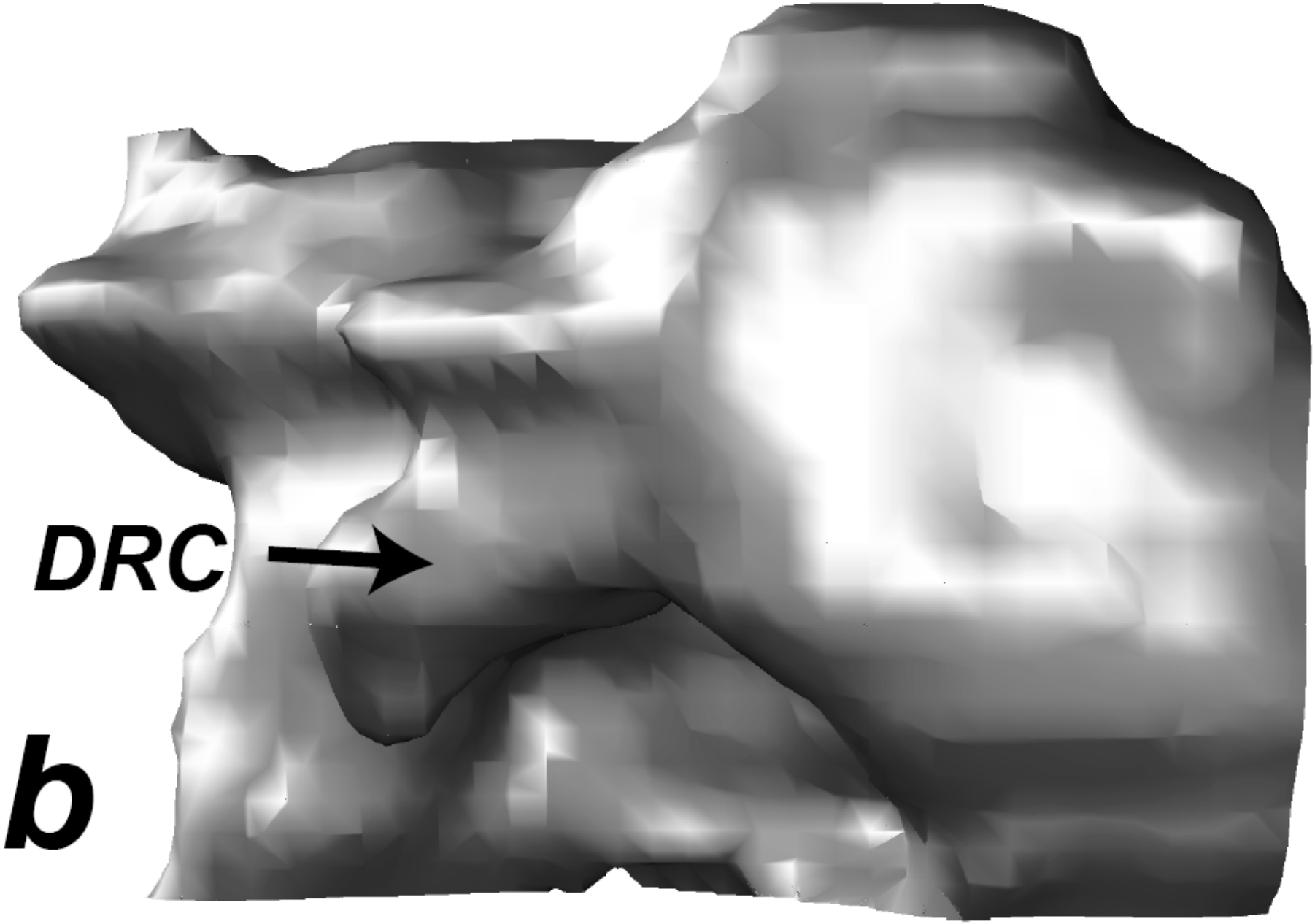




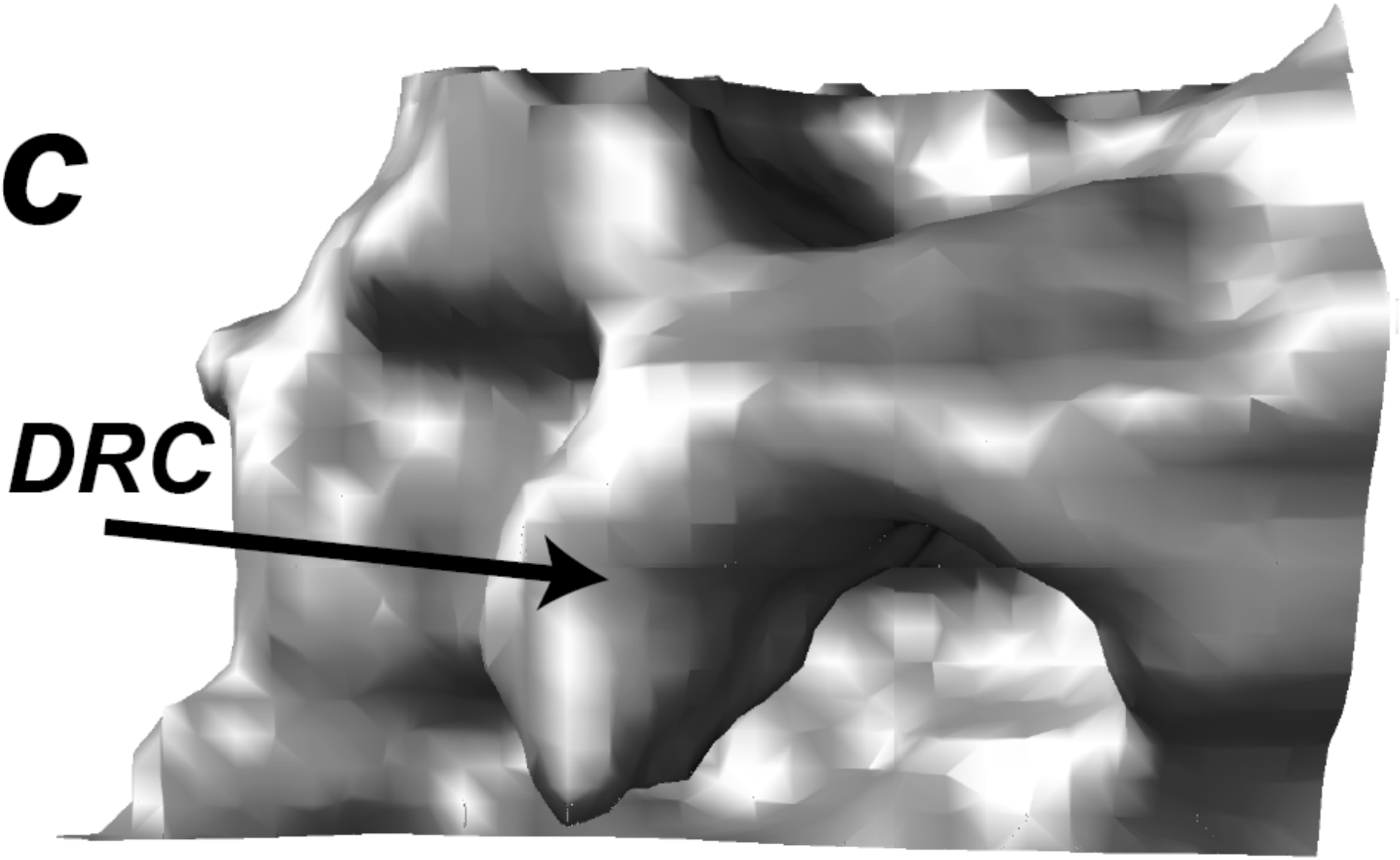
The following four slides are 40 dbZ isosurfaces of reflectivity of the Dimmitt, TX storm of 2 June 1995, viewed from the south



