Supercells and tornadoes: The past, present, and future roles of observations and numerical models in advancing our understanding

Paul Markowski

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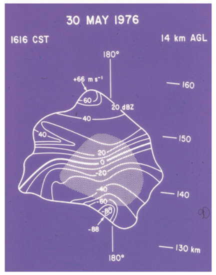
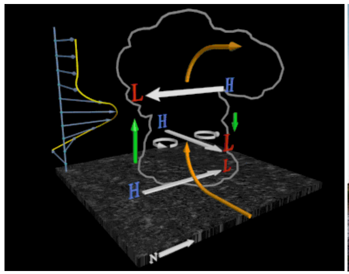
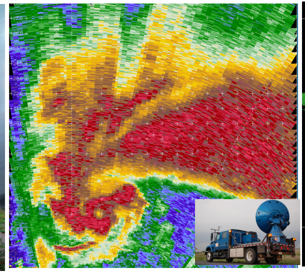
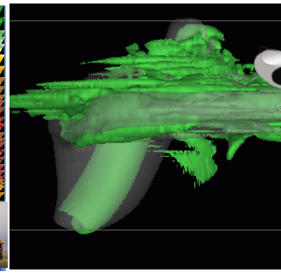
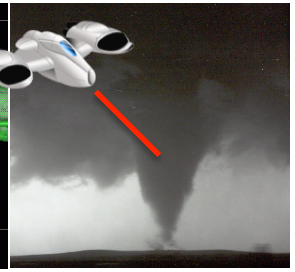
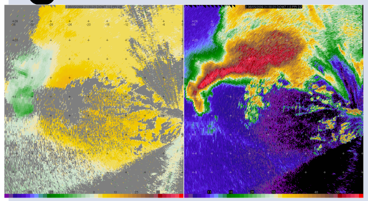
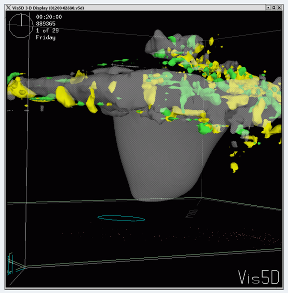




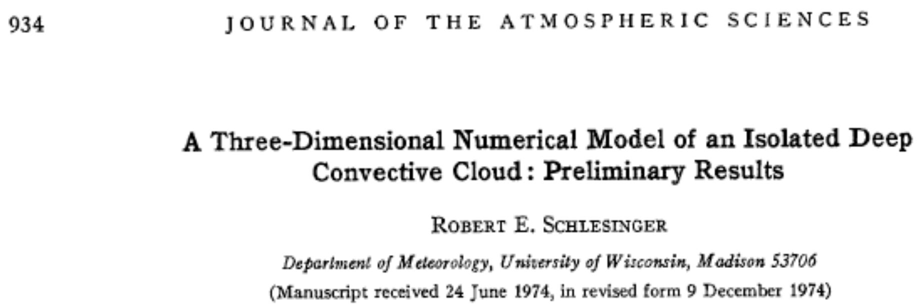




The complementary roles of observations and simulations

	Strengths	Weaknesses
Observations 	No parameterizations, discretization, or other simplifying assumptions	No observational dataset samples everything at all times Real cases are often too complex There are unavoidable uncertainties pertaining to the generality of findings given a finite number of cases
Simulations 	Physical processes can be isolated one at a time (a well-designed experiment can resolve cause-and-effect)	Simulations are only as good as the approximations used to represent physical processes (in the convective storms community, we are probably most familiar with the sensitivity of simulated storms to the microphysics parameterization, though there are other important parameterizations too)

What have we learned that we probably would not have learned if not for numerical simulations?

Bob Schlesinger (*JAS*, 1975)

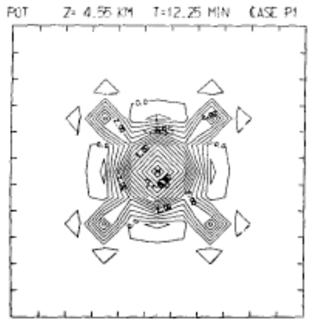

934 JOURNAL OF THE ATMOSPHERIC SCIENCES

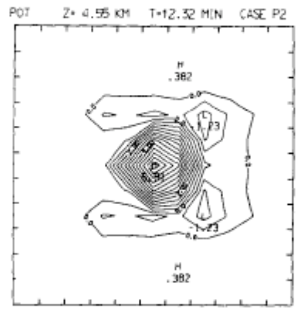
A Three-Dimensional Numerical Model of an Isolated Deep Convective Cloud: Preliminary Results

ROBERT E. SCHLESINGER

Department of Meteorology, University of Wisconsin, Madison 53706

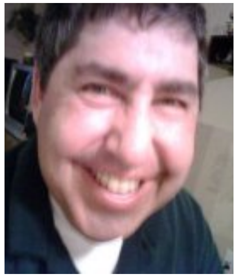
(Manuscript received 24 June 1974, in revised form 9 December 1974)





