# Tornado formation: What we know and don't know


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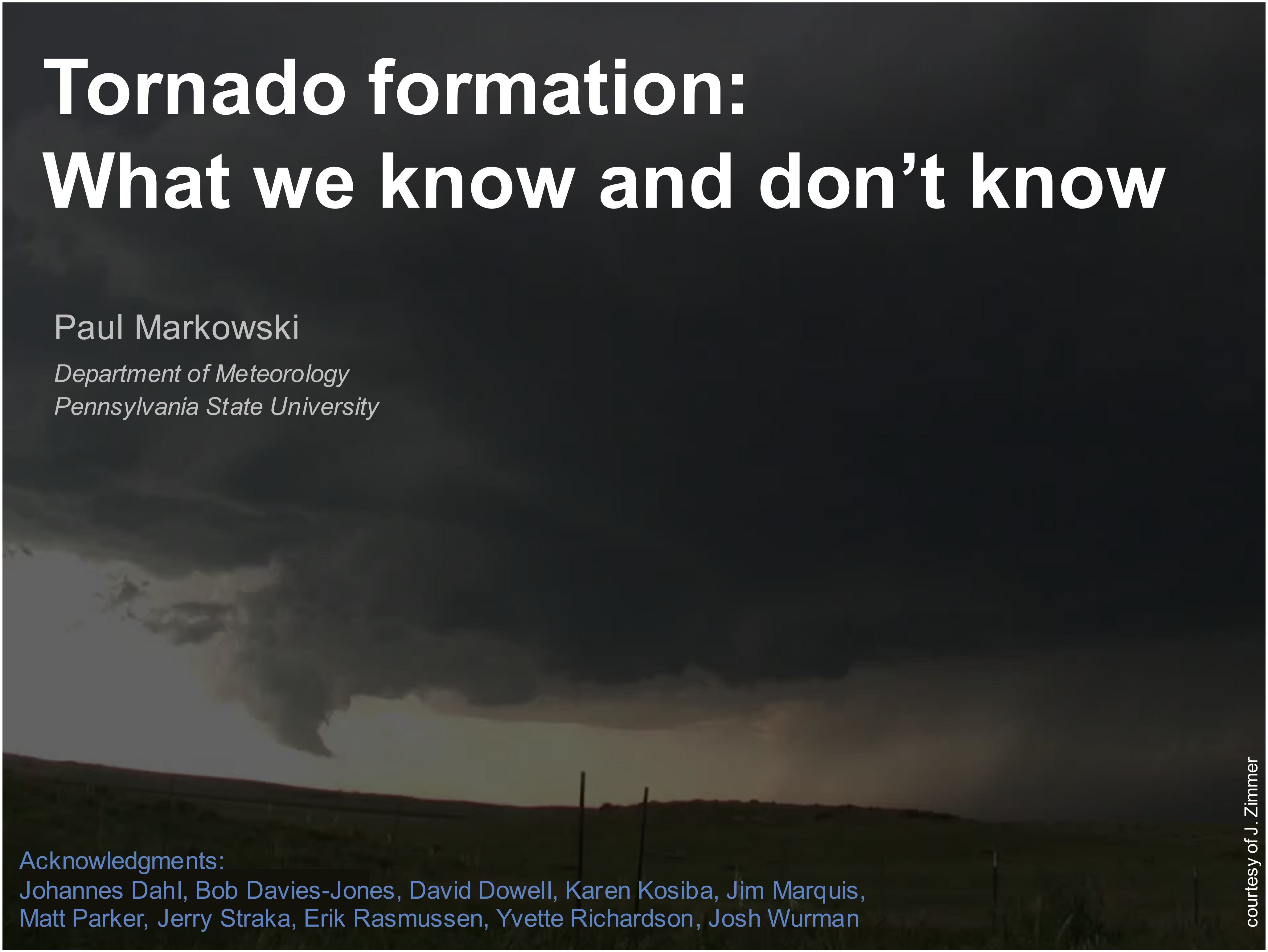
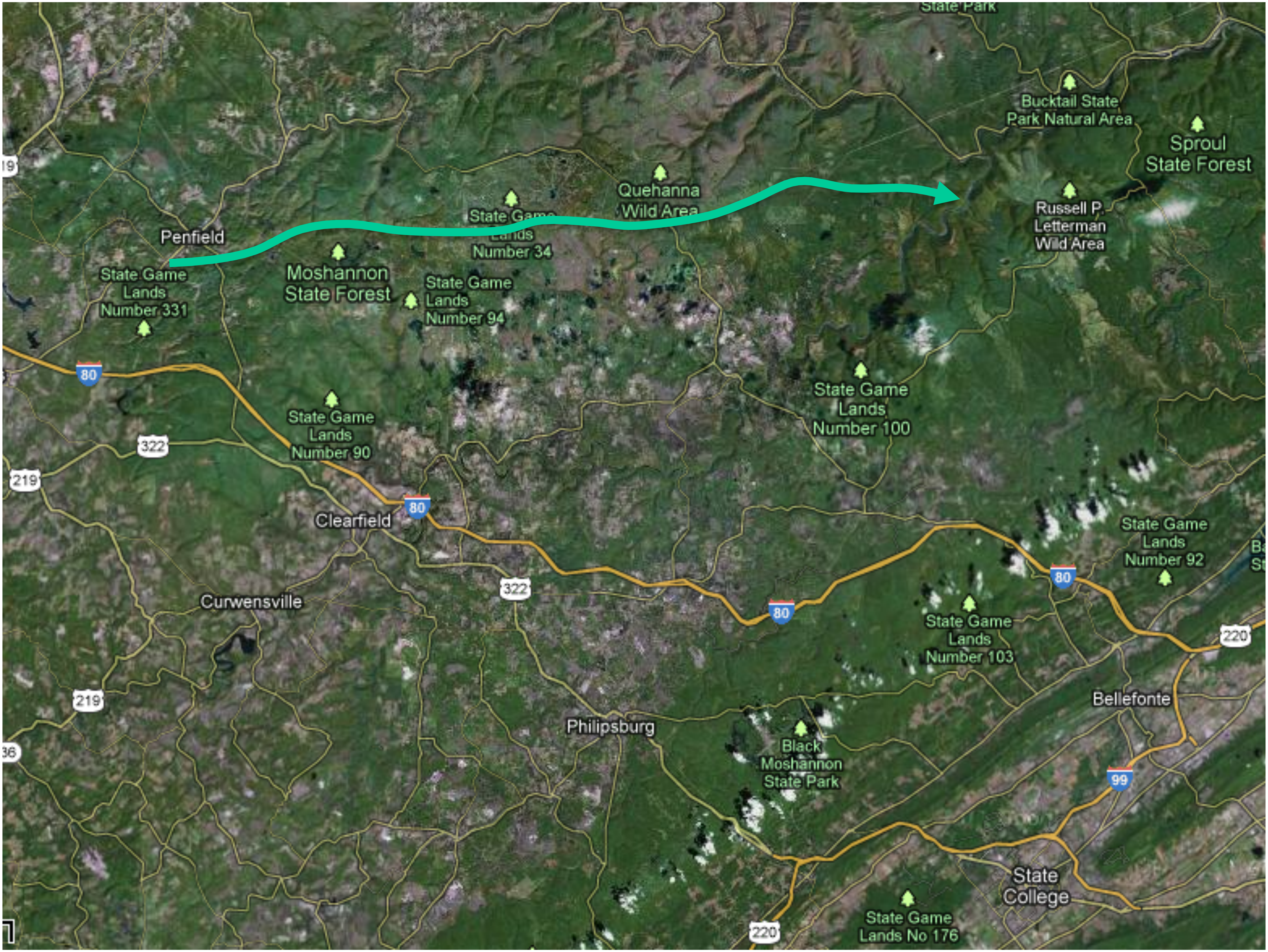


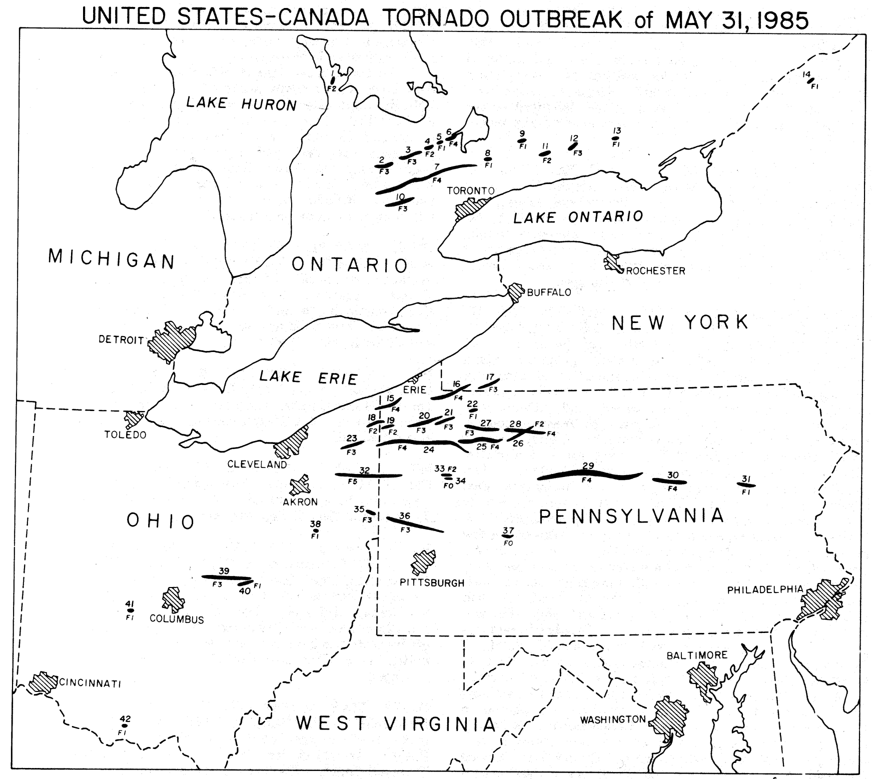
courtesy of J. Zimmer


Acknowledgments:
Johannes Dahl, Bob Davies-Jones, David Dowell, Karen Kosiba, Jim Marquis, Matt Parker, Jerry Straka, Erik Rasmussen, Yvette Richardson, Josh Wurman



Bucktail State Park Natural Area
Sproul State Forest
Quehanna Wild Area
Russell P. Letterman Wild Area
Penfield
State Game Lands Number 34
Moshannon State Forest
State Game Lands Number 331
State Game Lands Number 94
80
State Game Lands Number 90
State Game Lands Number 100
322
219
80
Clearfield
State Game Lands Number 92
80
322
Curwensville
80
State Game Lands Number 103
220
219
Bellefonte
Philipsburg
Black Moshannon State Park
99
State College
State Game Lands No 176
220