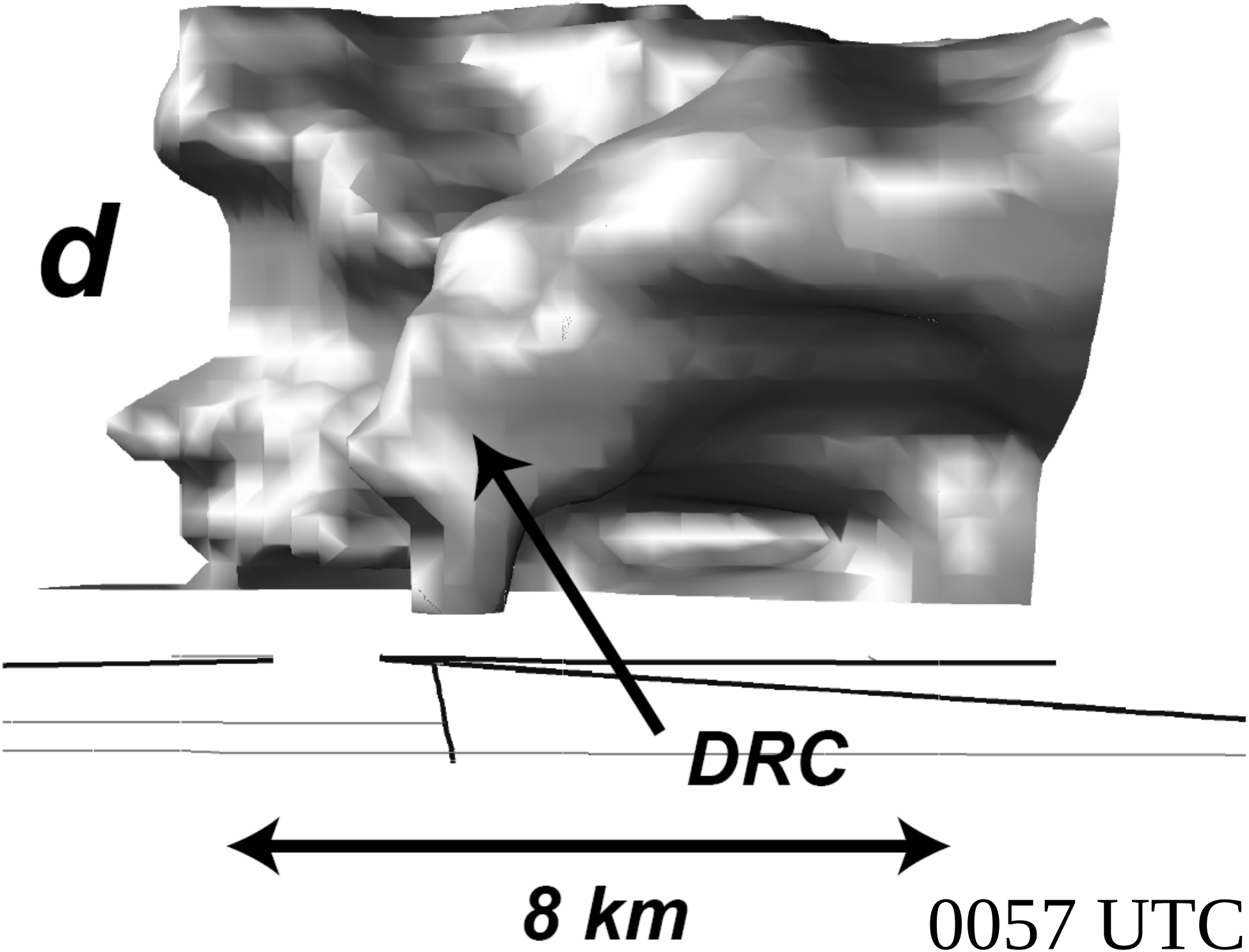
0042 UTC



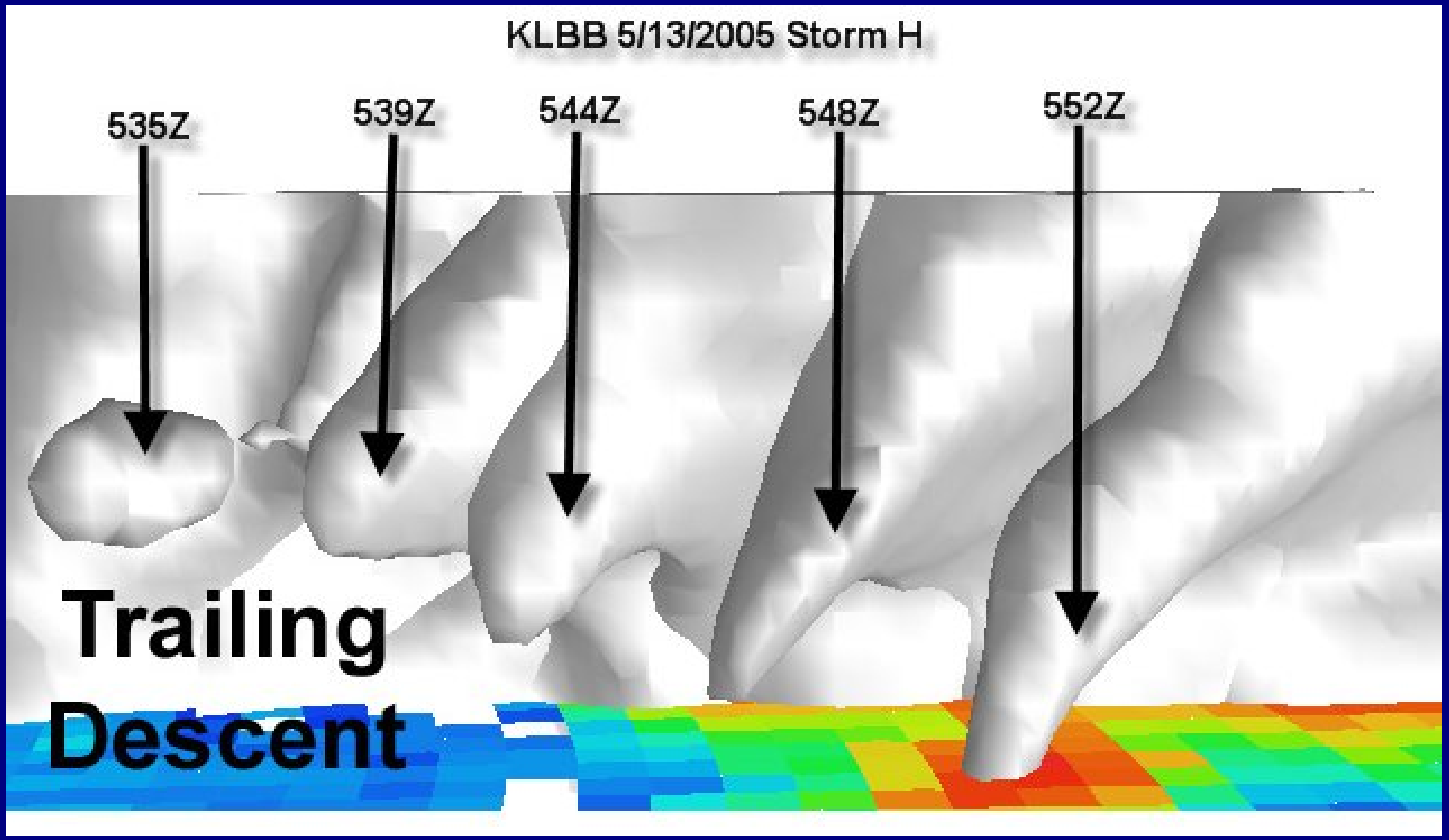
0047 UTC



0052 UTC


d
DRC
8 km
0057 UTC

One mode of DRC evolution



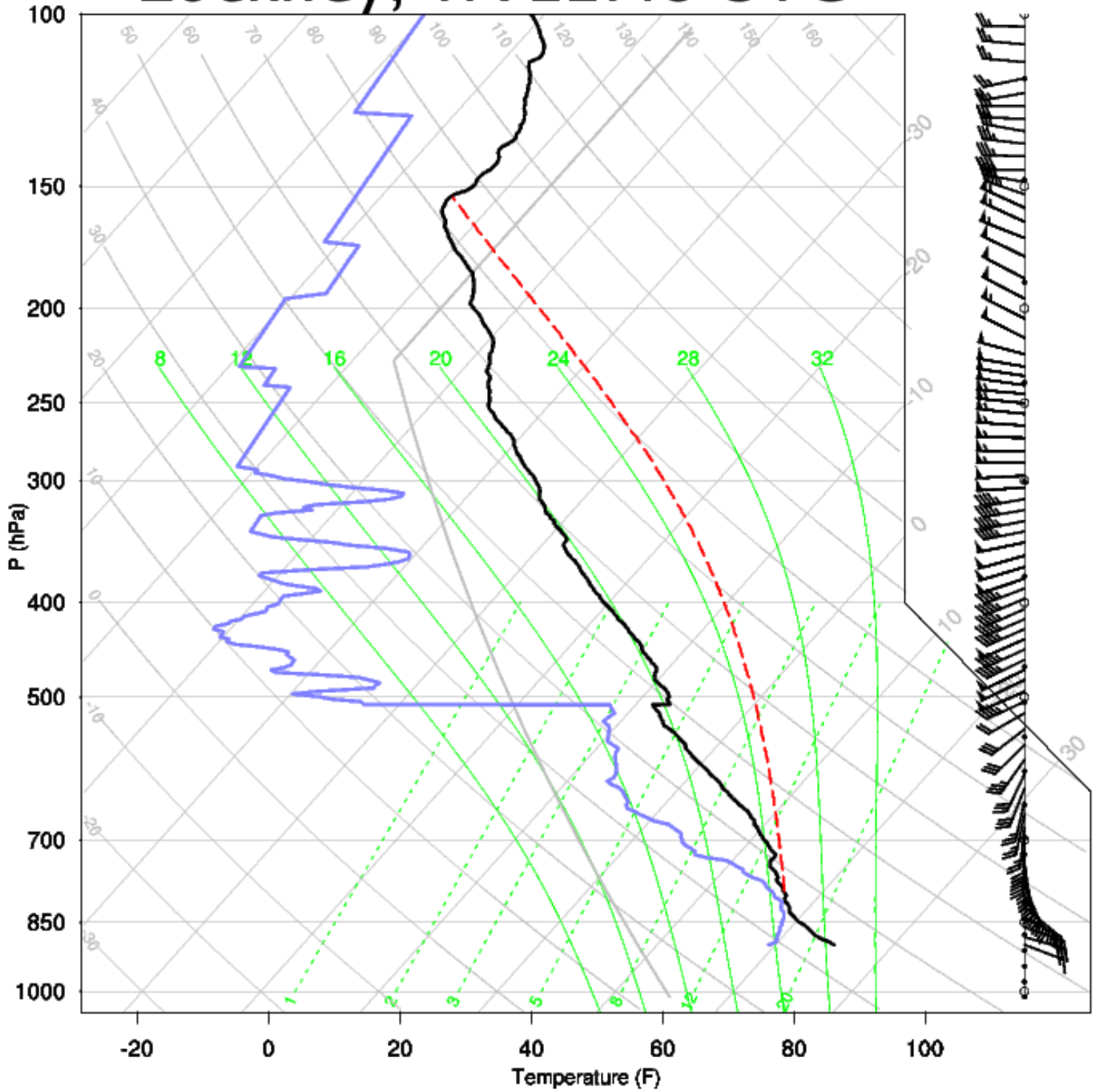
Aaron Kennedy (U of N Dakota)