Joe Klemp

2011 AMS Rossby Medal



Morris Weisman

Rich Rotunno

2004 AMS Charney Award

Bob Wilhelmson

- The "early" simulations were designed to isolate the leading-order dynamics and explore sensitivities via large parameter-space studies (e.g., the sensitivity of updraft strength to shear)
  - They generally used horizontally homogeneous environments, simple microphysics (e.g., Kessler), and idealized initiation (i.e., warm bubbles), and omitted surface fluxes and radiative transfer
- Some issues with the Klemp-Wilhelmson model specifically:
  - the numerics were somewhat primitive and the grids were coarse (the finite differences had large truncation errors)
  - as a result, the model applied a large (by today's standards) amount of artificial diffusion—fields looked smooth and "pretty"
  - the model's bottom boundary condition (when coupled with the vertical diffusion scheme) caused outflows artificially to keep getting colder with time (Bryan et al. 2006)
- Nevertheless, much of what we know about storm dynamics today was derived from these original experiments, and almost all of the results still stand the test of time.

Relationship between storm type and environmental CAPE & shear

- Although it was known since the earliest days of severe weather forecasting that vertical wind shear is important for severe convection, numerical simulations afforded controlled parameter space studies in which the hodograph length and curvature could be modified systematically, as well as the CAPE.

Relationship between storm type and environmental CAPE & shear

The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy

M. L. WEISMAN AND J. B. KLEMP

National Center for Atmospheric Research,[1] Boulder, CO 80307

Mon. Wea. Rev, 1982

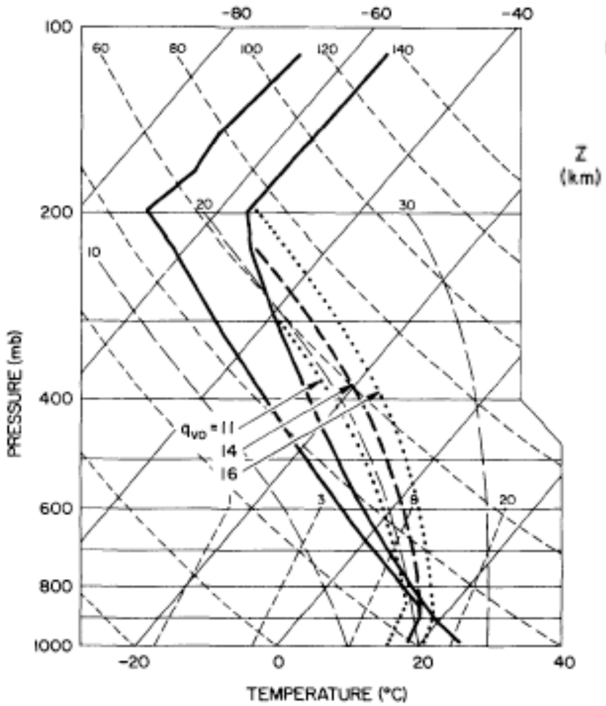
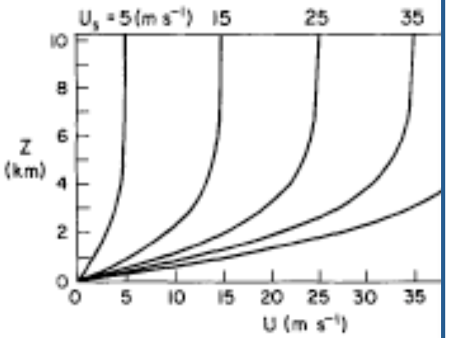
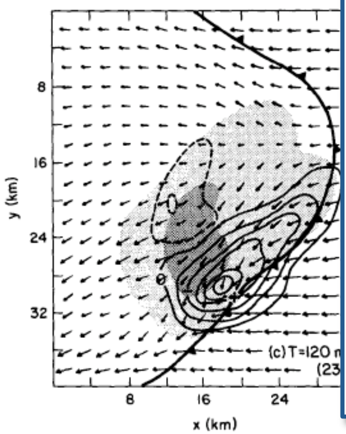


FIG. 1. Skew *T* diagram depicting temperature and moisture profiles used in model experiments (heavy solid lines). Heavy dashed line represents a parcel ascent from the surface based on a surface mixing ratio q_{vo} = 14 g kg^{-1}. Heavy dotted lines represent similar parcel ascents for q_{vo} = 11 g kg^{-1} and 16 g kg^{-1}. Tilted solid lines are isotherms, short dashed lines are dry adiabats, and long dashed lines are moist adiabats.





Illu
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Storr
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intensify in strong shear. If shear was too strong, storms died.