# ***31 May 1985:*** ***One of the worst tornado outbreaks in U.S. history***





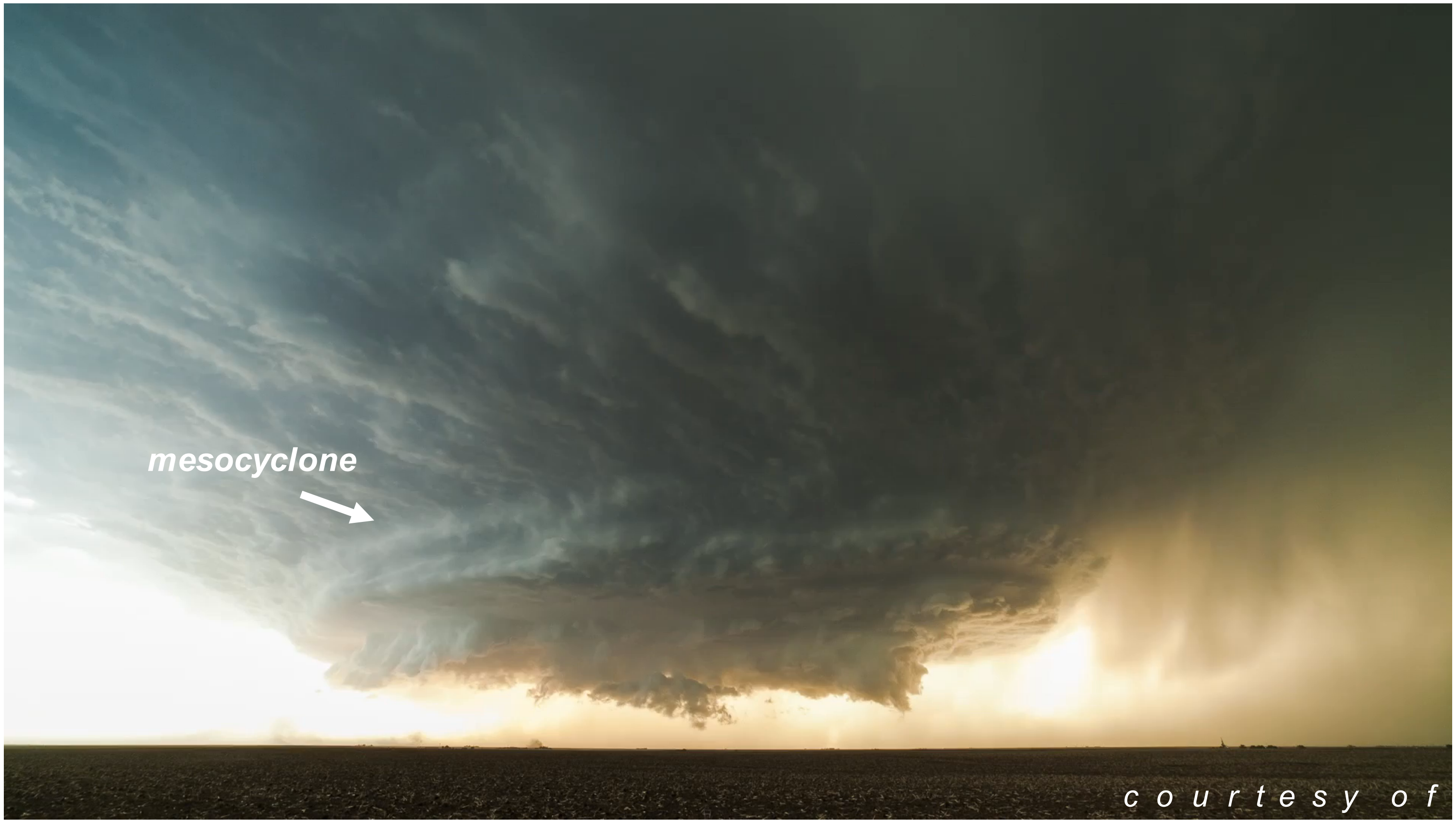

43 tornadoes; 10 violent (F4 or F5) tornadoes; 12 killer tornadoes

89 fatalities (65 in PA; 69 tornado deaths in PA in previous 50 years)

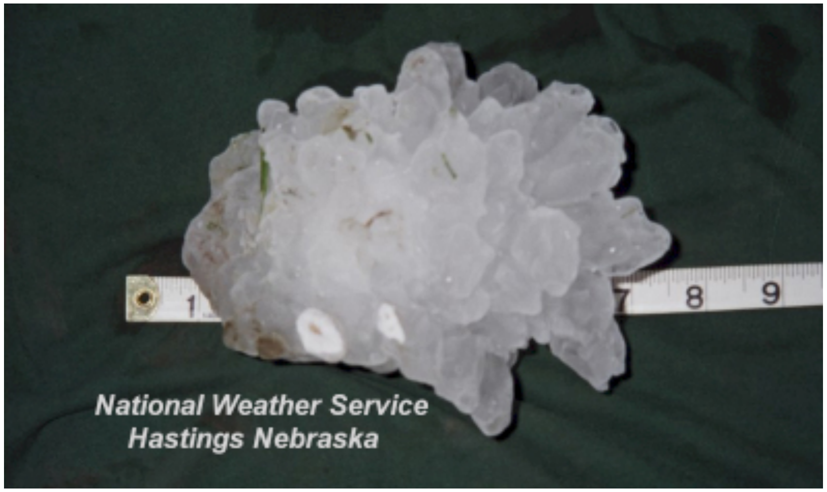
Deadliest tornado outbreak in U.S. in the 1980s

Since 5/31/1985, only two tornado days have been deadlier (4/27/2011 outbreak in AL-MS and 5/22/2011 Joplin, MO, tornado)