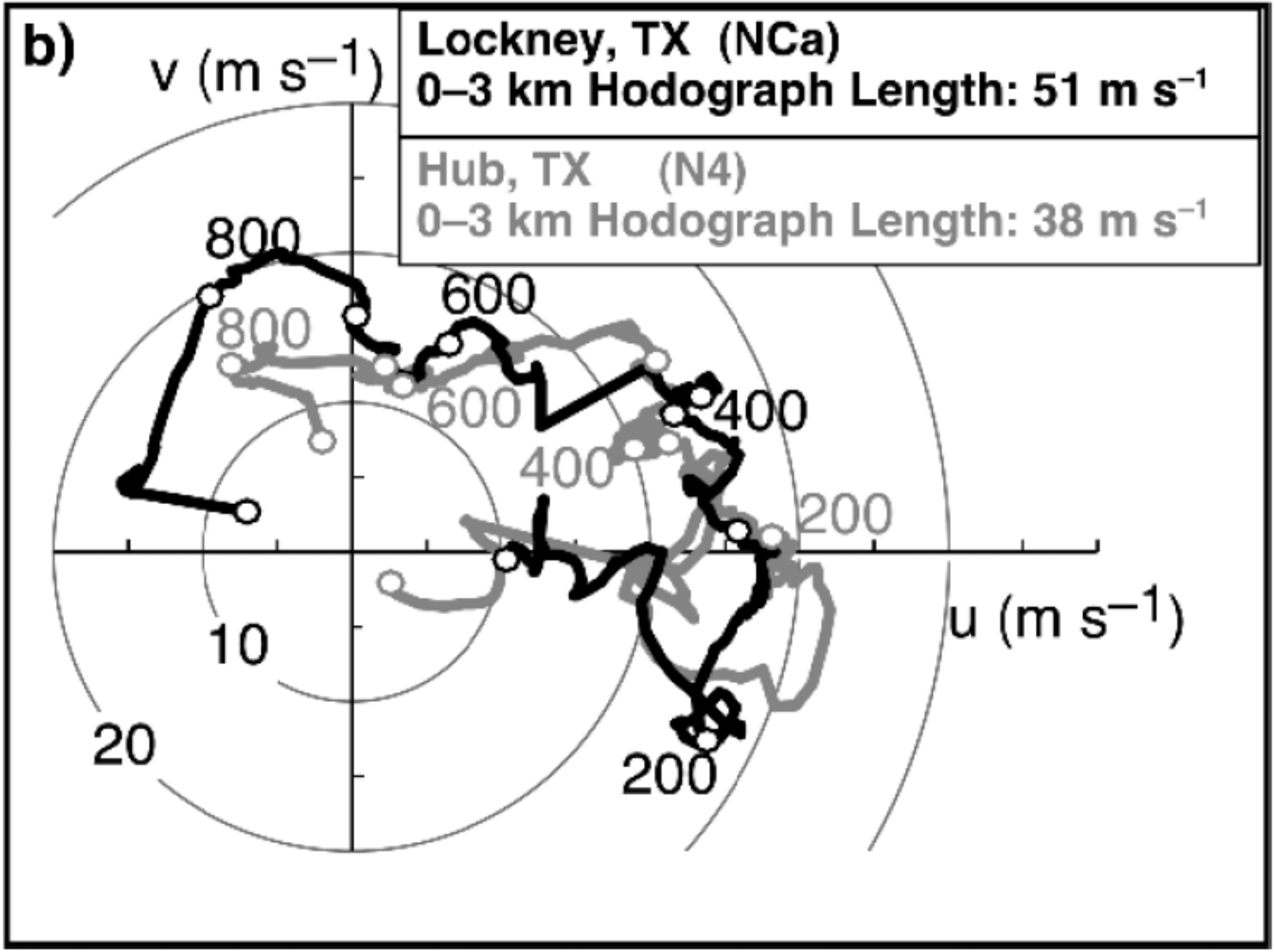
Kennedy et al (2006)

Questions

- **Given 2 June 1995 pre-storm environmental conditions as input, can a numerical model produce storms which exhibit DRCs?**
- Are DRCs indicative of wet microbursts?
- If so, how do DRC winds dynamically impact the storm's microscale structure?
- Is there any link between DRCs and tornadogenesis?

Lockney, TX 22:48 UTC




b)
v (m s−1)
Lockney, TX (NCa)
0–3 km Hodograph Length: 51 m s−1
Hub, TX (N4)
0–3 km Hodograph Length: 38 m s−1
800
600
400
200
800
600
400
200
10
20
u (m s−1)

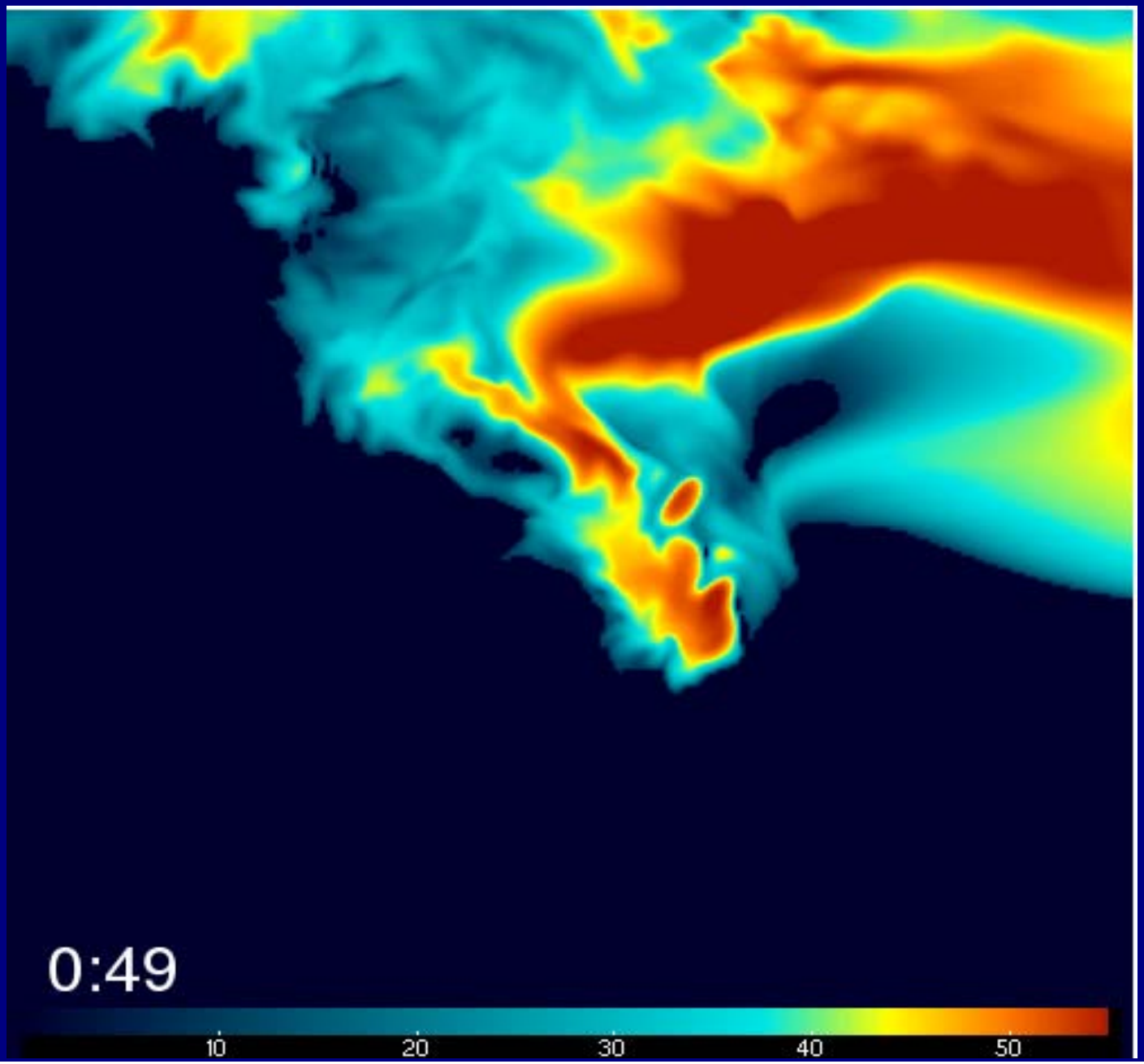
George Bryan's CM1 model

- 3ice microphysics (Gilmore et al 2004)
- Two simulations performed at this point:
  - 100 meter horiz. grid spacing, vertical stretch from 25 m
    - 1200 x 1200 x 100 gridpoints (120 km x 120 km x 20 km)
  - 50 meter horiz. grid spacing, vertical stretch from 25 m
    - 2400 x 2400 x 100 gridpoints (120 km x 120 km x 20 km)
- Horizontally homogeneous base state taken from Lockney, TX sounding
- Warm bubble initialization