- among the most heavily cited papers in the history of severe storms research (over 200x, and probably not cited as much any more because much of the understanding is now "common knowledge")
- safe to say that more storms have been simulated using the WK82 sounding than any other sounding
- CAPE & shear were varied; the hodographs were all straight.

Relationship between storm type and environmental CAPE & shear

The Structure and Classification of Numerically Simulated Convective Storms in Directionally Varying Wind Shears

MORRIS L. WEISMAN AND JOSEPH B. KLEMP

National Center for Atmospheric Research,[1] Boulder, CO 80307

Mon. Wea. Rev., 1984

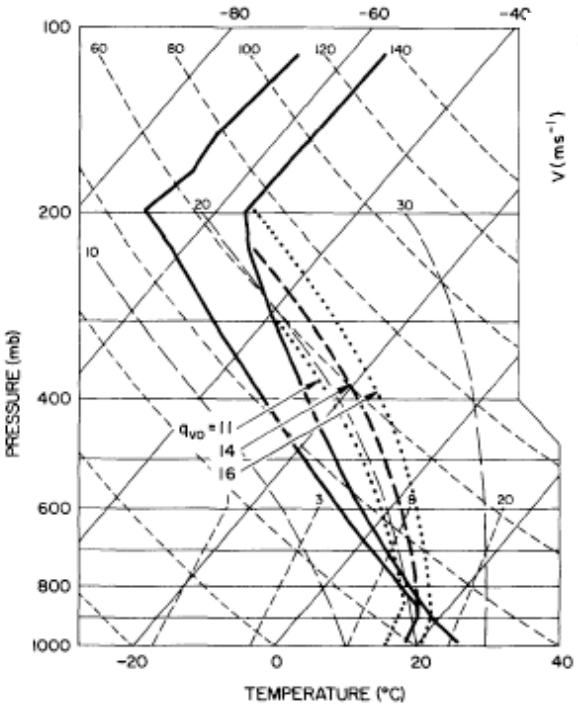
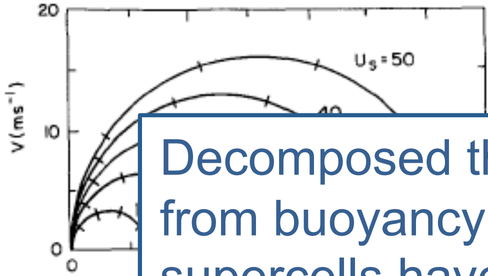
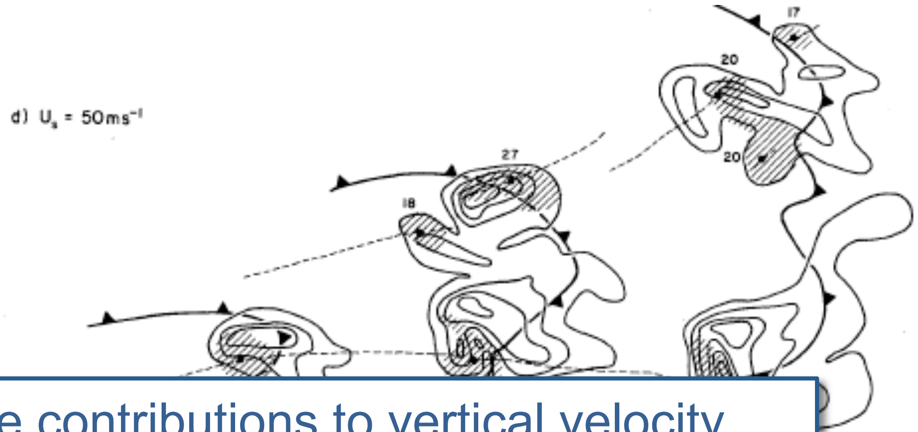


FIG. 1. Skew T diagram depicting temperature and moisture profiles used in model experiments (heavy solid lines). Heavy dashed line represents a parcel ascent from the surface based on a surface mixing ratio q_{vo} = 14 g kg^{-1}. Heavy dotted lines represent similar parcel ascents for q_{vo} = 11 g kg^{-1} and 16 g kg^{-1}. Tilted solid lines are isotherms, short dashed lines are dry adiabats, and long dashed lines are moist adiabats.