# Supercell storms: Storms with a mesocyclone

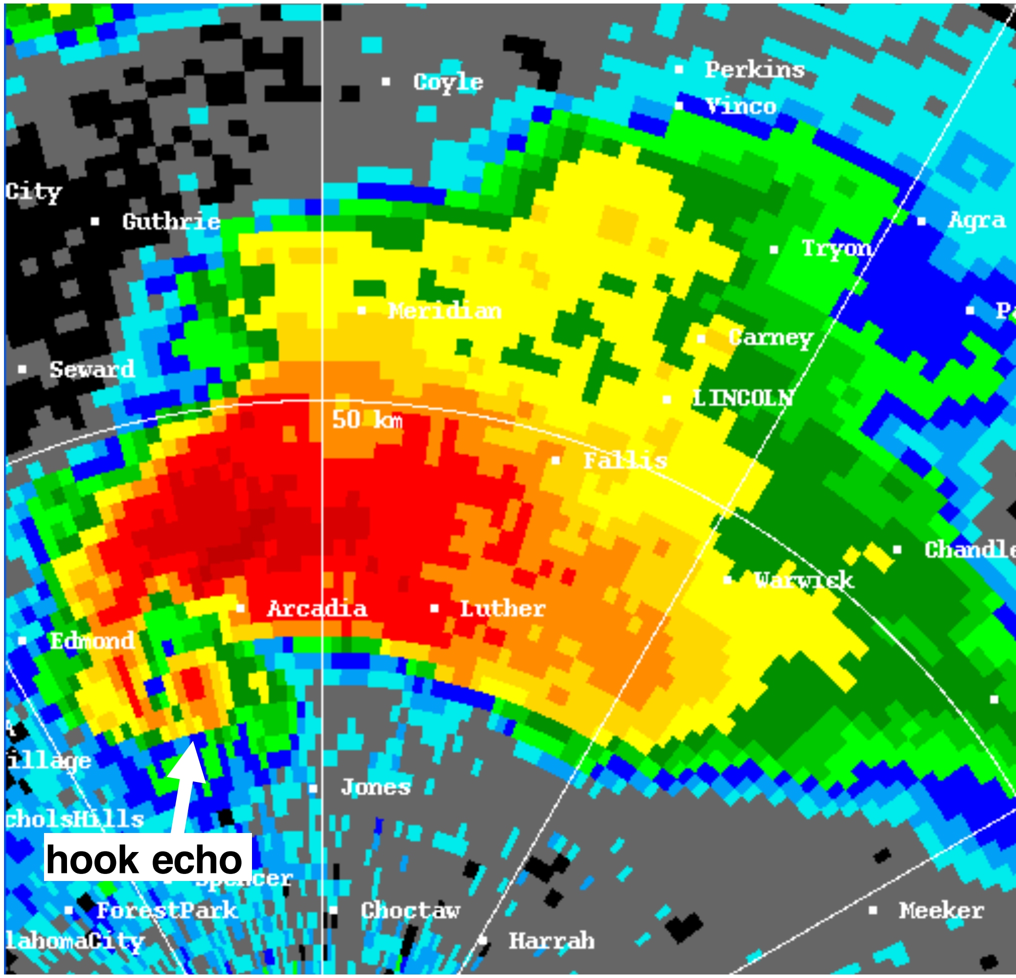




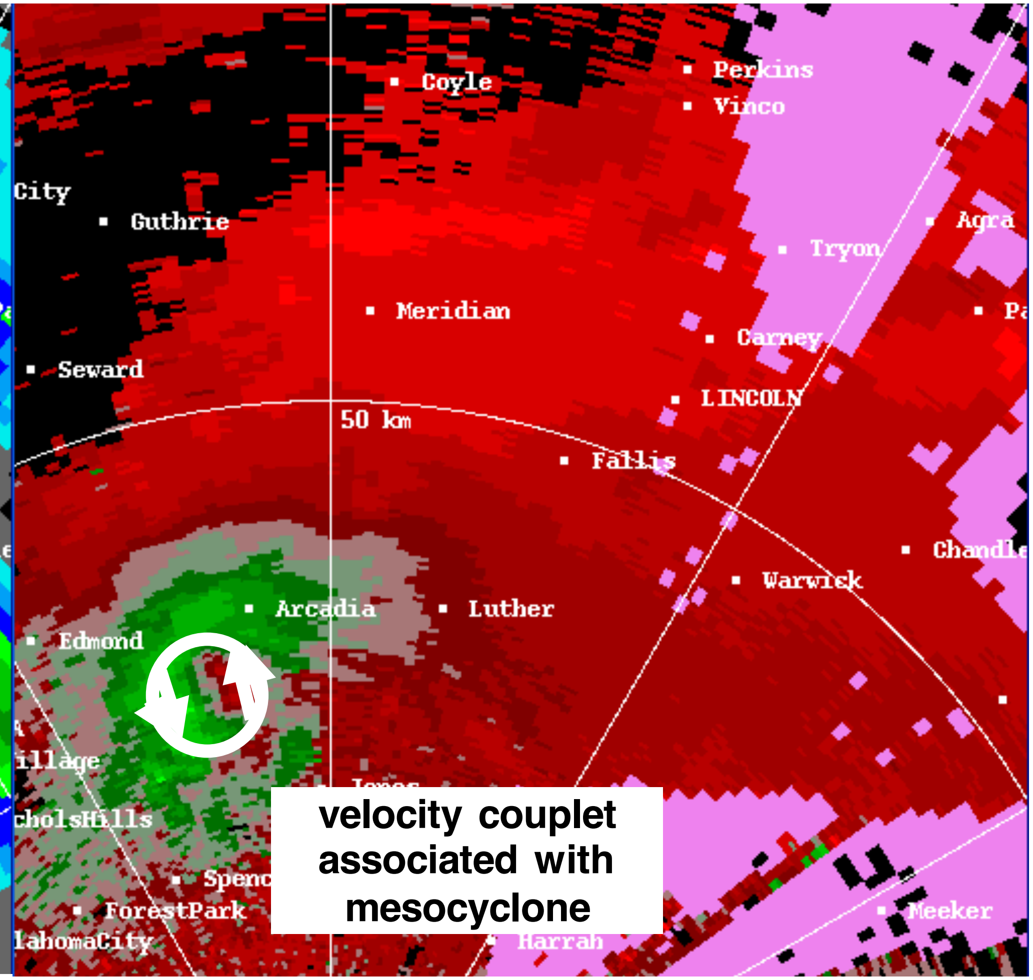


# Supercell storms: Storms with a mesocyclone

*reflectivity*



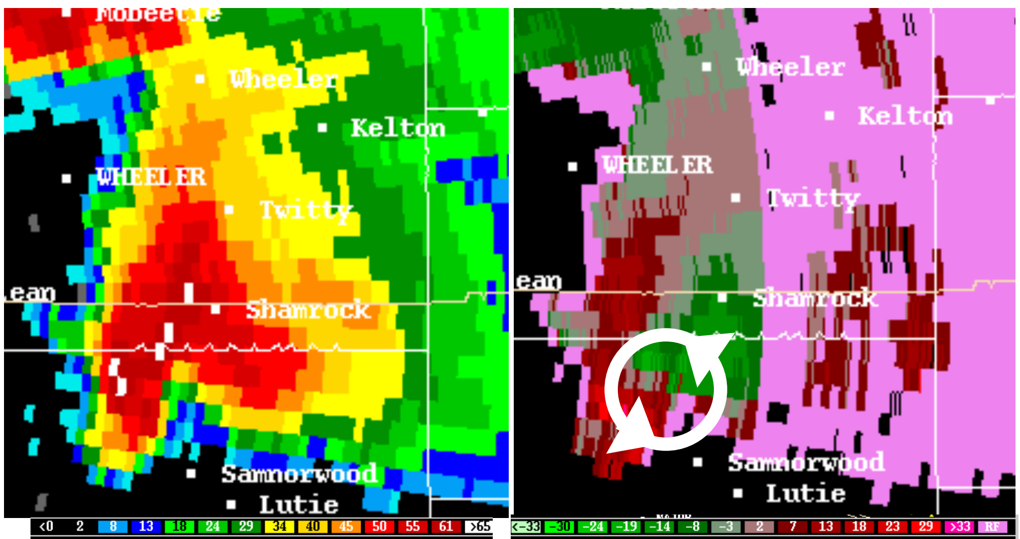

*Doppler velocity*



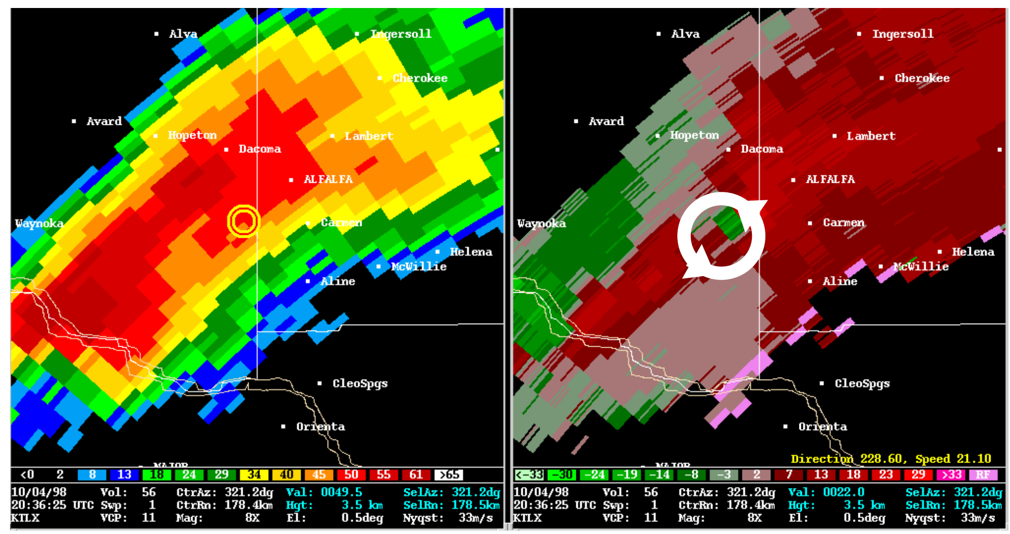
# What motivates supercell research

- **Although most significant tornadoes are associated with supercell thunderstorms, most supercells are *not* tornadic**
  - ***And the most intense mesocyclones are not necessarily the ones most likely to be associated with tornadogenesis!***

*22 May 1995* ***(nontornadic)***



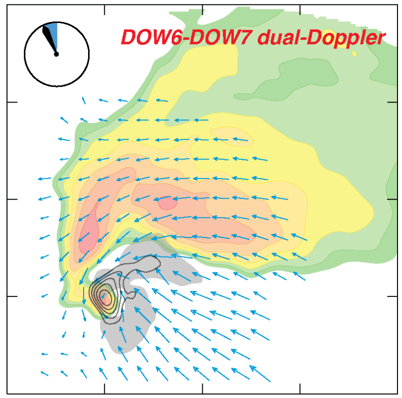

*4 October 1998* ***(tornadic)***

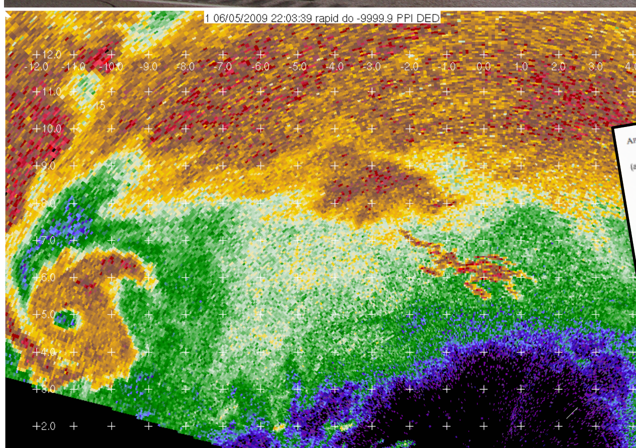


# How do we know what we know?

## Observations

2148:00 UTC *(t–4 min)*





## Theory

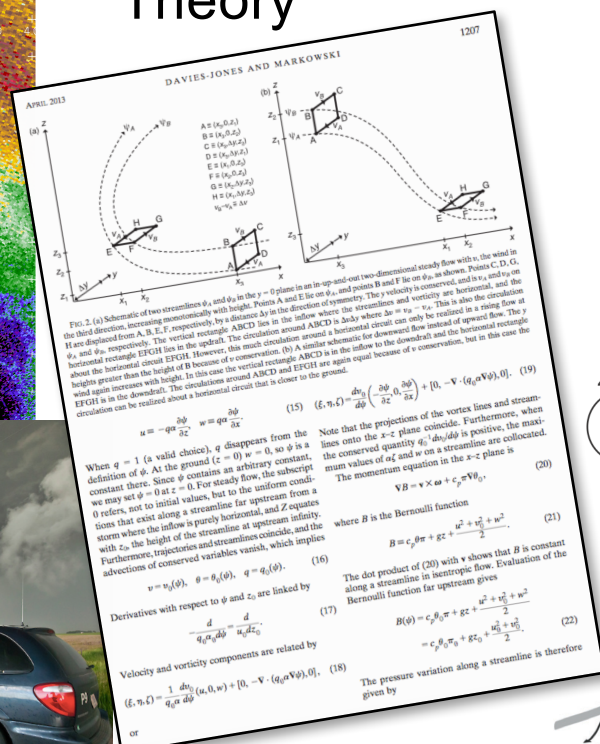


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FIG. 2. (a) Schematic of two streamlines $\psi_A$ and $\psi_B$ in the $y = 0$ plane in an in-up-and-out two-dimensional steady flow with $v$, the wind in the third direction, increasing monotonically with height. Points A and E lie on $\psi_A$, and points B and F lie on $\psi_B$, as shown. Points C, D, G, H are displaced from A, B, E, F, respectively, by a distance $\Delta y$ in the direction of symmetry. The $y$ velocity is conserved, and is $v_A$ and $v_B$ on $\psi_A$ and $\psi_B$, respectively. The vertical rectangle ABCD lies in the inflow where the streamlines and vorticity are horizontal, and the horizontal rectangle EFGH lies in the updraft. The circulation around ABCD is $\Delta v \Delta y$ where $\Delta v \equiv v_B - v_A$. This is also the circulation about the horizontal circuit EFGH. However, this much circulation around a horizontal circuit can only be realized in a rising flow at heights greater than the height of B because of $v$ conservation. (b) A similar schematic for downward flow instead of upward flow. The $y$ wind again increases with height. In this case the vertical rectangle ABCD is in the inflow to the downdraft and the horizontal rectangle EFGH is in the downdraft. The circulations around ABCD and EFGH are again equal because of $v$ conservation, but in this case the circulation can be realized about a horizontal circuit that is closer to the ground.

$$u = -q\alpha\frac{\partial\psi}{\partial z}, \quad w = q\alpha\frac{\partial\psi}{\partial x}. \qquad (15)$$

When $q = 1$ (a valid choice), $q$ disappears from the definition of $\psi$. At the ground ($z = 0$) $w = 0$, so $\psi$ is a constant there. Since $\psi$ contains an arbitrary constant, we may set $\psi = 0$ at $z = 0$. For steady flow, the subscript 0 refers, not to initial values, but to the uniform conditions that exist along a streamline far upstream from a storm where the inflow is purely horizontal, and Z equates with $z_0$, the height of the streamline at upstream infinity. Furthermore, trajectories and streamlines coincide, and the advections of conserved variables vanish, which implies

$$v = v_0(\psi), \quad \theta = \theta_0(\psi), \quad q = q_0(\psi). \qquad (16)$$

Derivatives with respect to $\psi$ and $z_0$ are linked by

$$-\frac{d}{q_0\alpha_0 d\psi} = \frac{d}{u_0 dz_0}. \qquad (17)$$

Velocity and vorticity components are related by

$$(\xi, \eta, \zeta) = \frac{1}{q_0\alpha}\frac{dv_0}{d\psi}(u, 0, w) + [0, -\nabla\cdot(q_0\alpha\nabla\psi), 0], \qquad (18)$$

or

$$(\xi, \eta, \zeta) = \frac{dv_0}{d\psi}\left(-\frac{\partial\psi}{\partial z}, 0, \frac{\partial\psi}{\partial x}\right) + [0, -\nabla\cdot(q_0\alpha\nabla\psi), 0]. \qquad (19)$$

Note that the projections of the vortex lines and streamlines onto the $x$–$z$ plane coincide. Furthermore, when the conserved quantity $q_0^{-1}dv_0/d\psi$ is positive, the maximum values of $\alpha\xi$ and $w$ on a streamline are collocated.

The momentum equation in the $x$–$z$ plane is

$$\nabla B = \mathbf{v}\times\boldsymbol{\omega} + c_p\pi\nabla\theta_0, \qquad (20)$$

where $B$ is the Bernoulli function

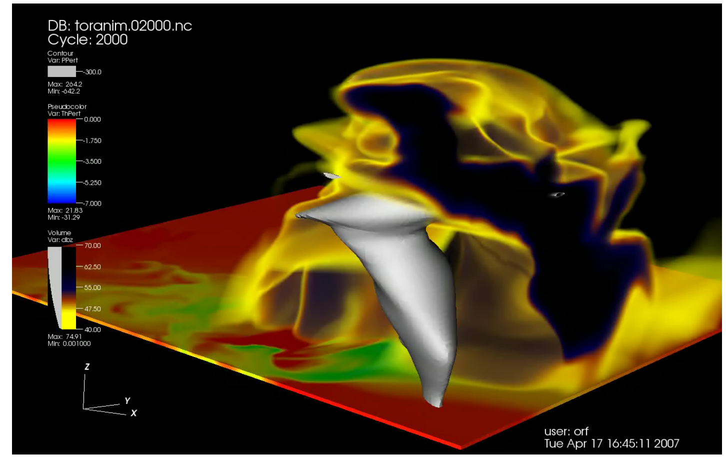
$$B = c_p\theta\pi + gz + \frac{u^2 + v_0^2 + w^2}{2}. \qquad (21)$$

The dot product of (20) with $\mathbf{v}$ shows that $B$ is constant along a streamline in isentropic flow. Evaluation of the Bernoulli function far upstream gives

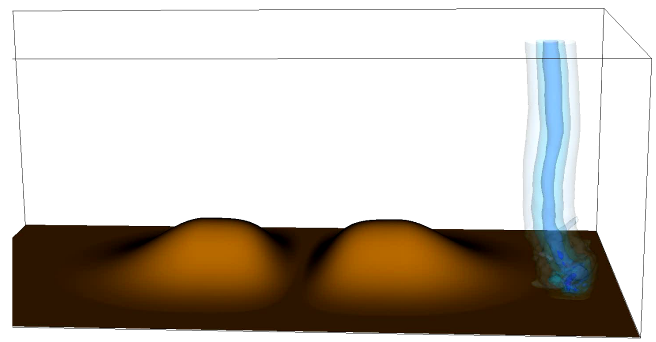
$$B(\psi) = c_p\theta_0\pi + gz + \frac{u^2 + v_0^2 + w^2}{2} = c_p\theta_0\pi_0 + gz_0 + \frac{u_0^2 + v_0^2}{2}. \qquad (22)$$