Preliminary results of 100 m run

- Long lived tornadic supercell which contains several DRCs
- DRCs overlap with downdrafts some of which are downbursts
- At 1:04 tornado vortex forms on flank of DRC, and is modified by downburst outflow
- At 1:20 tornadogenesis occurs adjacent to DRC
- At 1:40 tornadogenesis occurs without adjacent DRC

Surface reflectivity

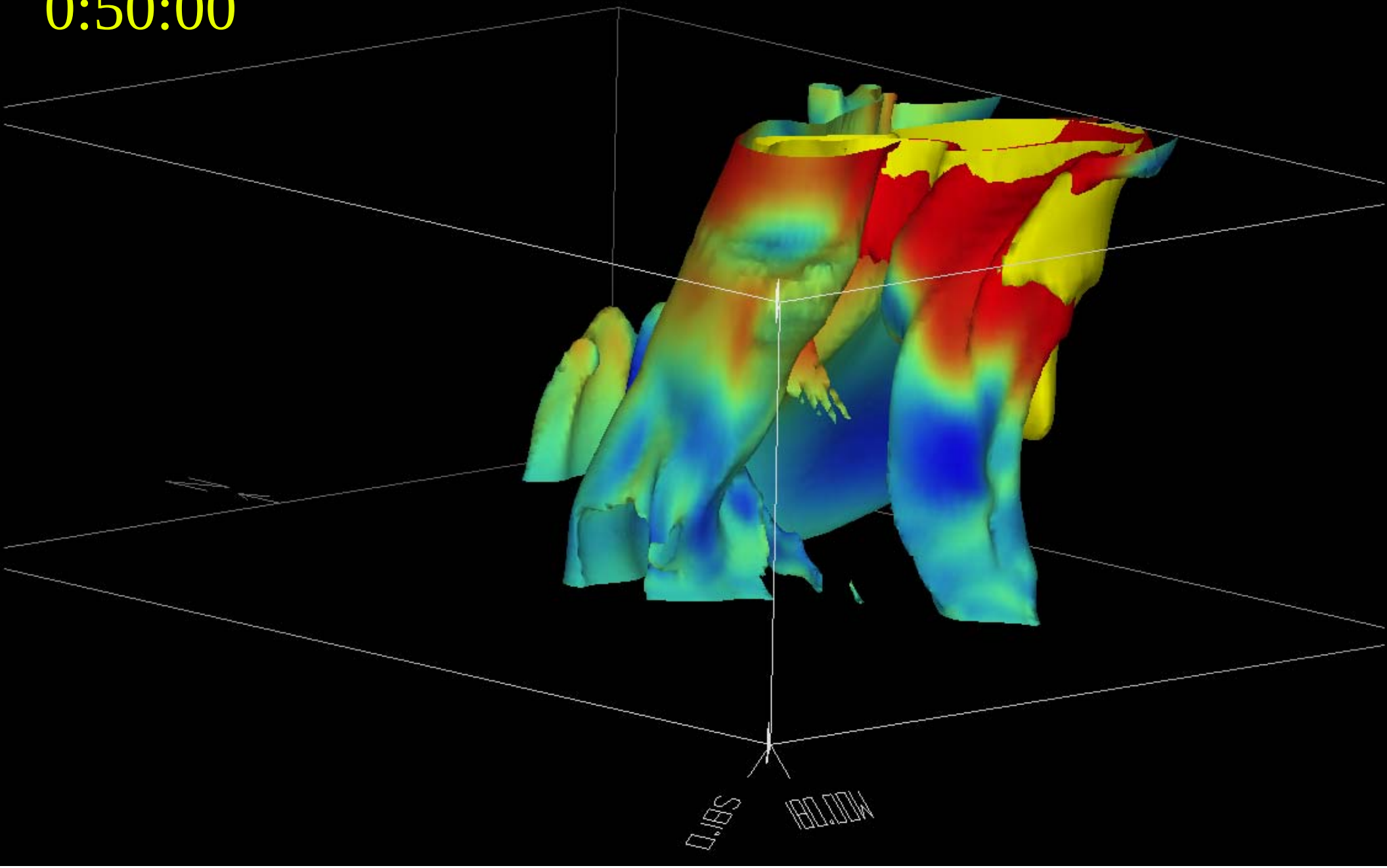


Movie: sfc dBZ (100 m run)

53 dbZ isosurface colored by w

30 m/s w isosurface (yellow)

0:50:00

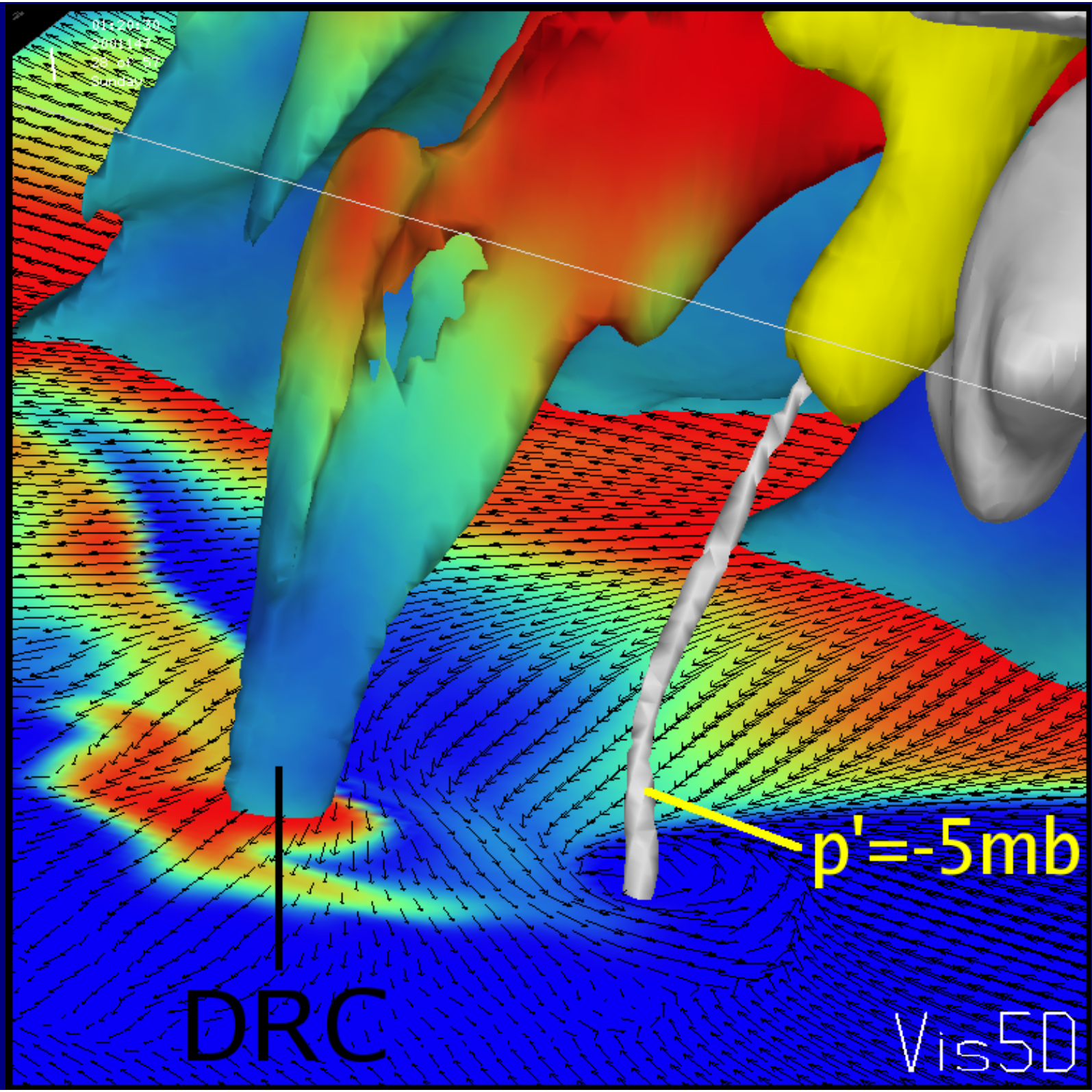


Movie: dBZ colored by w (100 m run)