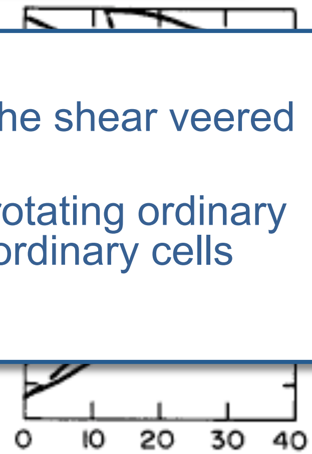


Decomposed the contributions to vertical velocity from buoyancy and from dynamic VPGF (found that supercells have a large contribution from the dynamic VPGF)

- Follow-on study in which hodographs were curved
- Updraft enhanced on the storm's right flank when the shear veered with height
- Proposed dynamically based classification of non-rotating ordinary cells and rotating supercells; multicells comprised ordinary cells

$$+ \int PZDN\,dt + \int PZBY\,dt$$

$$w = w_0 + w_{DN} + w_{BY} \qquad (5)$$



Relationship between storm type and environmental CAPE & shear

- Subsequent studies (too numerous to mention!) have investigated the effects of the vertical distribution of CAPE and shear, midlevel relative humidity, magnitude of the mid- and upper-level storm-relative winds, low-level specific humidity, and the orientation of low-level shear, among other things.

- Where things stand now (based on many observational studies as well)
  - Although deep-layer shear is important for supercells, the shear and relative humidity *at low levels* can discriminate between nontornadic and tornadic supercells (strong shear and high RH at low levels favor tornadic supercells).

e.g., Rasmussen & Blanchard (1998), Rasmussen (2003), Markowski et al. (2003), Thompson et al. (2003), Craven & Brooks (2004)

The role of pressure perturbations: storm-splitting

- Although it had been surmised since at least the early 1960s (e.g., Ludlam 1963, Barnes 1970) that the horizontal vorticity associated with environmental vertical wind shear could be the source of midlevel mesocyclone rotation via the tilting term in the vorticity equation (and shown in theoretical work by Davies-Jones, Lilly, and Rotunno in the early 1980s), *simulations were crucial for illustrating how tilting of environmental vortex lines can produce splitting storms and left- and right-movers*.

The role of pressure perturbations: storm-splitting

Simulations of Right- and Left-Moving Storms Produced Through Storm Splitting

JOSEPH B. KLEMP
National Center for Atmospheric Research,[1] Boulder, Colo. 80307

ROBERT B. WILHELMSON
University of Illinois, Urbana 61801

J. Atmos. Sci., 1978

A Numerical Study of Storm Splitting that Leads to Long-Lived Storms

ROBERT B. WILHELMSON
University of Illinois, Urbana 61801

JOSEPH B. KLEMP
National Center for Atmospheric Research,[1] Boulder, CO 80307

J. Atmos. Sci., 1978

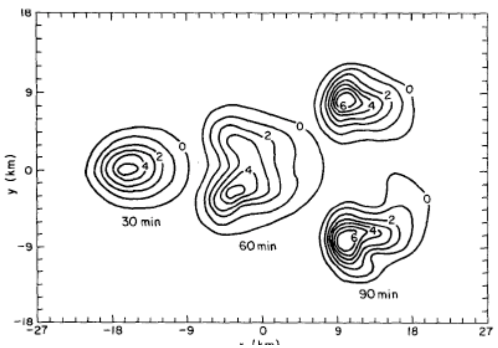
A Three-Dimensional Numerical Simulation of Splitting Severe Storms on 3 April 1964

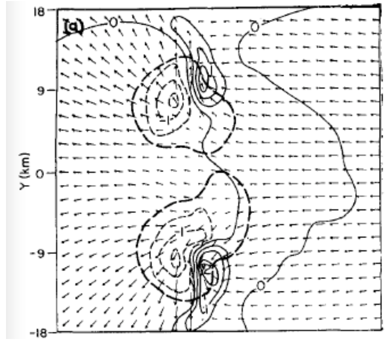
ROBERT B. WILHELMSON
University of Illinois, Urbana, IL 61801

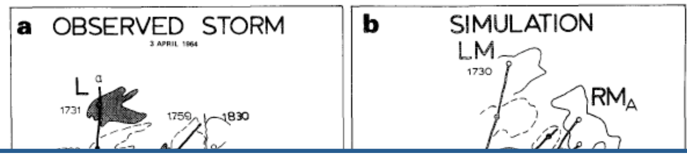
JOSEPH B. KLEMP
National Center for Atmospheric Research,[1] Boulder, CO 80307