The pressure variation along a streamline is therefore given by

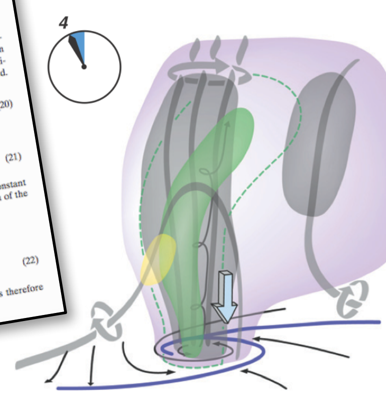
## Numerical simulations

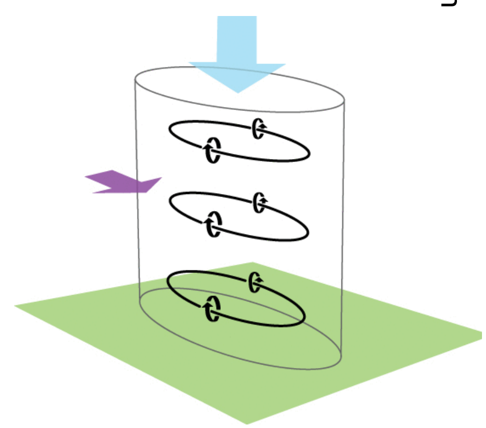


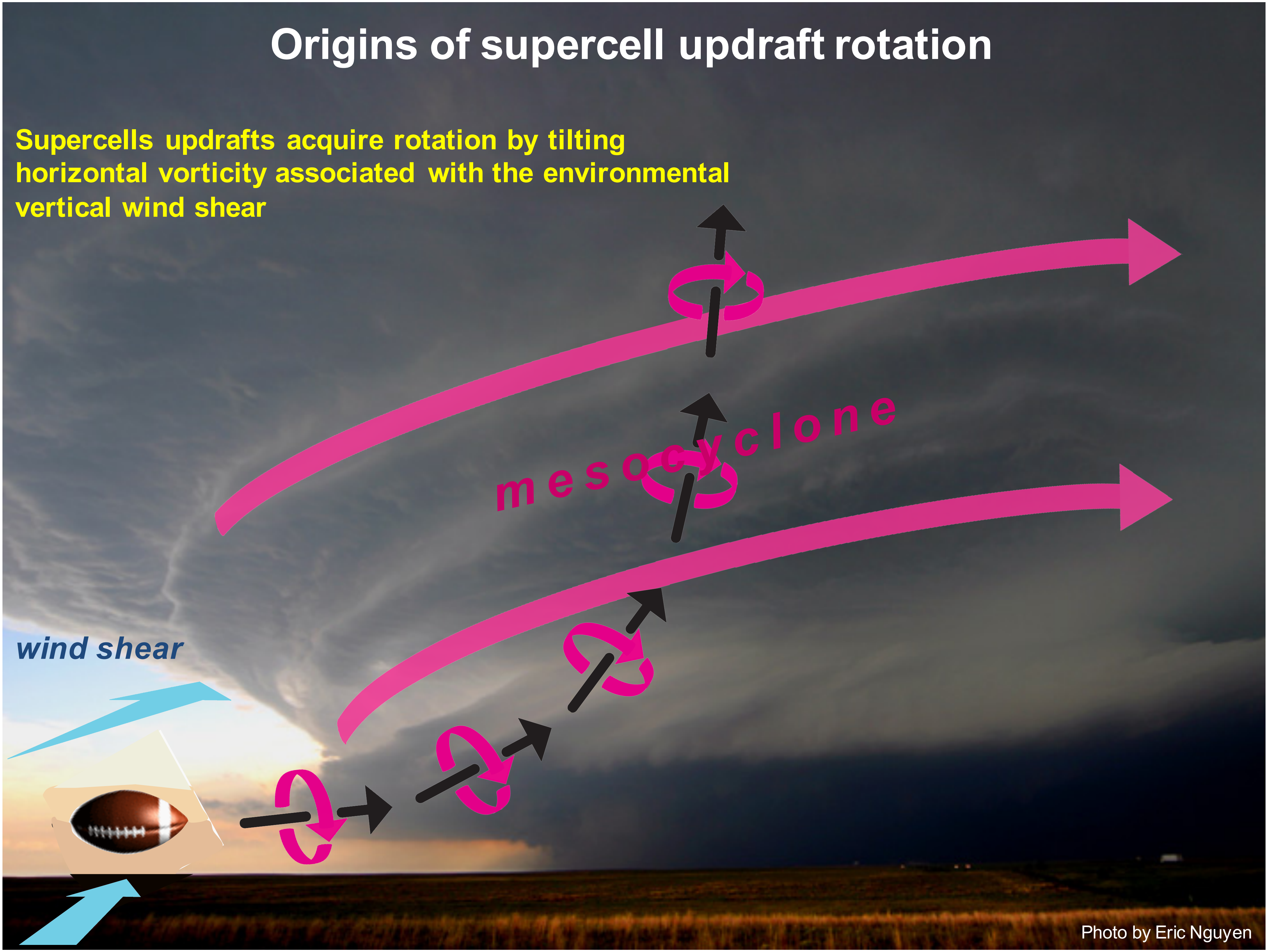

Courtesy of Leigh Orf

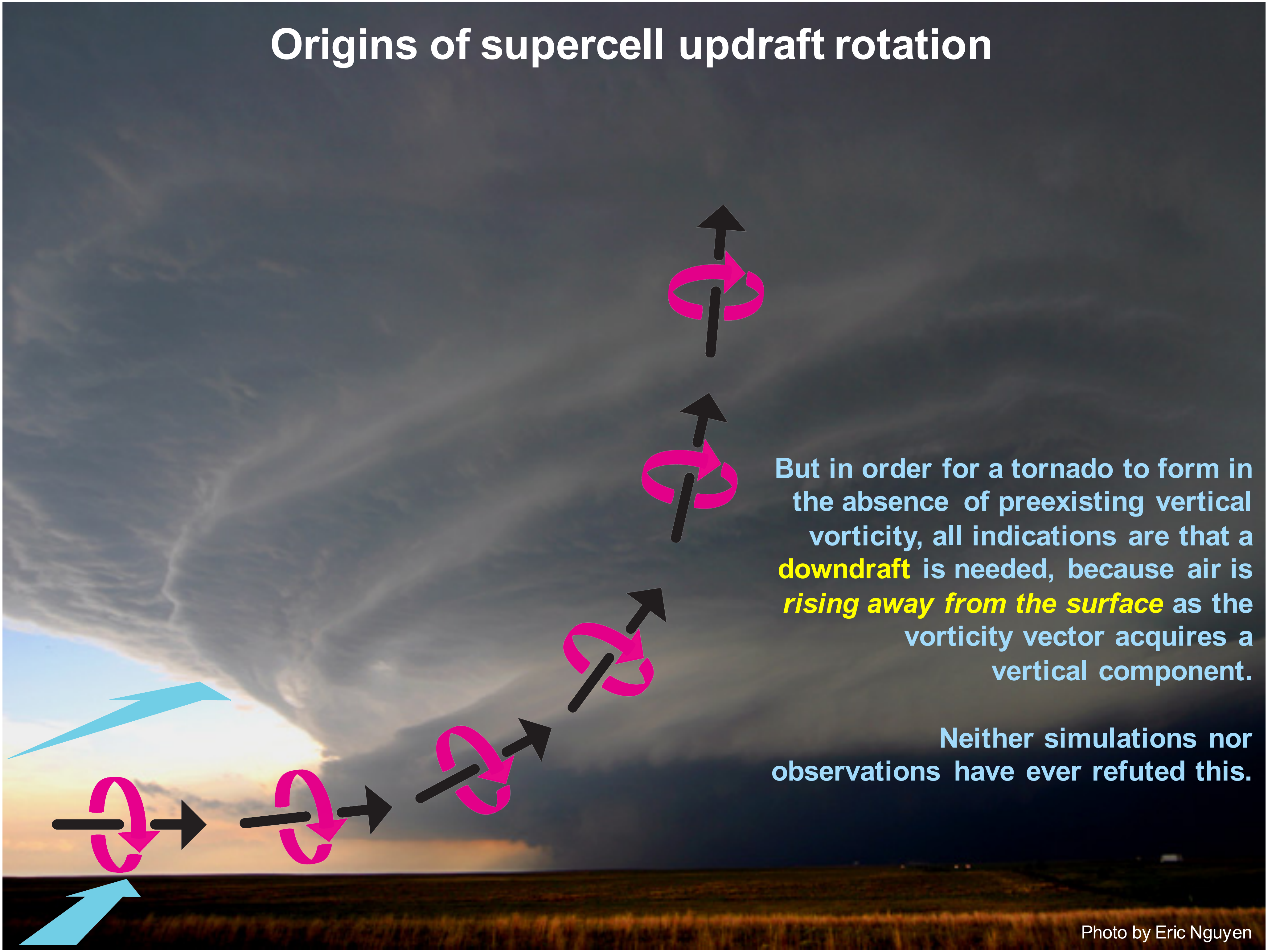


Courtesy of Dave Lewellen



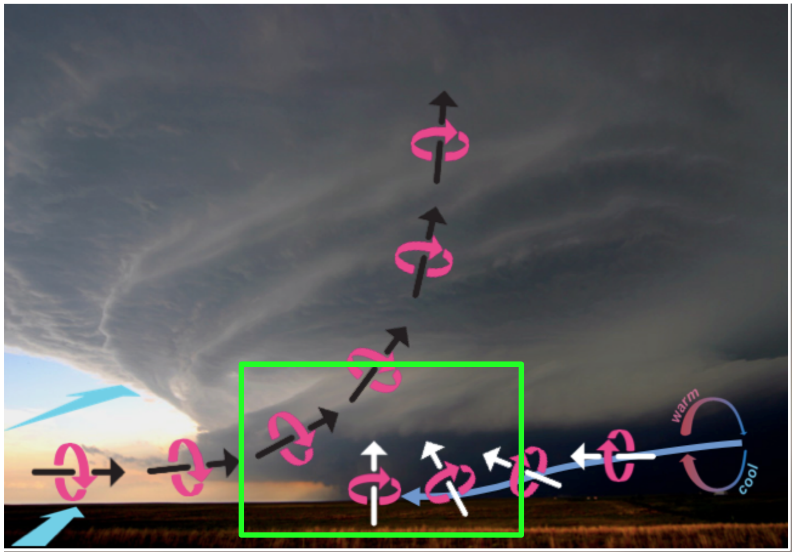




Origins of supercell updraft rotation
Supercells updrafts acquire rotation by tilting horizontal vorticity associated with the environmental vertical wind shear
mesocyclone
wind shear
Photo by Eric Nguyen


Origins of supercell updraft rotation
But in order for a tornado to form in the absence of preexisting vertical vorticity, all indications are that a downdraft is needed, because air is rising away from the surface as the vorticity vector acquires a vertical component.
Neither simulations nor observations have ever refuted this.
Photo by Eric Nguyen

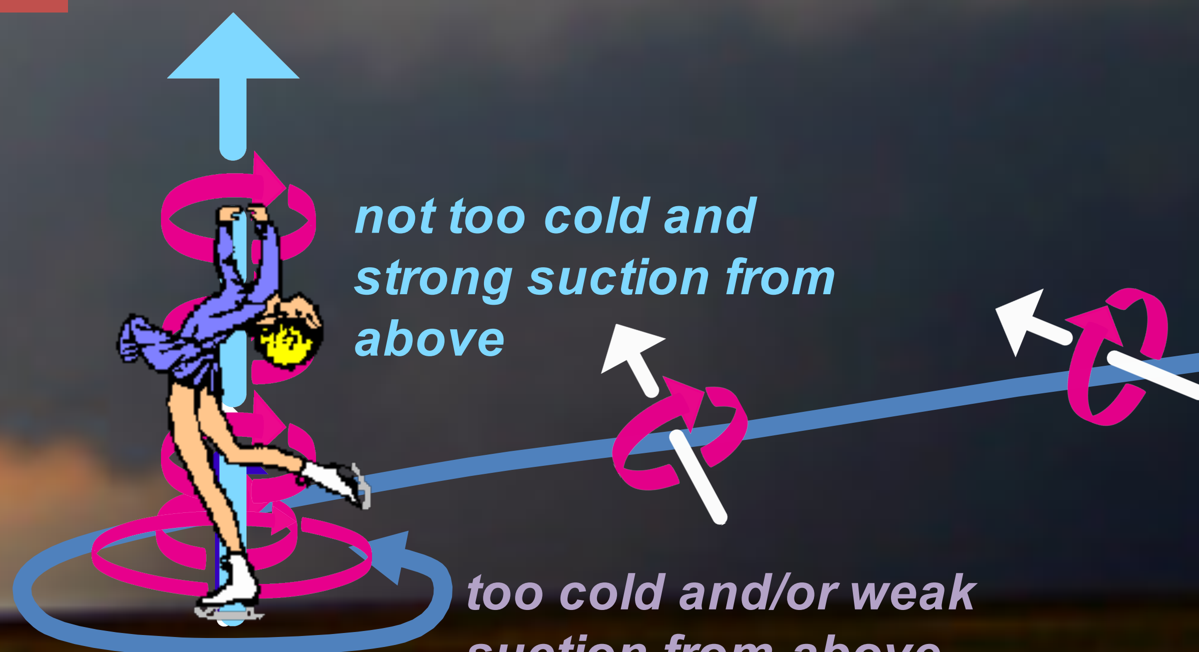
# Development of vertical vorticity next to the ground