View from southeast

1:20:30

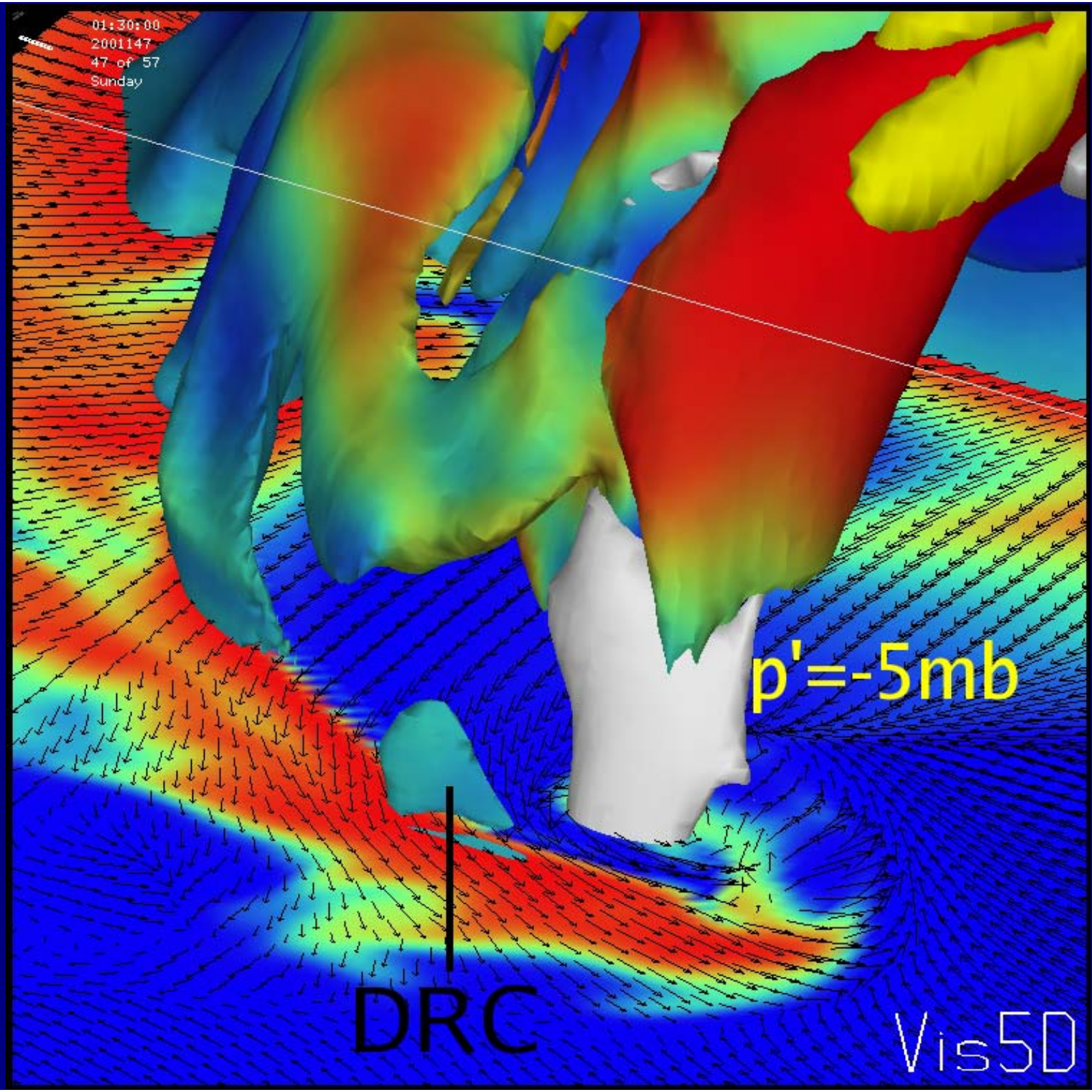
p' = -5mb



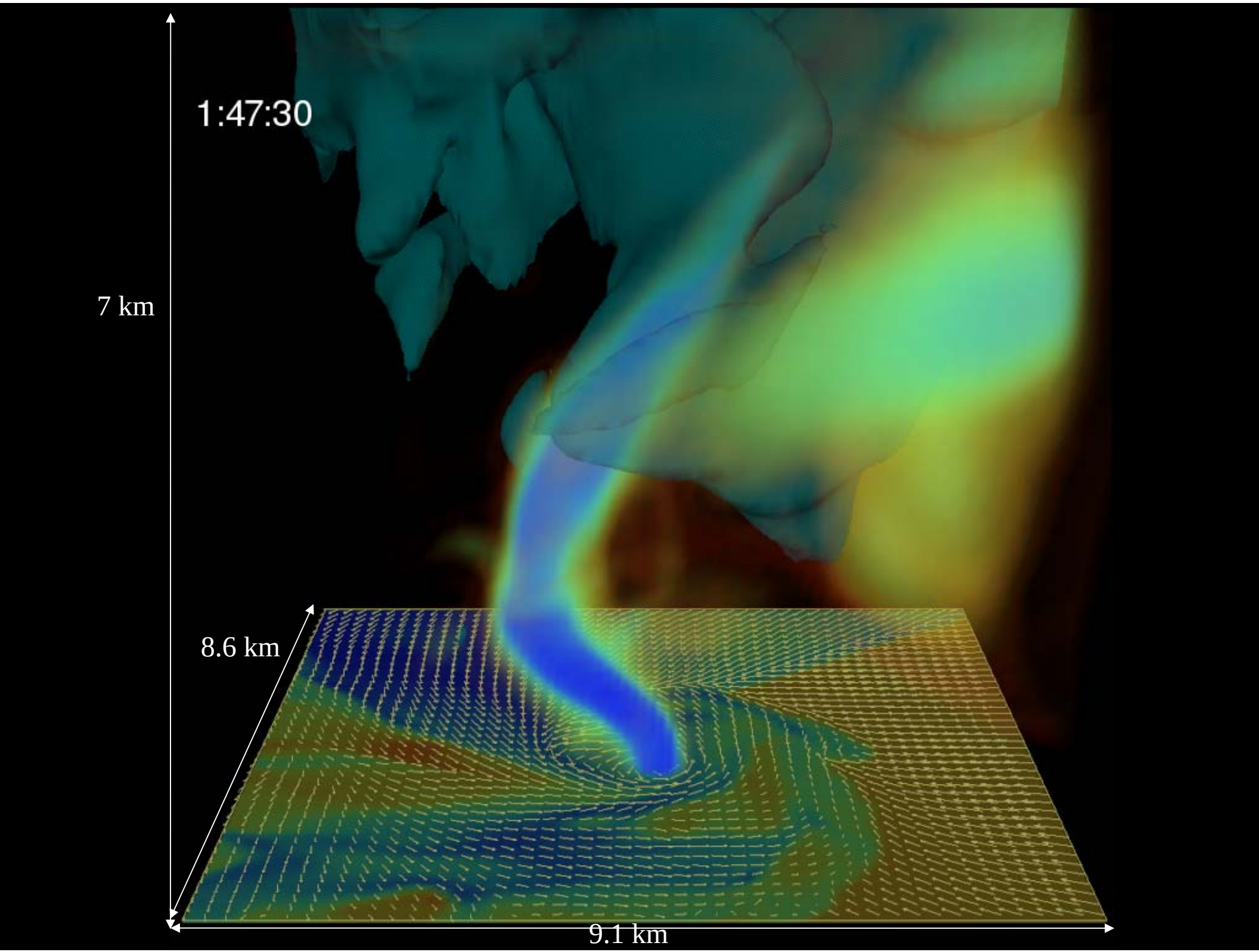
View from southeast

1:30:00

p' = -5mb



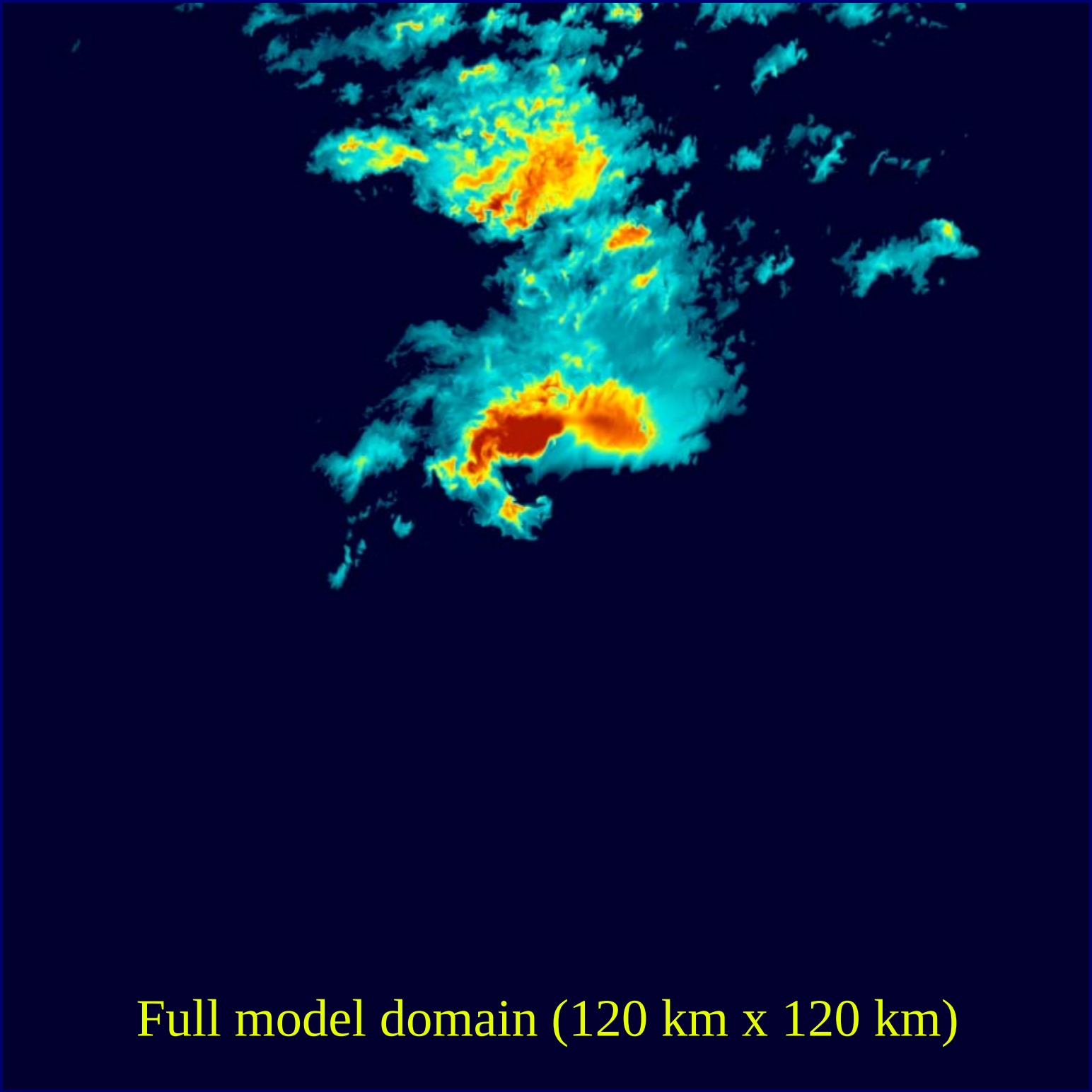
Movie: DRC and tornado (100 m run)