J. Atmos. Sci., 1981

motivated by observations of splitting storms on 3 April 1964



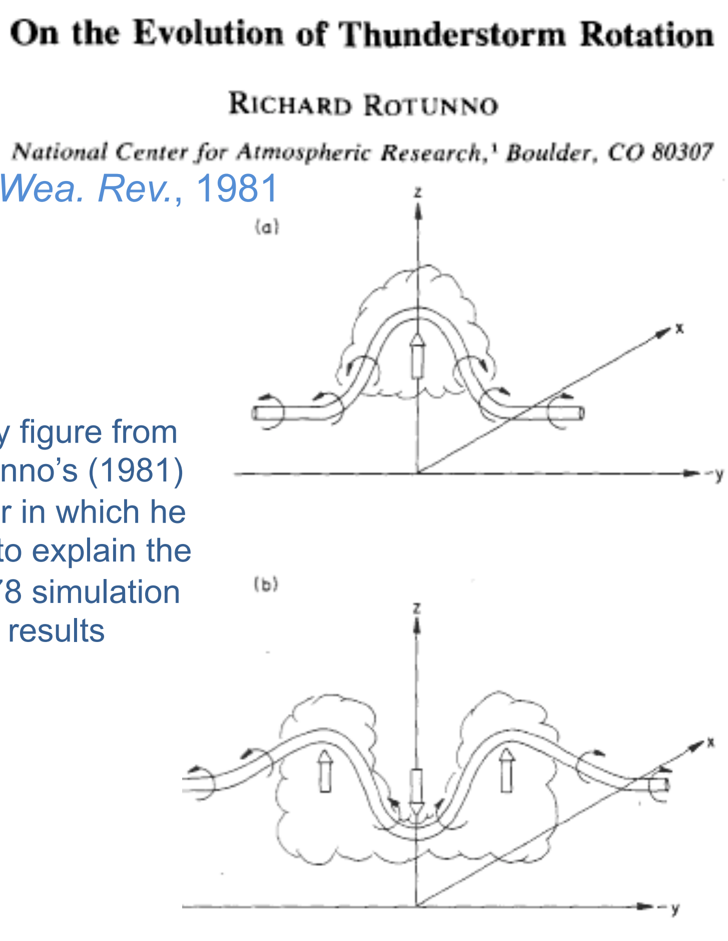




Also verified Browning's (1964) airflow model—not possible even with today's dual-Doppler observations given the lack of scatterers at midlevels outside of the storm!

- Strong shear led to storm-splitting
- Left- or right-mover could be enhanced depending on hodograph curvature

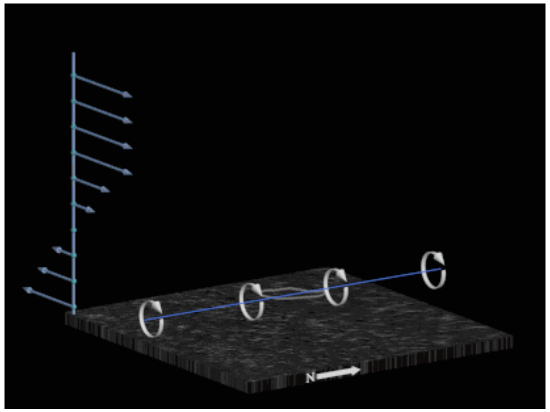
Browning (1964)



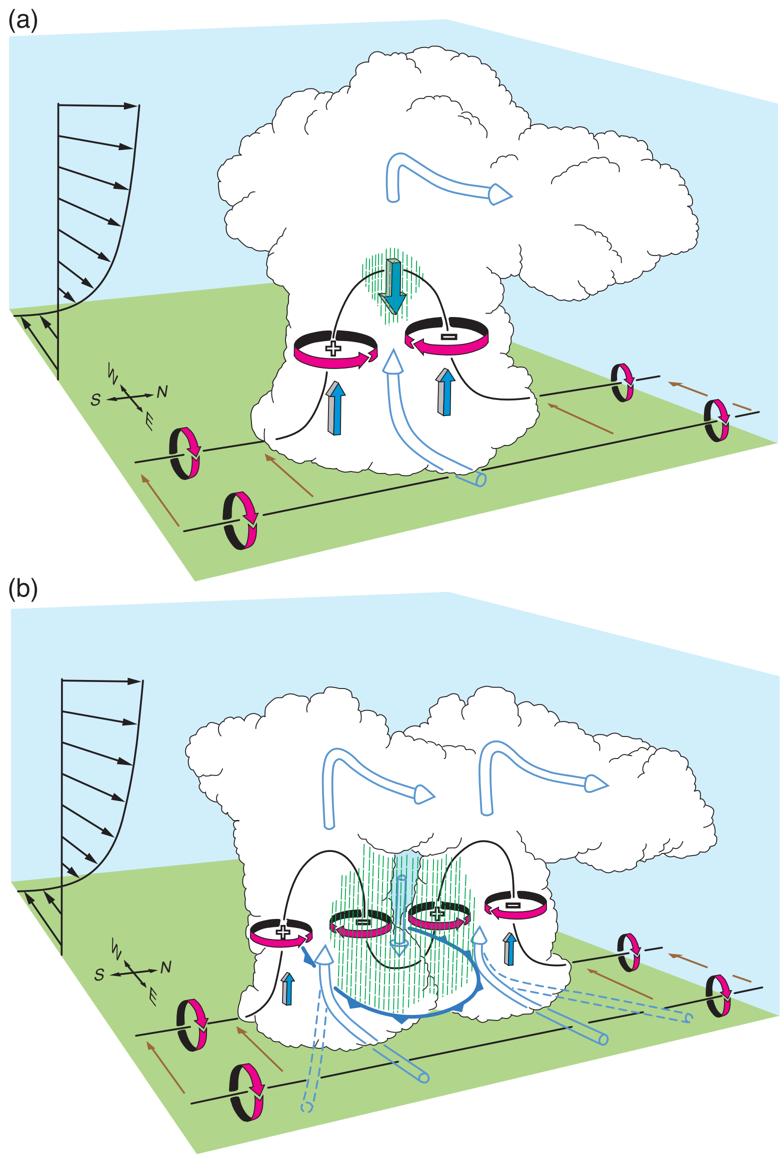
Mon. Wea. Rev., 1981

Early figure from Rotunno's (1981) paper in which he tried to explain the KW78 simulation results