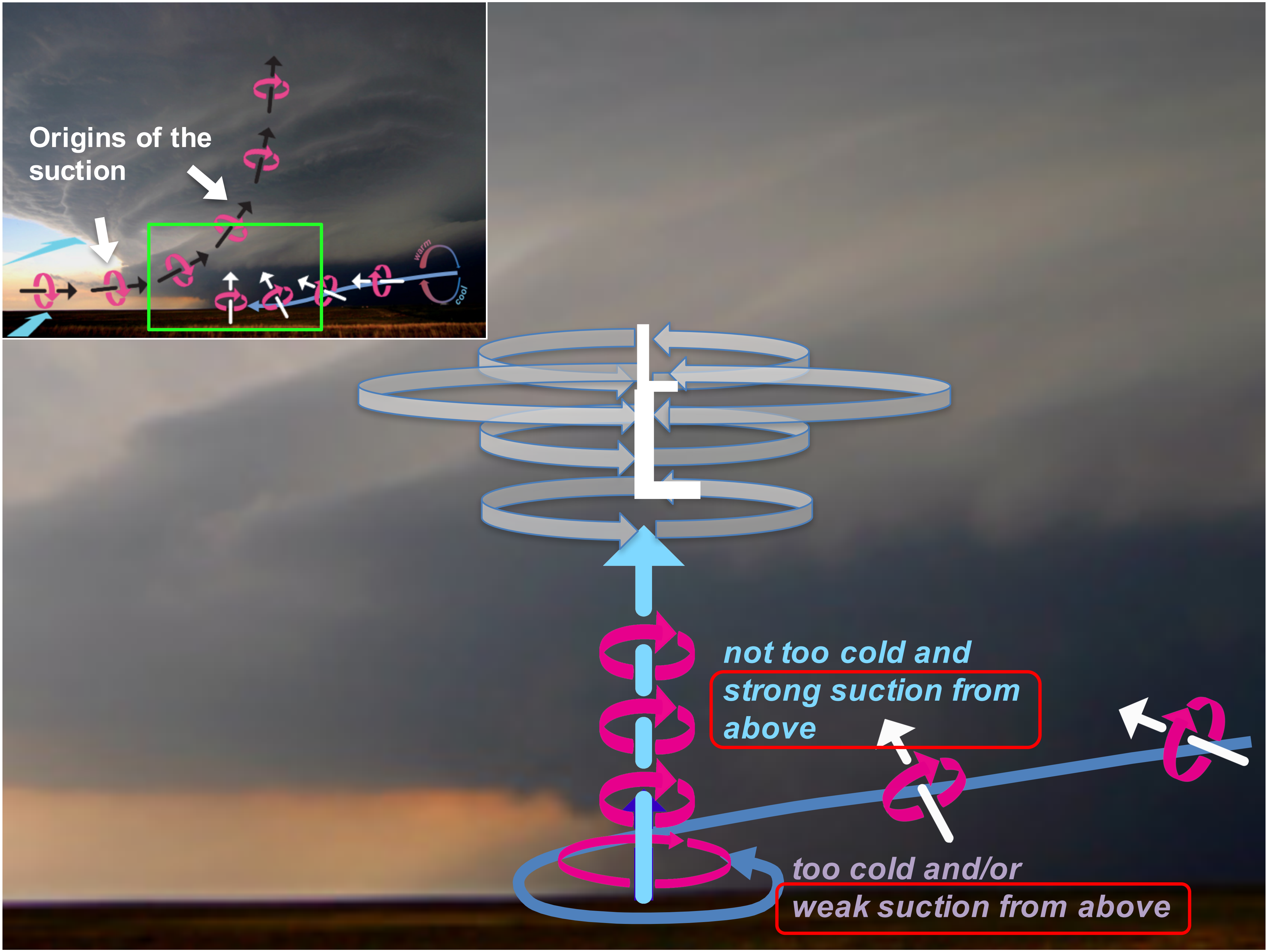

Development of vertical vorticity next to the ground
warm
cool

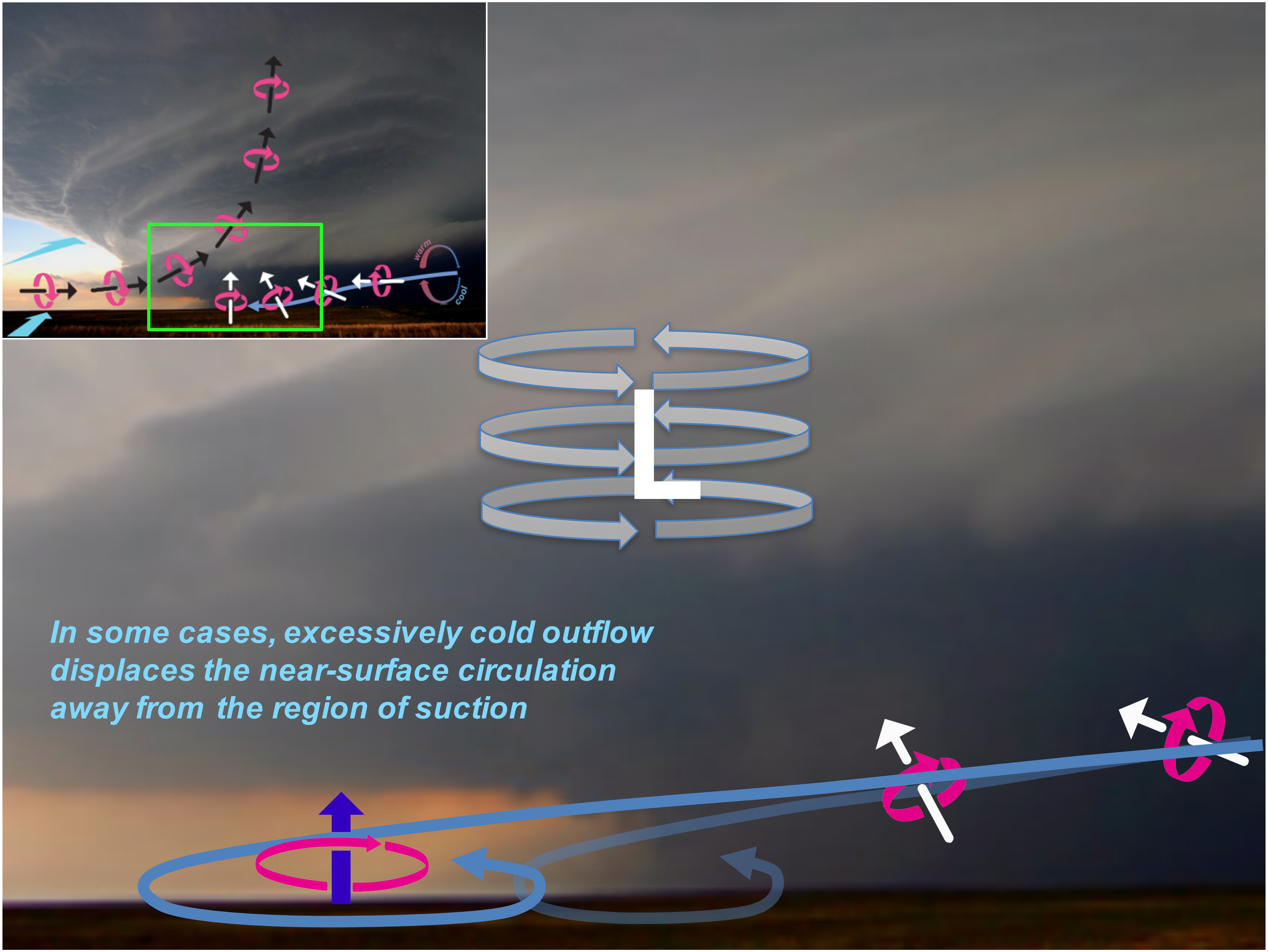



Though the development of near-surface rotation is a prerequisite for tornadogenesis, **it is insufficient for tornadogenesis**—the near-surface mesocyclone-strength rotation must be amplified to tornado strength (by roughly a factor of 100) via convergence of angular momentum.

**Paradox: Though downdrafts are crucial for tornadogenesis, excessively cold/strong downdrafts appear to be detrimental to tornadogenesis!**



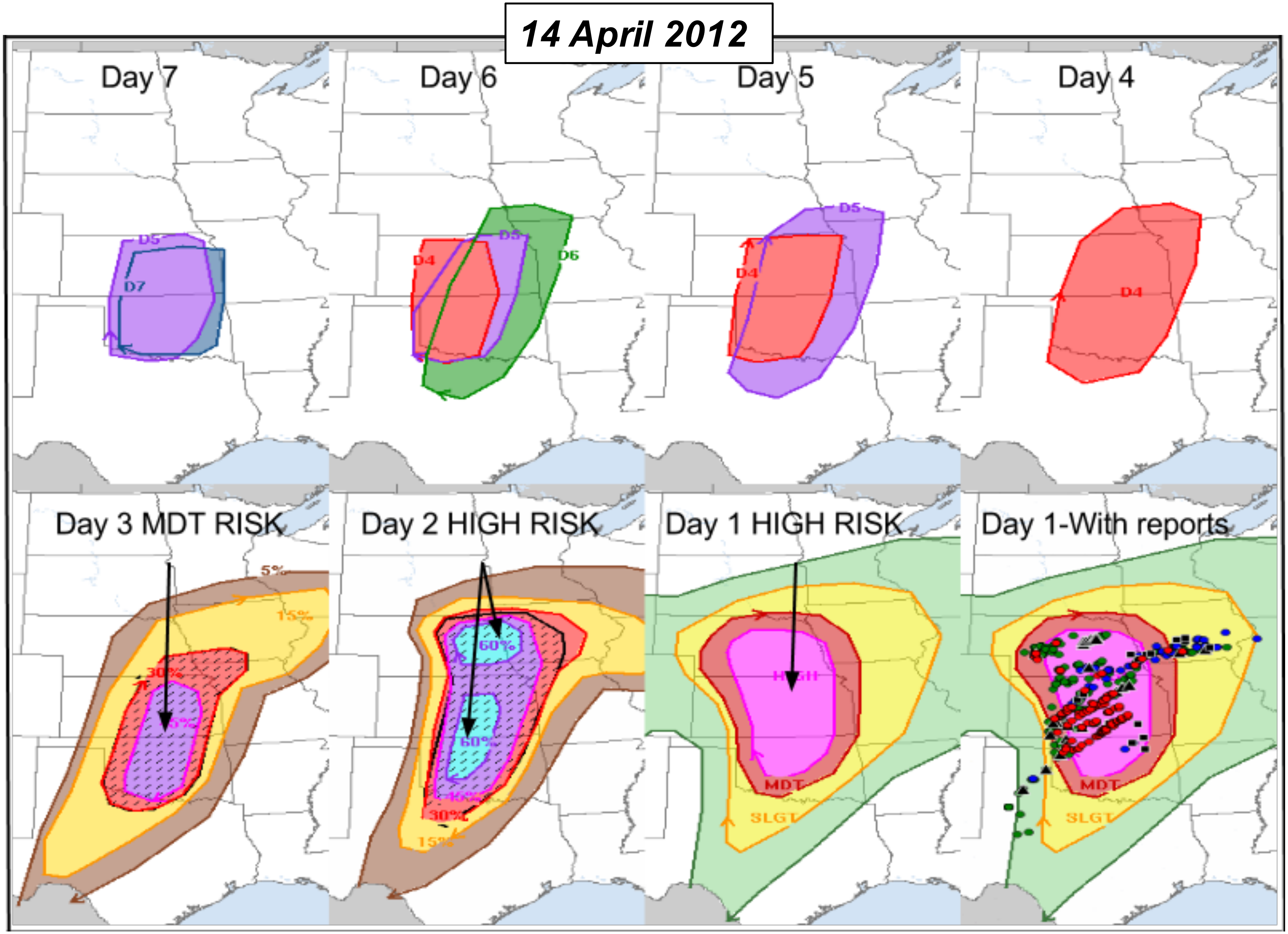

Origins of the suction
warm
cool
L
not too cold and
strong suction from above
too cold and/or
weak suction from above


warm
cool
L
In some cases, excessively cold outflow displaces the near-surface circulation away from the region of suction