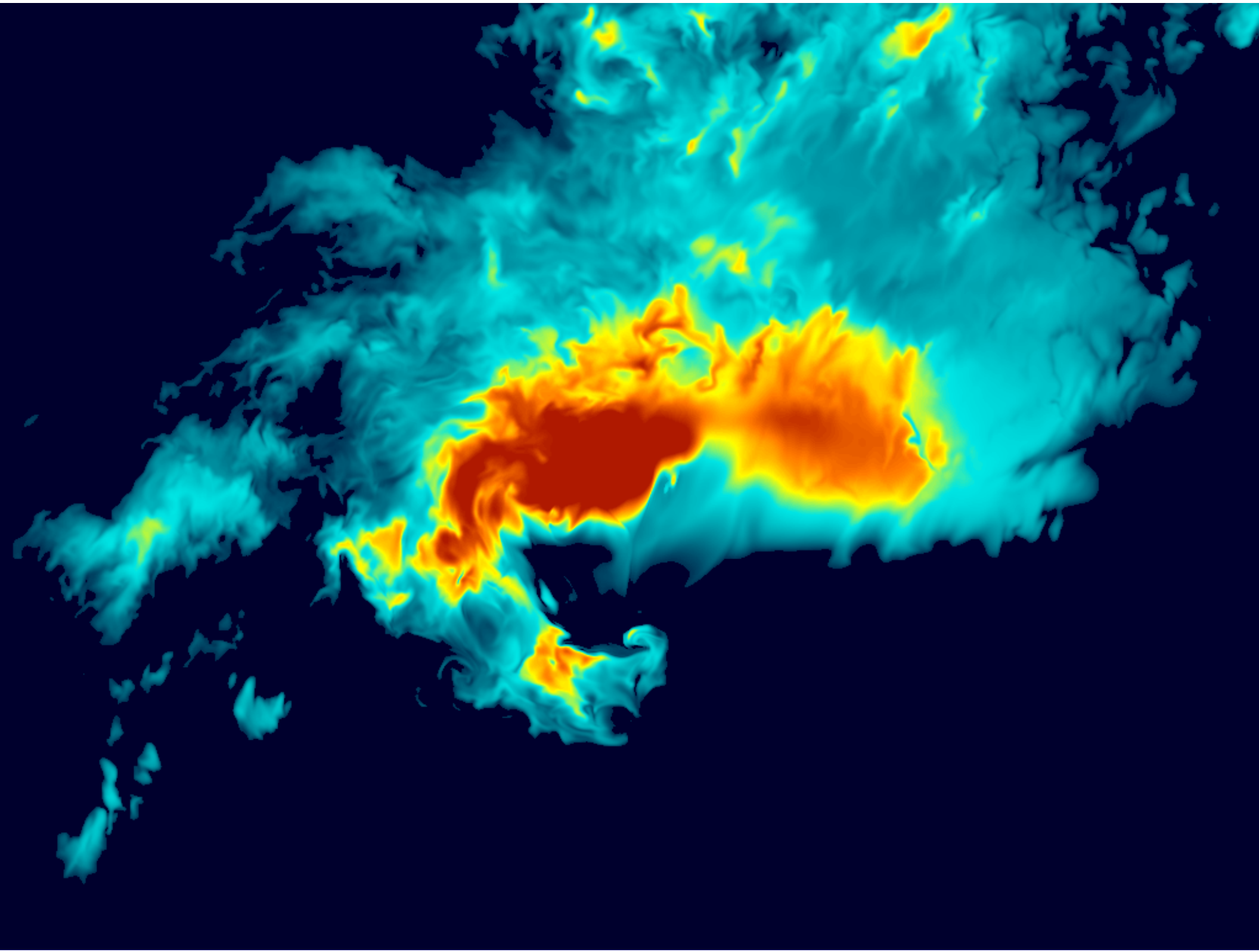

1:47:30
7 km
8.6 km
9.1 km

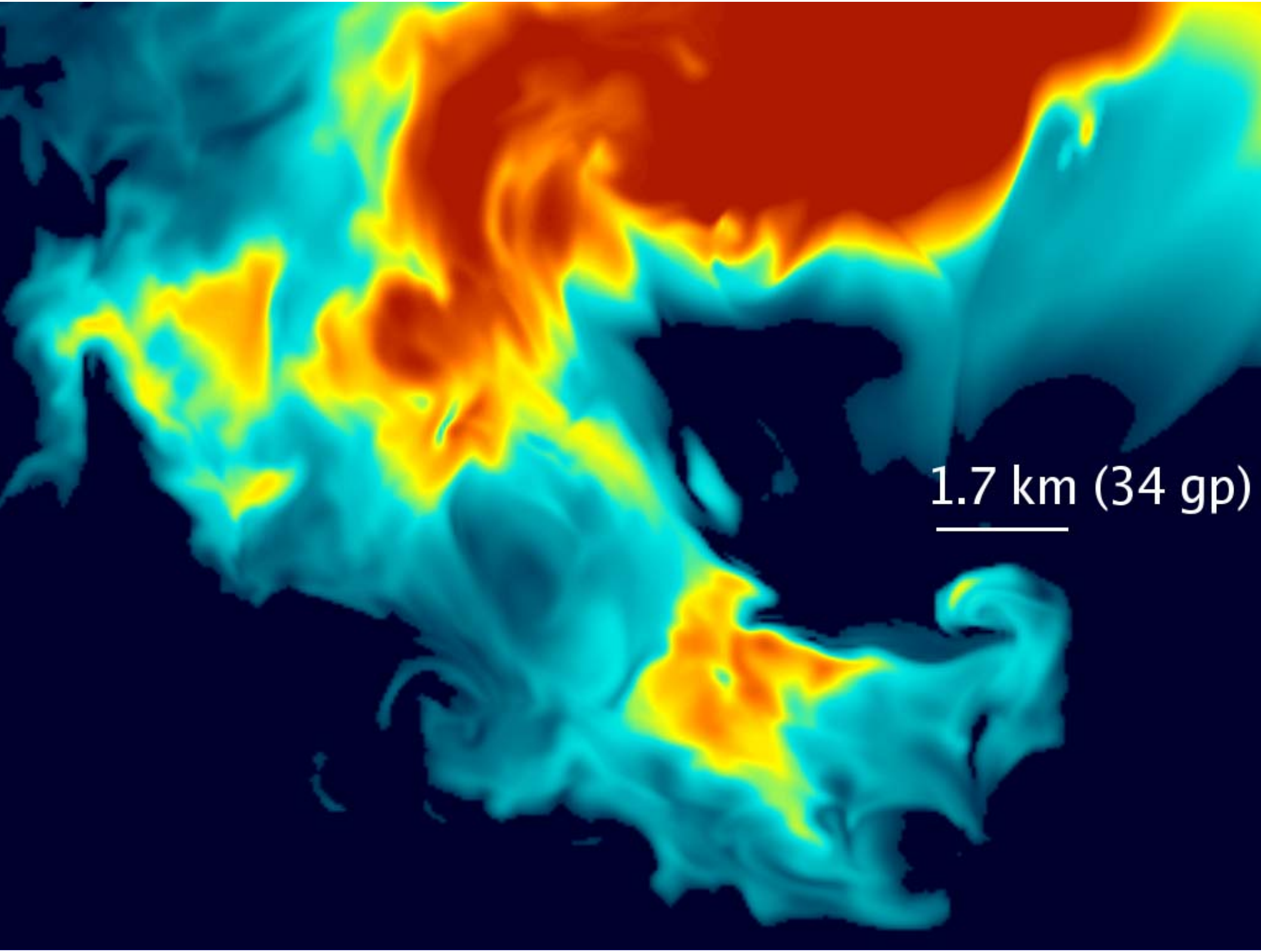
Movie: tornadogenesis

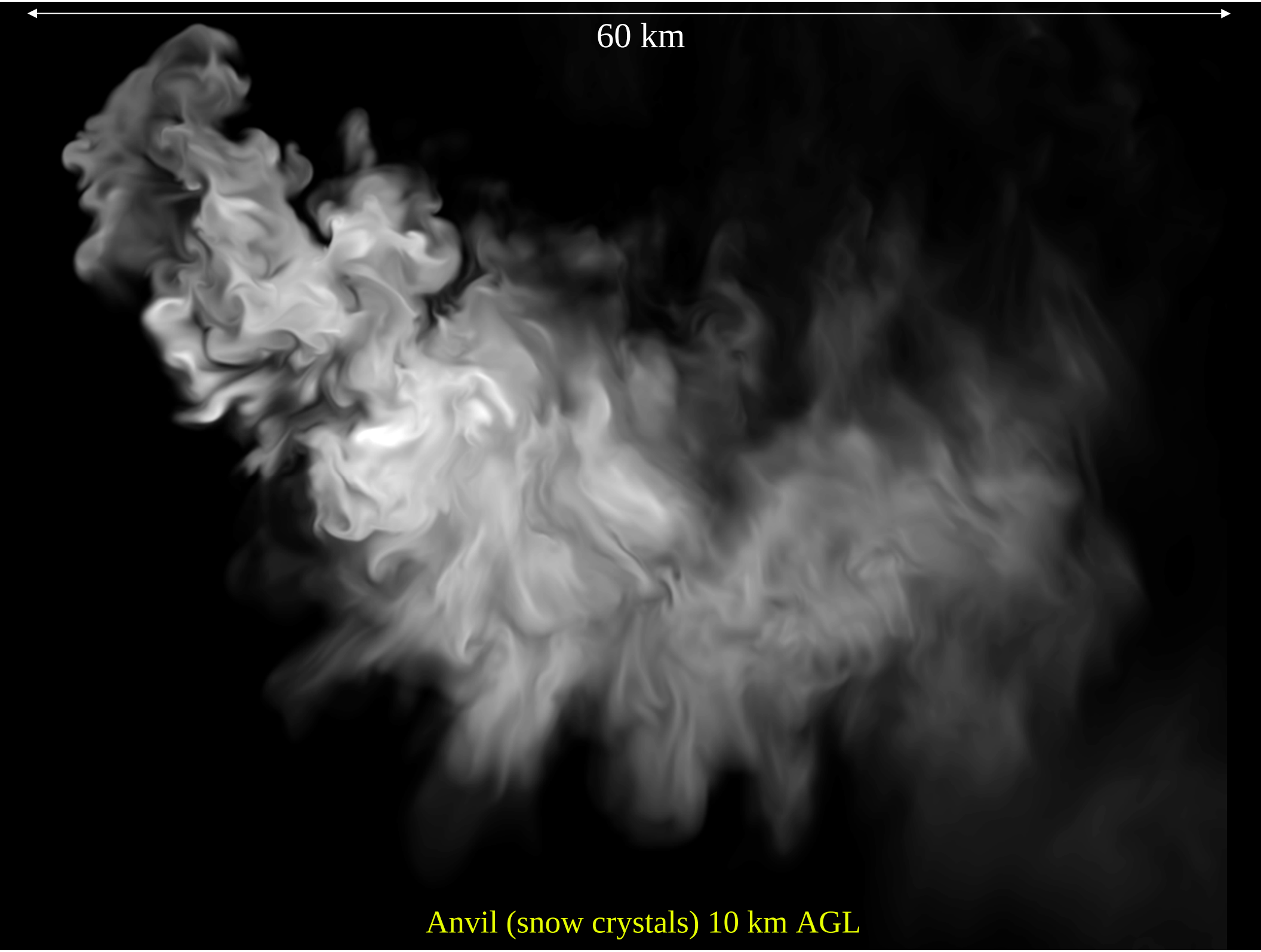
50 meter simulation

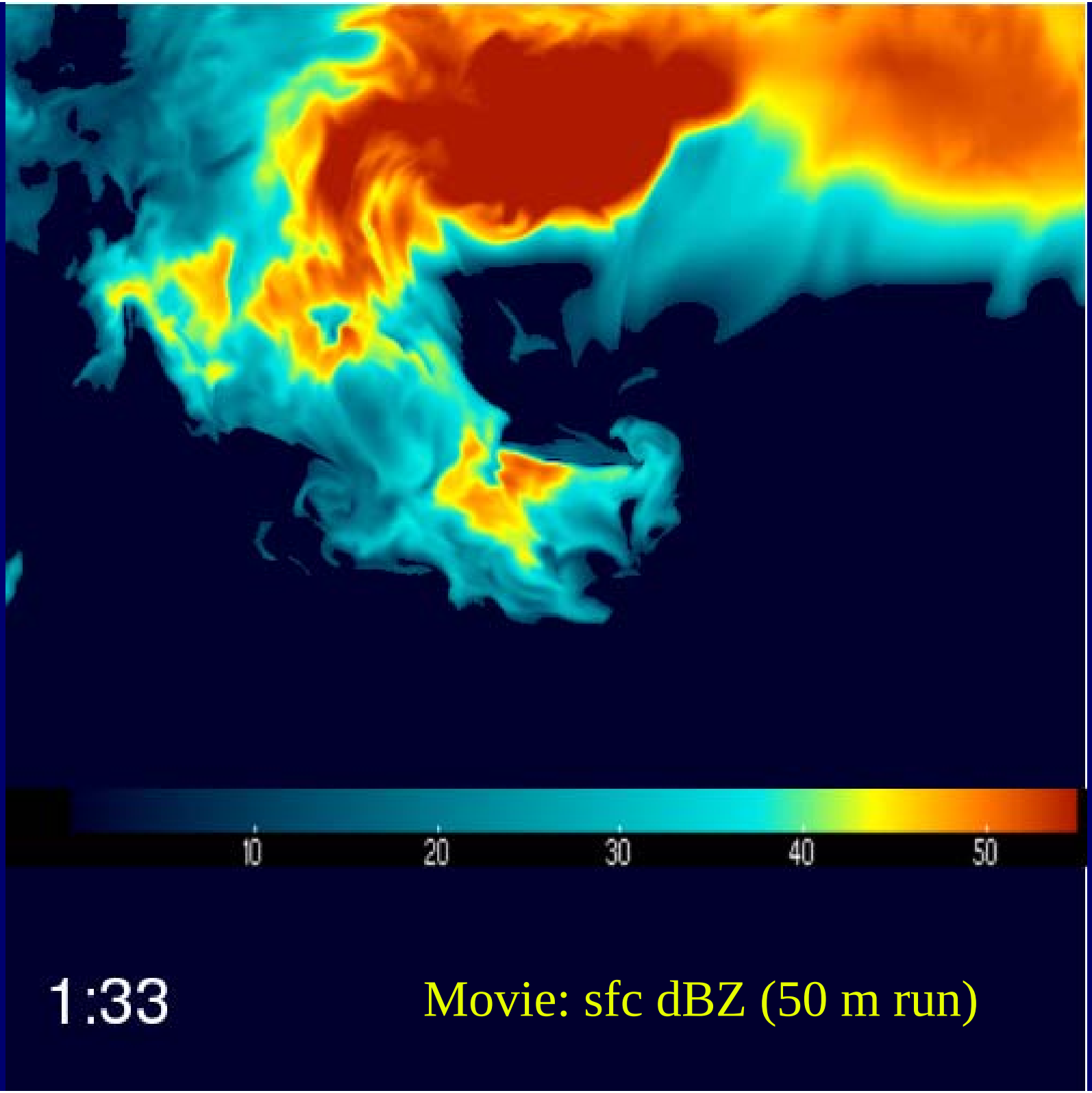
- Simiar in general evolution
- Produces DRCs
- Does not produce the tornado you just saw
- Does contain several tornado-like “spinups” and arguably a couple of weak tornadoes
- Keep in mind that changing the resolution will change the soloution
- Also keep in mind only ~20% of supercells produce tornadoes
- Simulated tornadogenesis is extremely sensitive to physical and numerical parameters