Ann. Rev. Fluid Mech., 1987

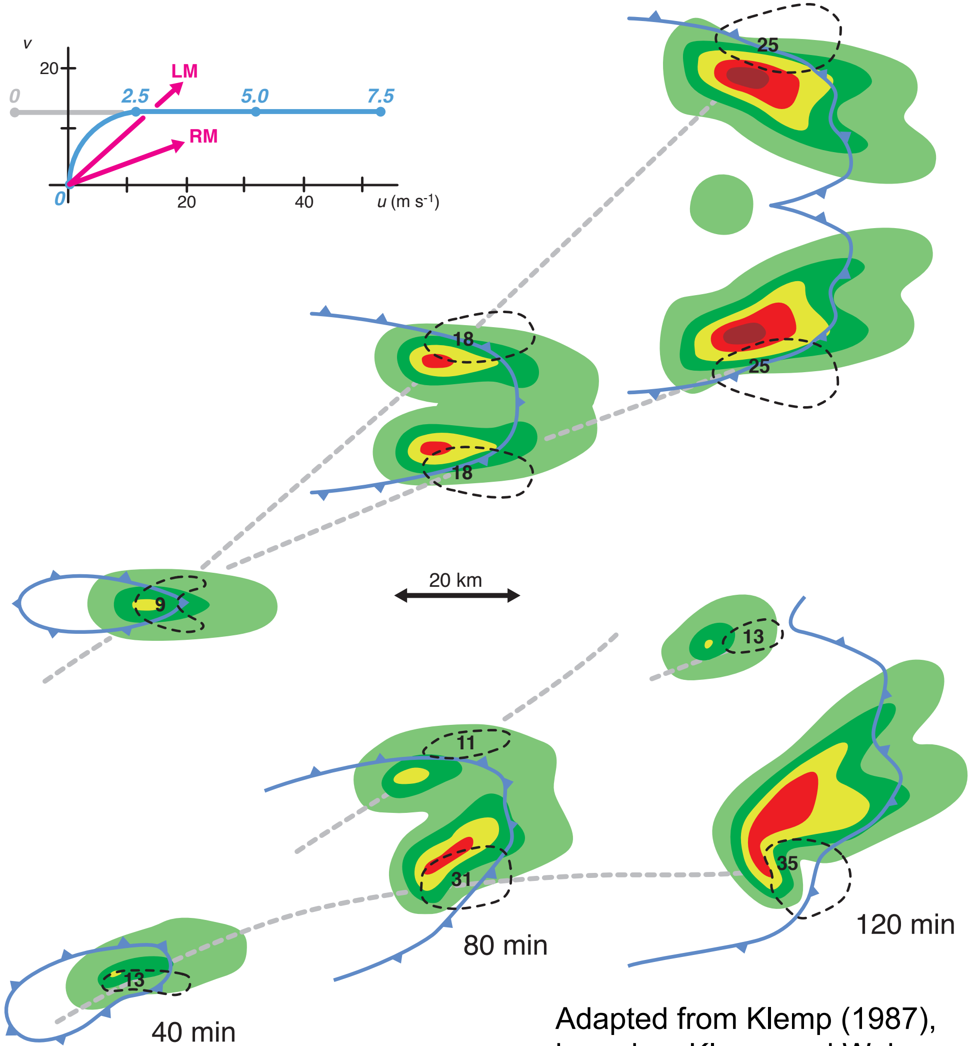


Animation from COMET

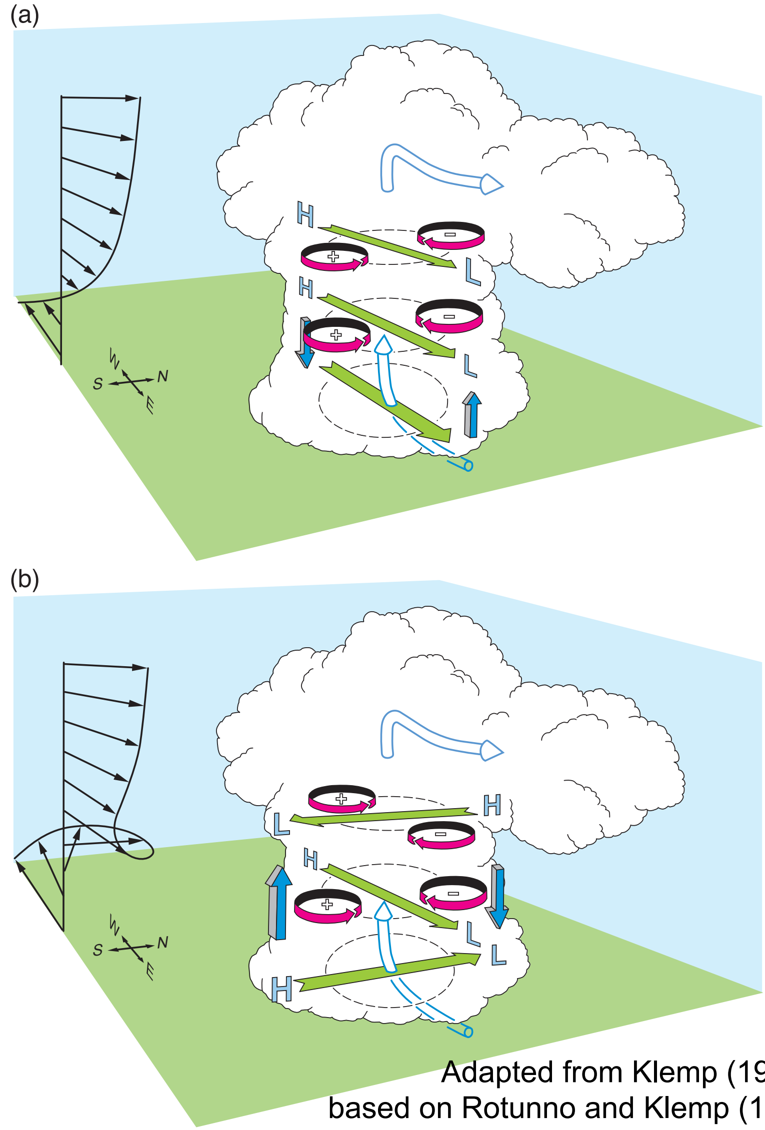


The conceptual model was better "brought to life" in Klemp's (1987) paper.

The role of pressure perturbations: supercell propagation and the effects of hodograph curvature



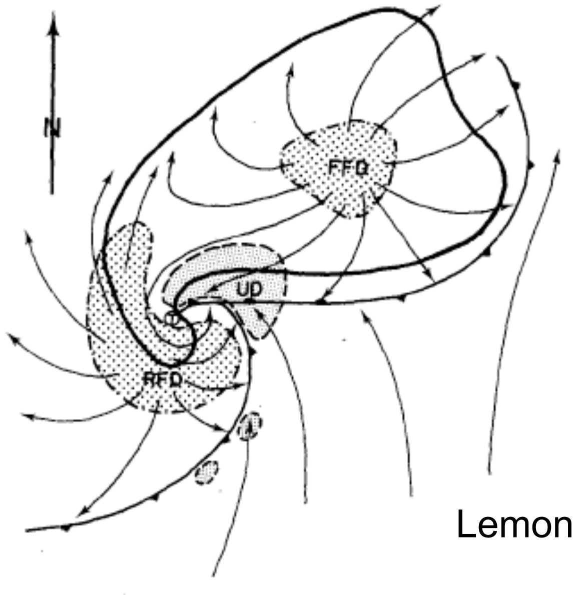
Adapted from Klemp (1987), based on Klemp and Weisman (1983)



Adapted from Klemp (1987), based on Rotunno and Klemp (1982)

The development of low-level rotation

- Although it was known from theory that a downdraft is needed in order for vertical vorticity to develop at the surface in a horizontally homogeneous environment (e.g., Davies-Jones 1982), simulations implicated a *dynamical role* for the forward-flank downdraft (FFD) that had previously appeared in Lemon & Doswell's (1979) supercell conceptua



Lemon and Doswell (1979)