Courtesy of Mike Olinski

# We're pretty good at forecasting tornadic supercell environments, *at least on the "high-end" days*

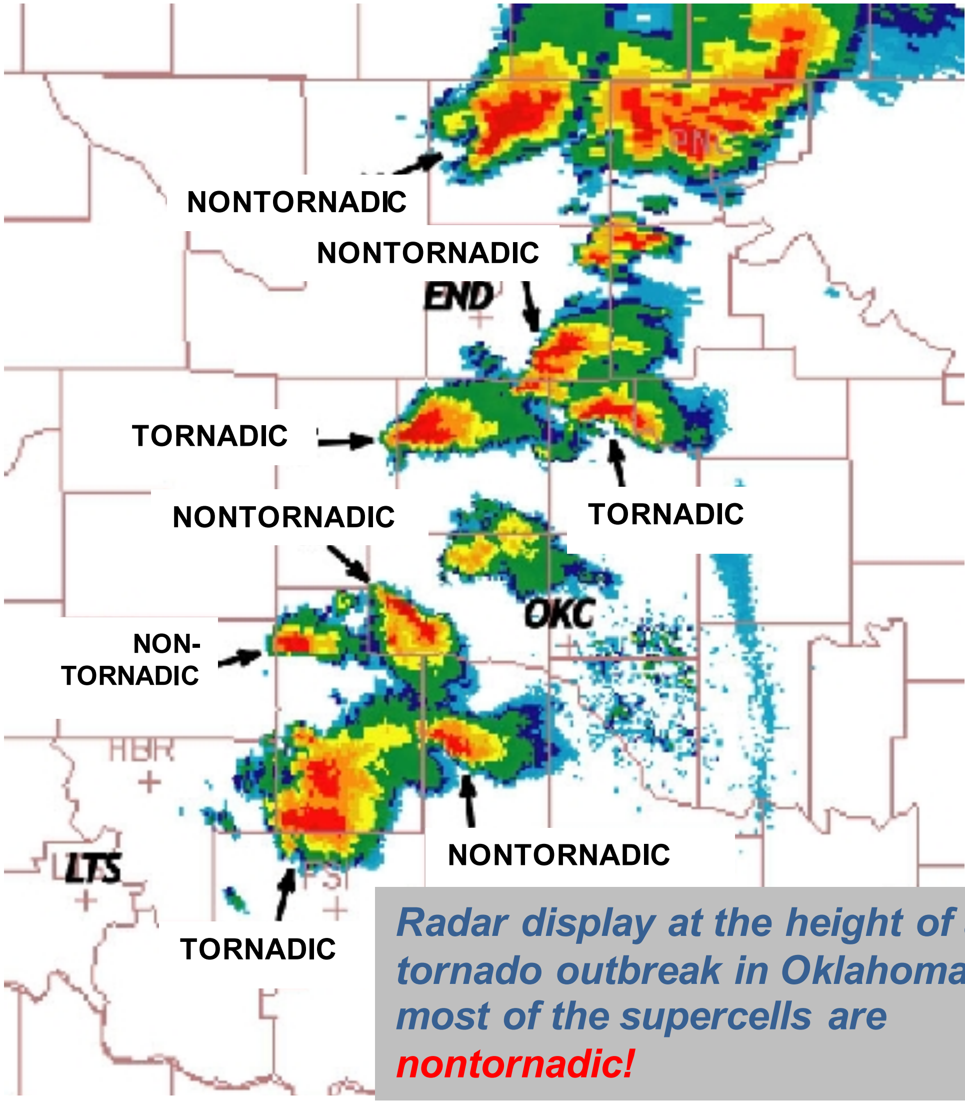
*(i.e., predicting where/when the ingredients will be present)*




https://en.wikipedia.org/wiki/List_of_Storm_Prediction_Center_high_risk_days#/media/File:Evolution_of_SPC_Forecasts_Leading_to_April_14,_2012.png

# However, we're not very skillful at forecasting the development and behavior of specific storms

**Even in tornado outbreaks, *all storms* aren't tornadic, and tornadic storms aren't tornadic *all of the time*!**



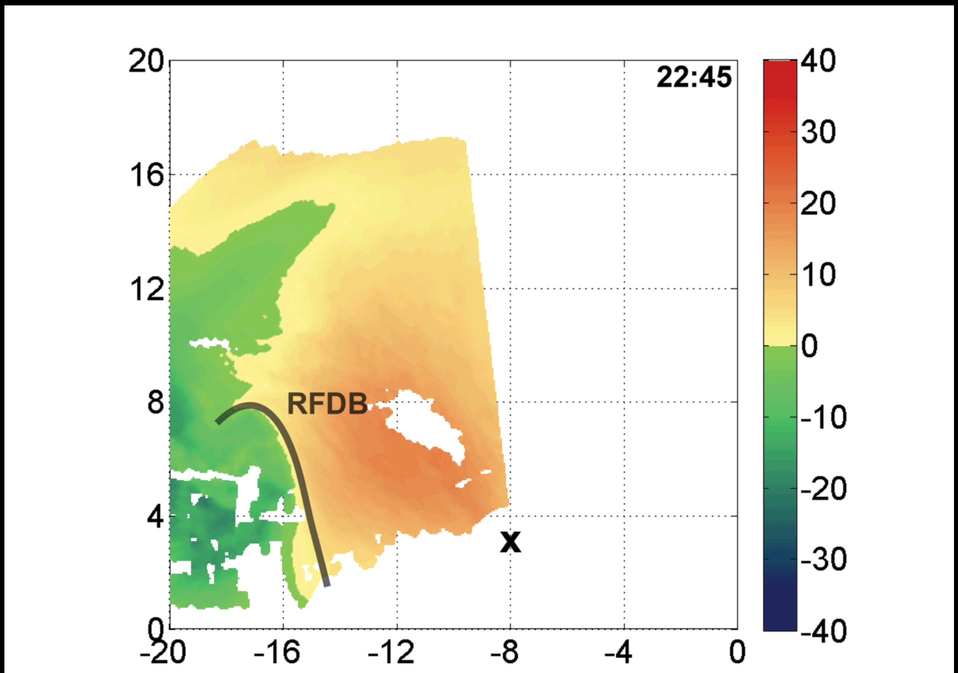

*Radar display at the height of a tornado outbreak in Oklahoma—most of the supercells are **nontornadic!***

- We have a limited ability to say when/if a *specific storm* will make a tornado, even if the environment is known to be extremely favorable.
- If a tornado is occurring, we have a limited ability to provide guidance to the public on the tornado's current intensity, future intensity, or expected duration.

# Current Areas of Research

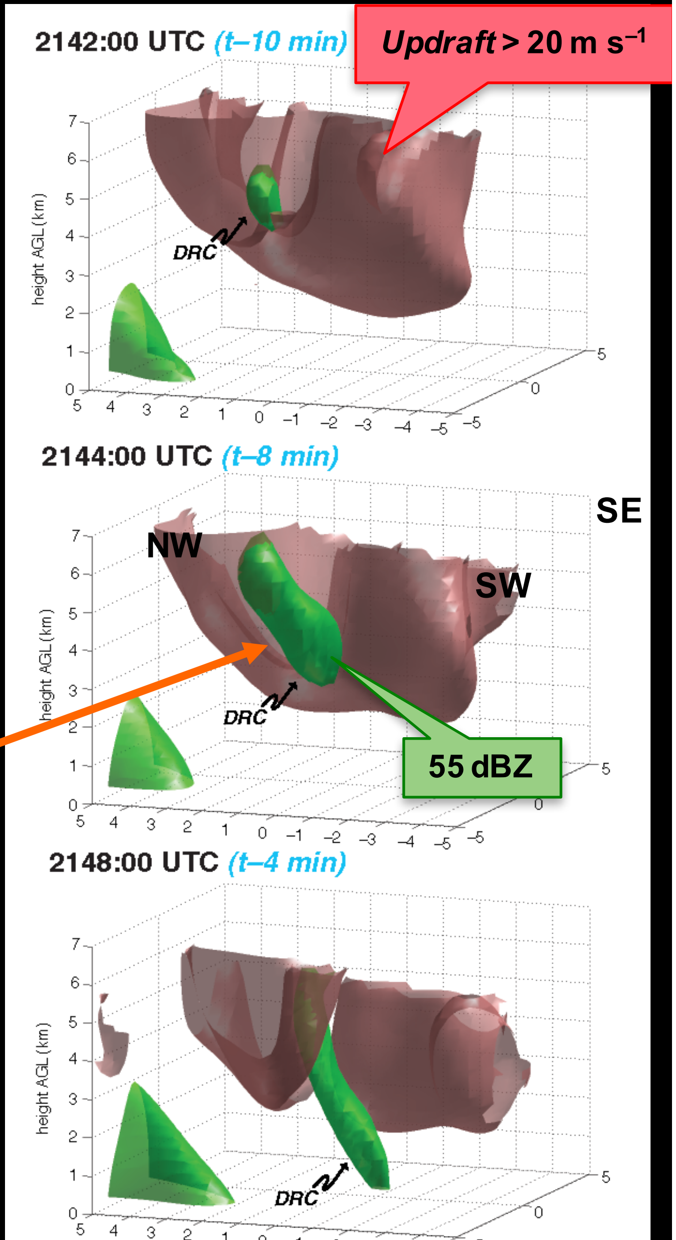
- Tornadogenesis "triggers"—even in tornado outbreaks, *all storms* aren't tornadic, and tornadic storms aren't tornadic *all of the time*

Mobile radar observations of radial velocity in the 18 May 2010 VORTEX2 supercell showing outflow surges (dashed lines) behind the primary gust front (solid line)



courtesy of Pat Skinner and Chris Weiss

precipitation shaft that immediately preceded tornadogenesis in the 6/5/09 supercell intercepted by VORTEX2



Markowski et al. (2012)

# Current Areas of Research

- Tornadogenesis "triggers"—even in tornado outbreaks, *all storms* aren't tornadic, and tornadic storms aren't tornadic *all of the time*

- To what extent do precipitation characteristics (e.g., small drops versus large drops versus large hail) influence the buoyancy, vorticity generation, and intensification of near-surface rotation?

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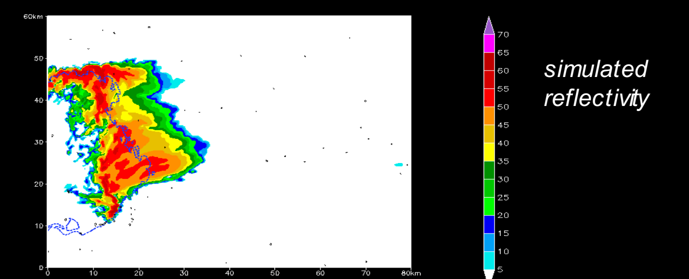
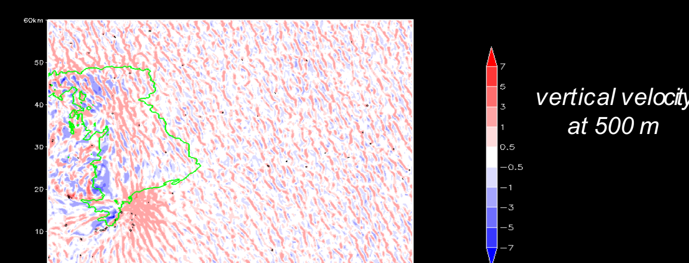
- Tornadogenesis "triggers"—even in tornado outbreaks, *all storms* aren't tornadic, and tornadic storms aren't tornadic *all of the time*

- To what extent does the precipitation type (e.g., small drops vs large drops vs large hail) influence buoyancy, baroclinic vorticity generation, and intensification of near-surface rotation?