Full model domain (120 km x 120 km)



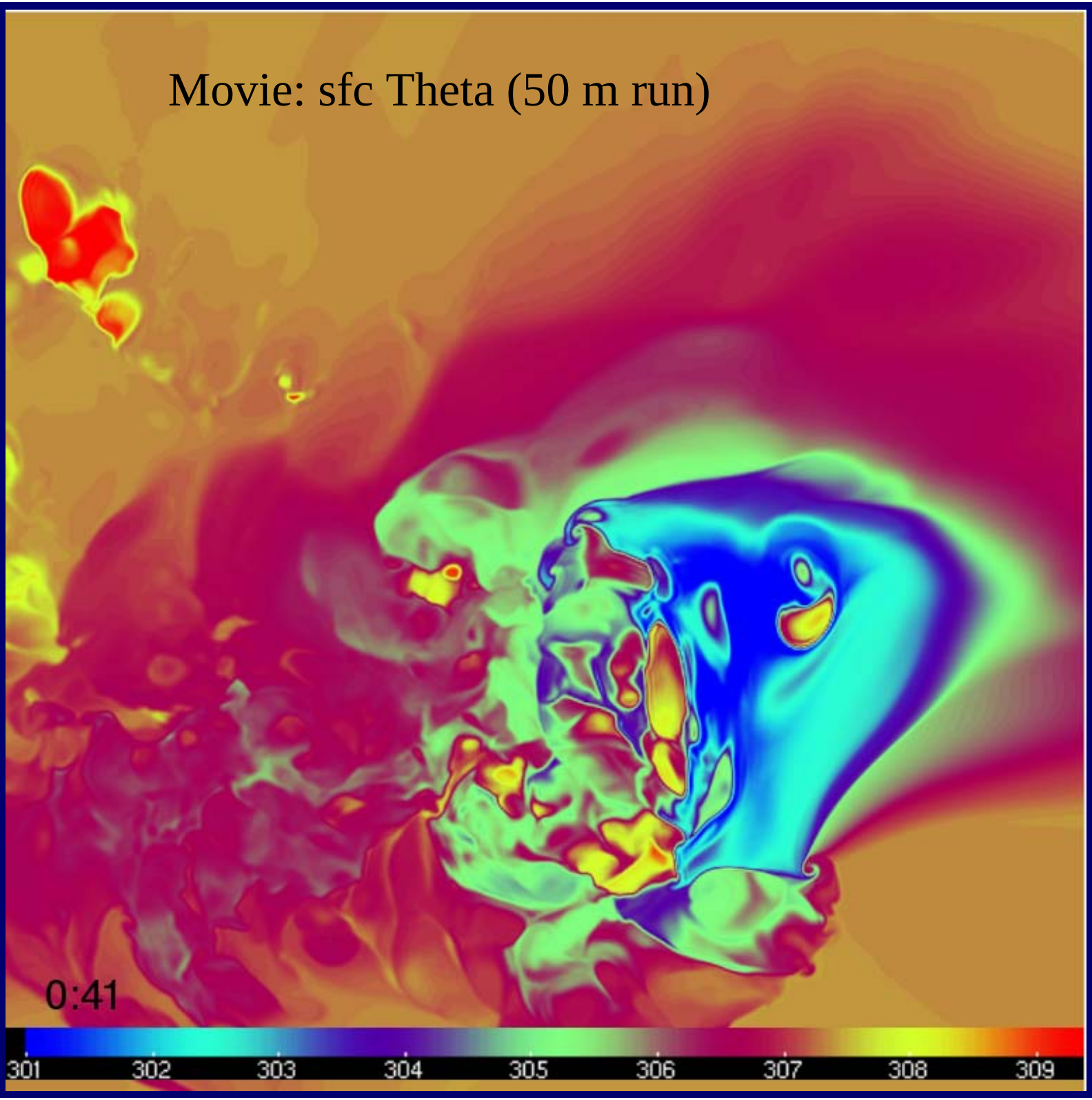

1.7 km (34 gp)

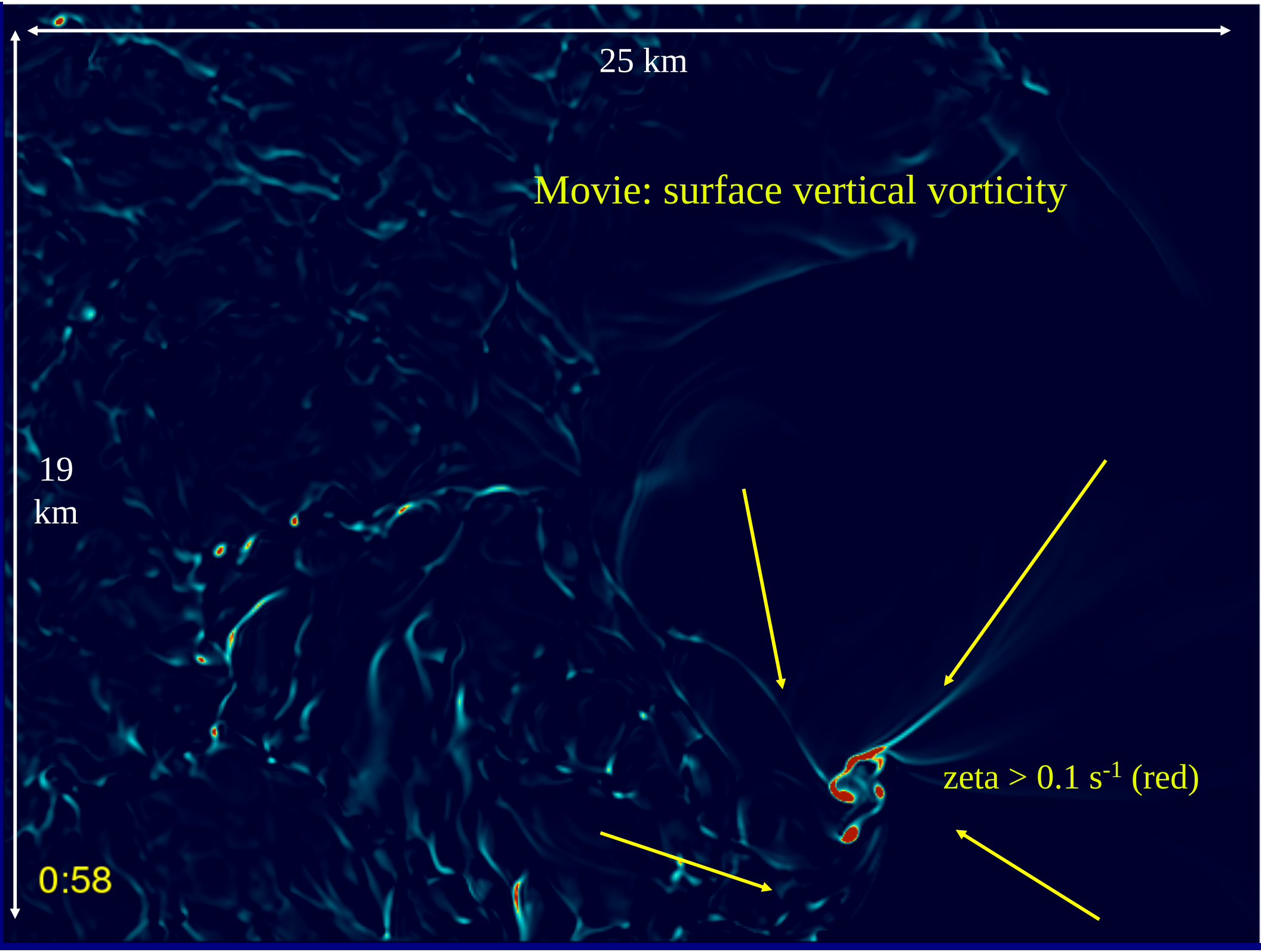

60 km
Anvil (snow crystals) 10 km AGL



Movie: sfc dBZ (50 m run)

Movie: sfc Theta (50 m run)




25 km
Movie: surface vertical vorticity
19
km
zeta > 0.1 s-1 (red)
0:58

Preliminary findings of DRC / tornadogenesis simulations

- DRCs are common in a simulated supercell initialized with 2 June 1995 environment
- DRCs are *sometimes* associated with downbursts
- There are compelling similarities in observed 2 June storms and simulated storm
- Causation between DRCs and tornadogenesis has not been determined
- 50 meter simulation contains similar overall evolution but different microscale structure (e.g., significant tall tornado does not form)

Final remarks

- We can do billion grid zone cloud simulations *now*
  - *However model must be constructed from the ground up with this sized problem in mind*
  - *Special consideration must be made for dealing with large amounts (~ 10's of TB) of data*
  - *Visualization tools need to be developed specifically for these large problems*
  - *Beware of data overload*