- Importance of surface drag, terrain, storm mergers, interaction of storms with environmental heterogeneities

Courtesy of Chris Nowotarski



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large drops vs large hail) infl
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storms with environmental he

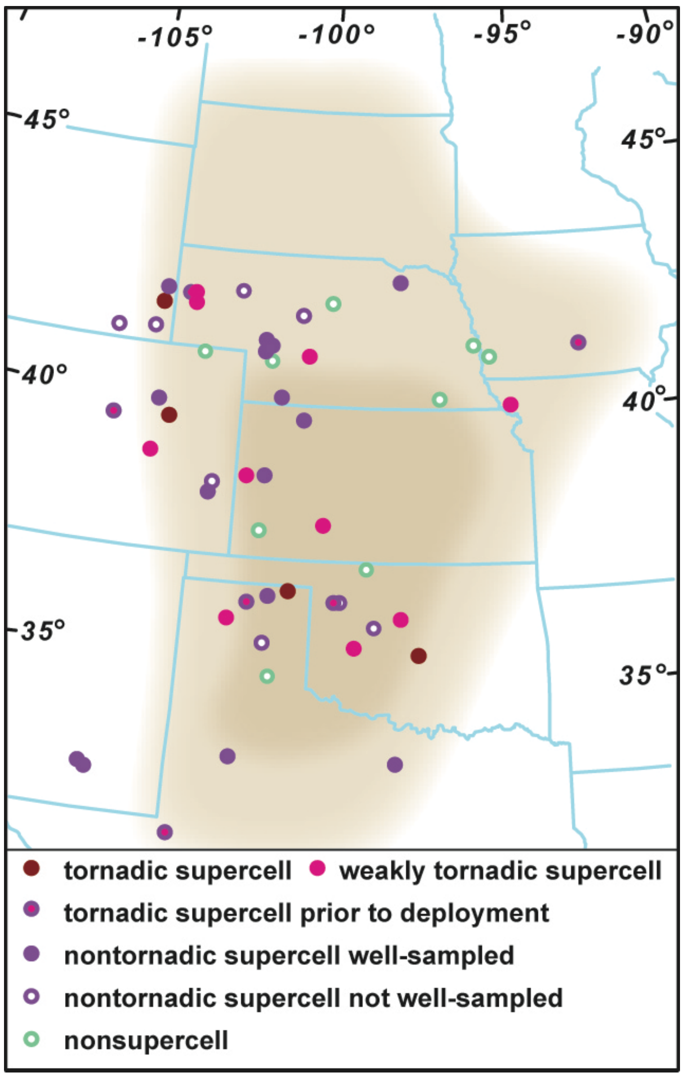
*Courtesy of Walker Ashley*

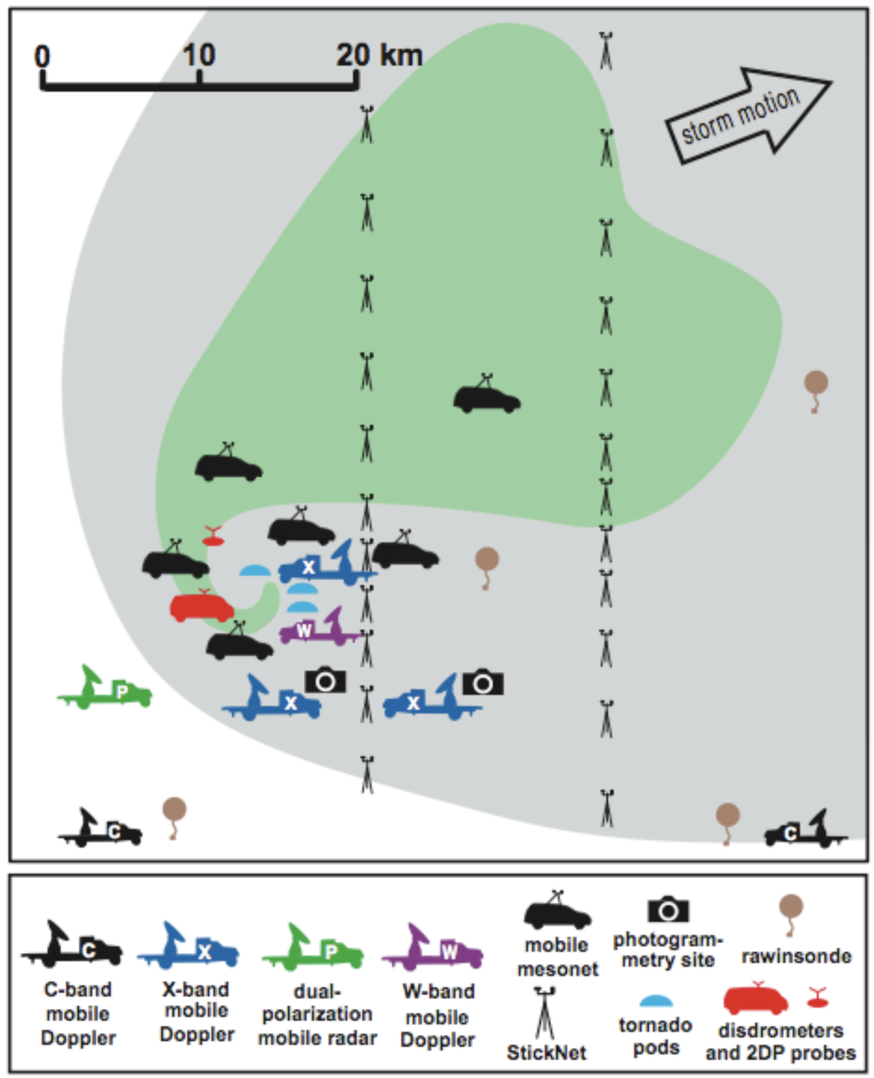
- Tornado maintenance
  - As of now, if a tornado is occurring, forecasters have a limited ability to provide guidance to the public on the tornado’s current intensity (spotter reports are about the only source of information), future intensity, or expected duration.
  - Not knowing the optimal tornado warning duration affects the number of people who are potentially unnecessarily warned.

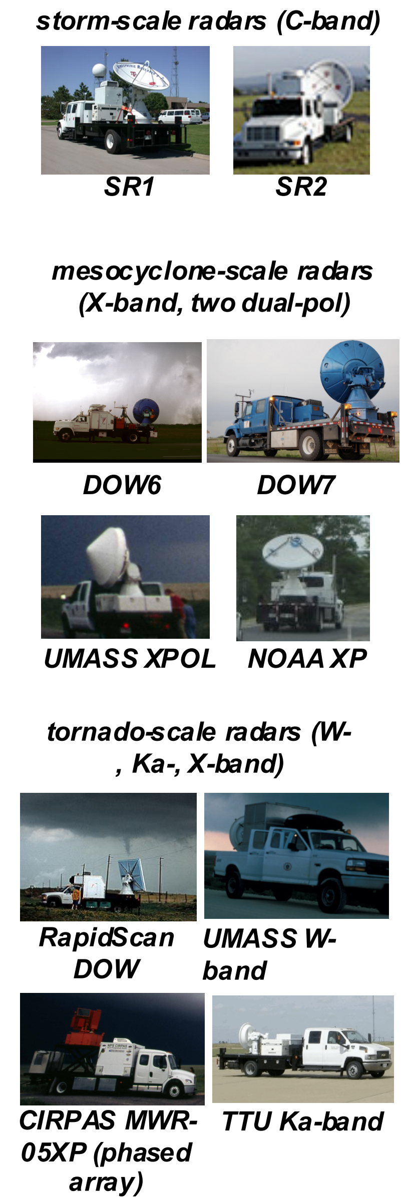
# Possible Roles for "Big Data" (and challenges)

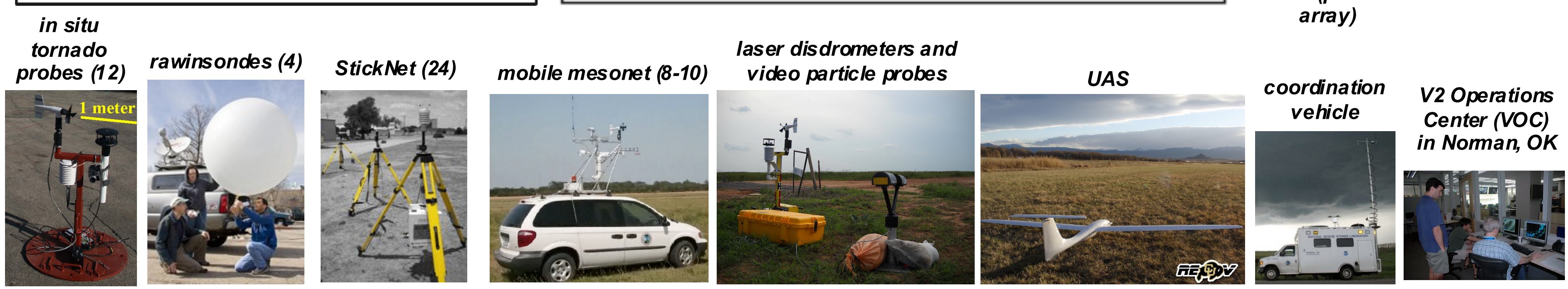
- We still collect a lot of data in field experiments that we don't know best how to assimilate into models. Or model analyses/forecasts get worse as more data are assimilated! (parameterizations of precipitation microphysics and surface physics are probably to blame in many cases)

# Idealized Deployment



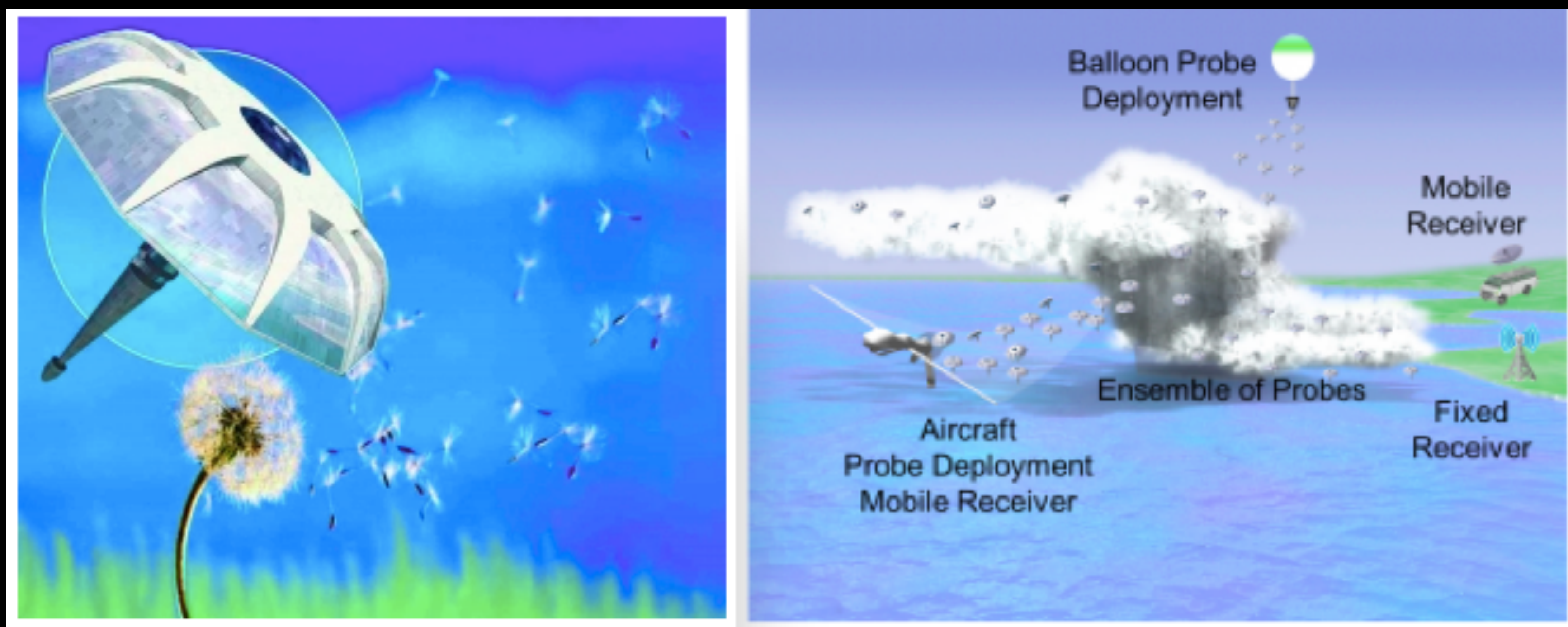



# Possible Roles for "Big Data" (and challenges)

- Biggest observing challenges
  - We sorely lack thermodynamic observations above the surface in field experiments.




Courtesy of John Manobianco

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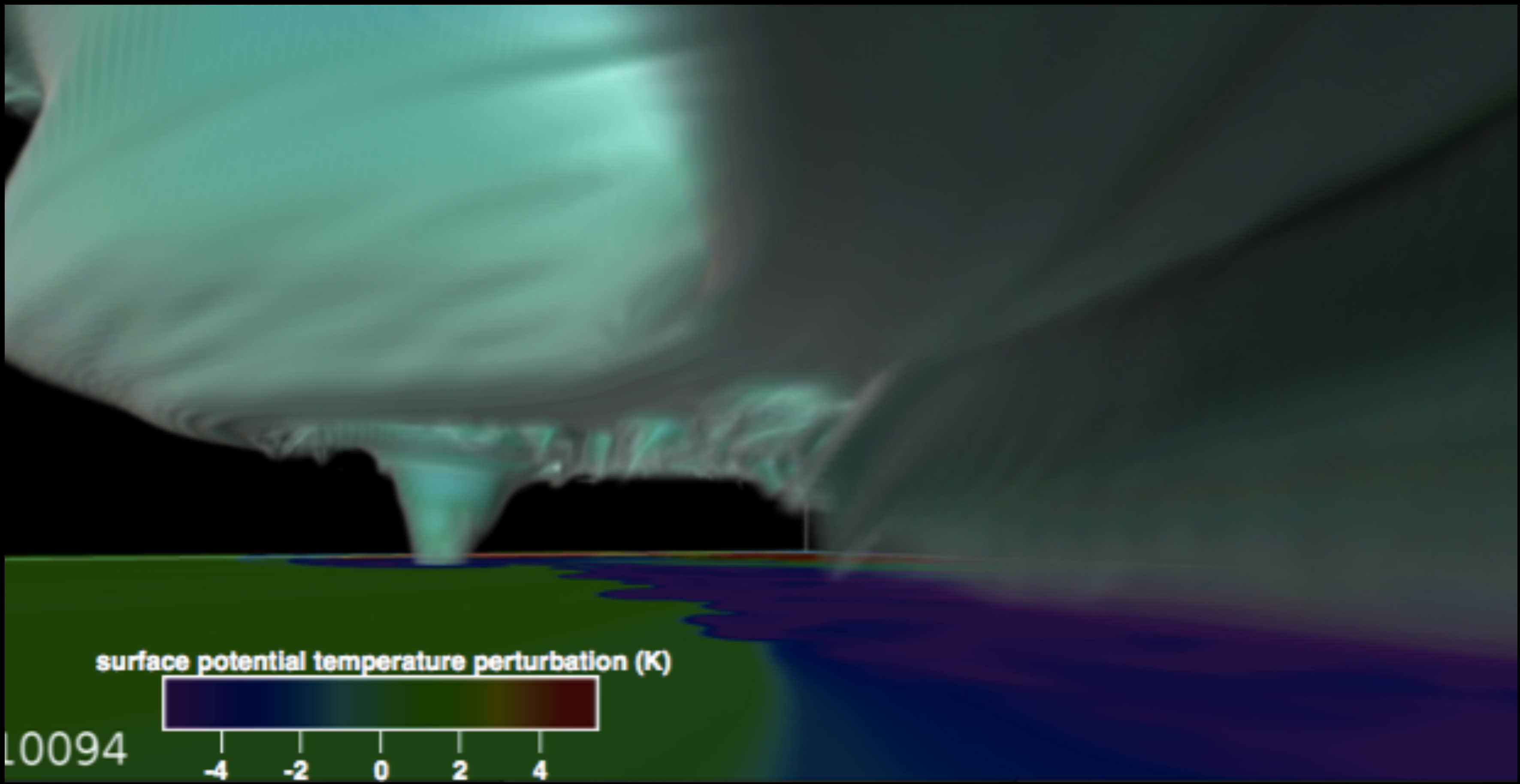
- We now can run simulations of tornadoes and the entire parent thunderstorm (domain size ~100 x 100 x 20 km) with 20–30-m grid spacing.




Orf et al. (2016)

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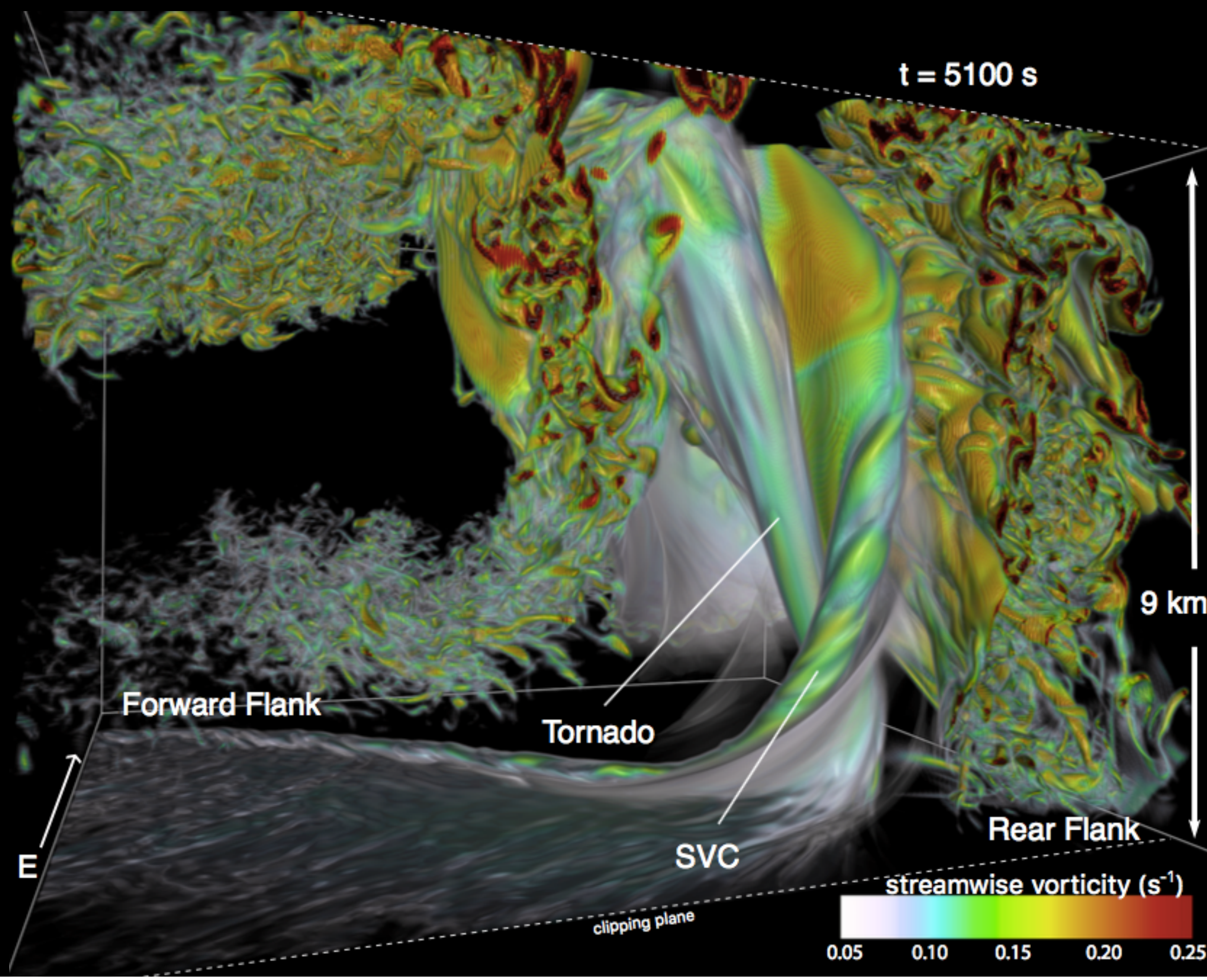


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- Analyzing the data, understanding how the tornado forms in the simulation, and understanding the sensitivities is much harder than running the simulation!
  - Each simulation produces ~100 TB of data, at least if data are saved every few seconds, but saving data every few seconds is actually not frequent enough for most budget calculations along trajectories (air parcels moving at 50 m/s move 3–5 grid lengths in just 2 seconds!)
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- Biggest modeling challenges
  - Parameterization of precipitation process and interactions between the overlying storm and underlying land surface

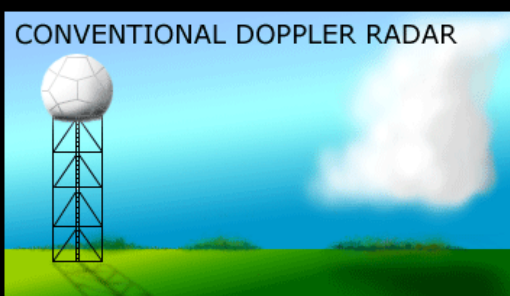
# Possible Roles for “Big Data” (and challenges)

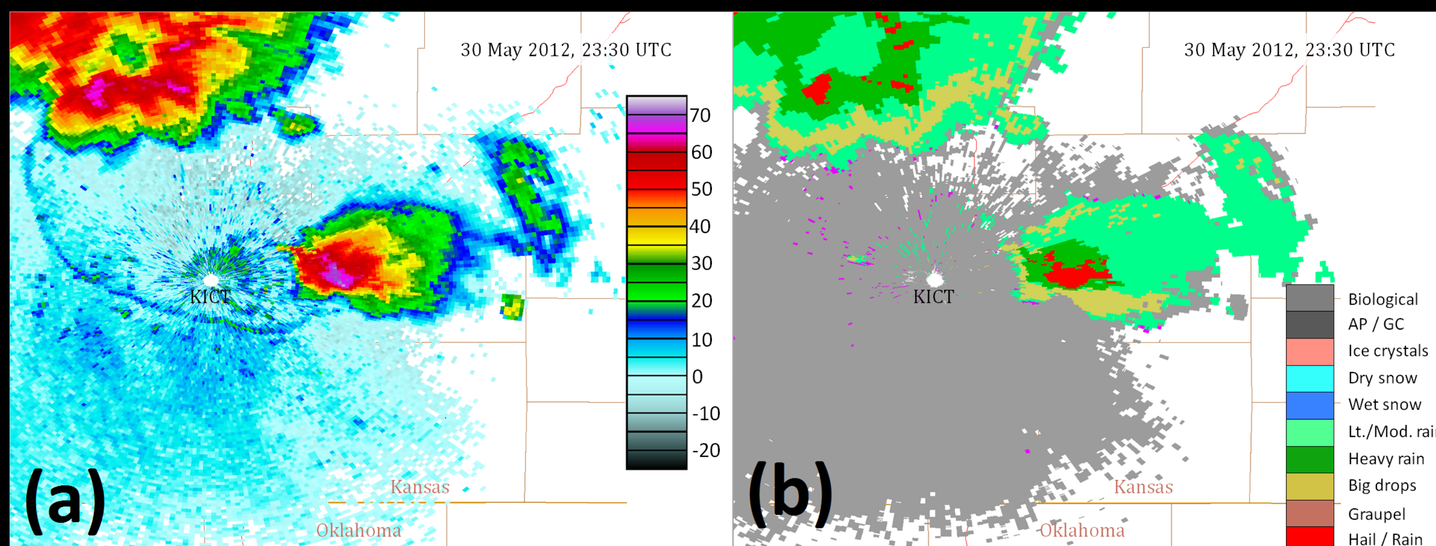
- We now have 20+ years of archived WSR-88D data nationwide, no doubt capturing 10s of thousands of storms from various ranges
  - Are there subtle signatures (they must be subtle or they would not have escaped detection by human forecasters all of these years) that can be exposed by data mining that can inform us about storm behavior in the subsequent 5–20 min? (forecasters already know about hook echoes, Doppler velocity couplets, and descending reflectivity cores—these yield only mediocre success)

Same goes for storm environments, though a lot more work has already been done in this area (and we’re already pretty good at identifying favorable tornado environments, sometimes even days in advance)

# Possible Roles for "Big Data" (and challenges)

- Polarimetric radar data—can it tell us something about tornado potential within storms? (it's already been proven to be valuable for large-hail detection and detection of tornado debris; it remains to be seen whether it might be helpful for detecting precipitation characteristics/processes in storms that might have ***predictive*** value)




Courtesy of Matt Kumjian

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  - Basic idea: use multiple extremely short-range, high-resolution computer simulations that are updated in real time with observations (Dave Stensrud will talk about this)

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