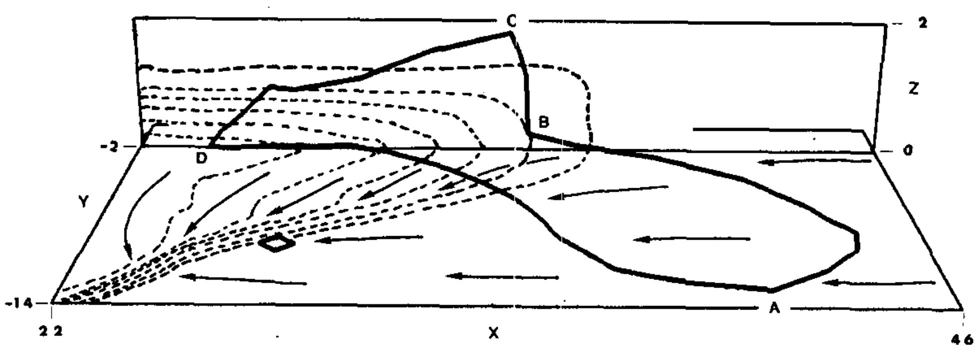
The development of low-level rotation

On the Rotation and Propagation of Simulated Supercell Thunderstorms

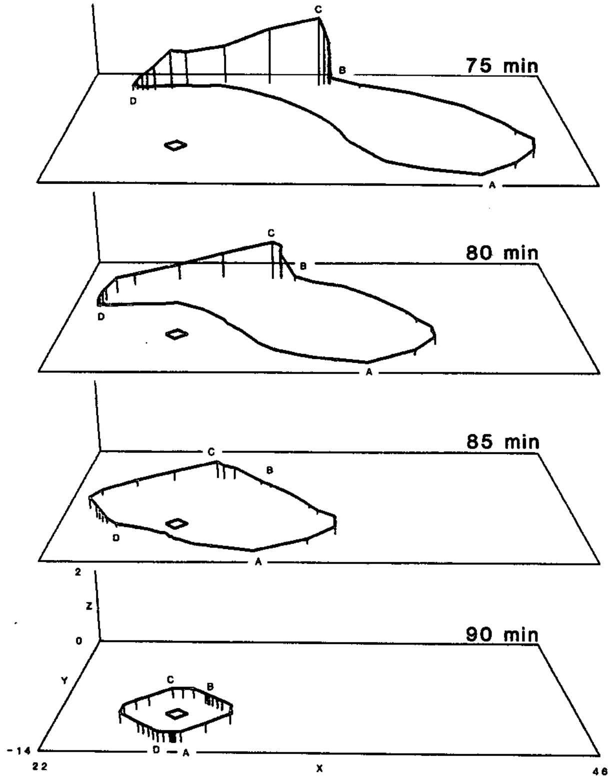
RICHARD ROTUNNO AND JOSEPH KLEMP

National Center for Atmospheric Research,[1] *Boulder, CO 80307*

J. Atmos. Sci., 1985



$$\frac{DC}{Dt} = \oint B\mathbf{k} \cdot \mathbf{dl} = \oint B\ dz$$

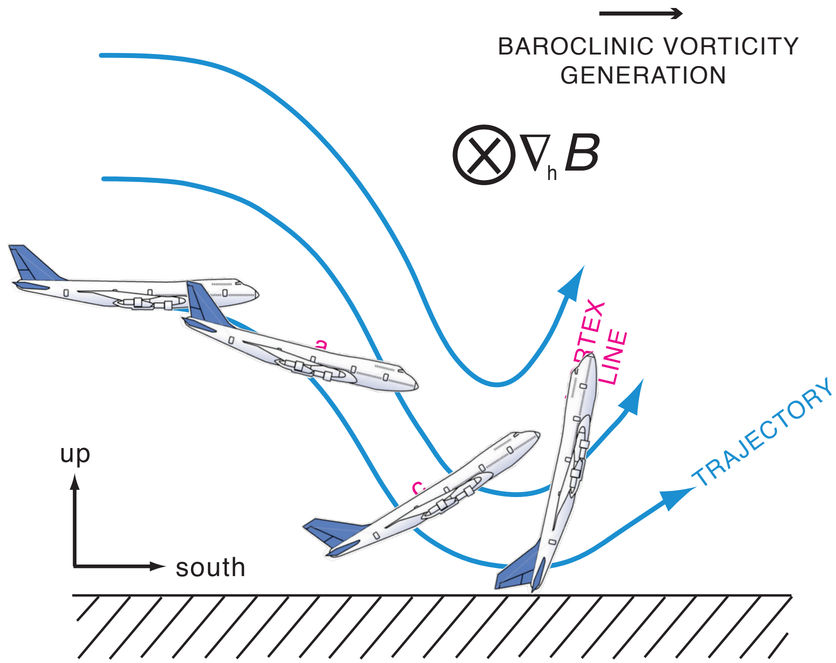


The development of low-level rotation

- Subsequent work involving theory and simulations demonstrated the "slippage" of the vorticity vector from descending trajectories that occurs when baroclinic vorticity generation occurs during descent.

The vorticity vector is initially tipped downward during descent, but with less inclination than the trajectories because southward-pointing horizontal vorticity is continually being generated baroclinically; the vorticity vector is then tilted upward by velocity gradients.

This is something that's generally unobservable because the rapid transformation of anticyclonic vertical vorticity to cyclonic vorticity occurs very close to the surface, well below the level of dual-Doppler observations that we'd obtain in a field project!



Adapted from Davies-Jones & Brooks (1993); airplane idea taken from Johannes Dahl.

The development of low-level rotation

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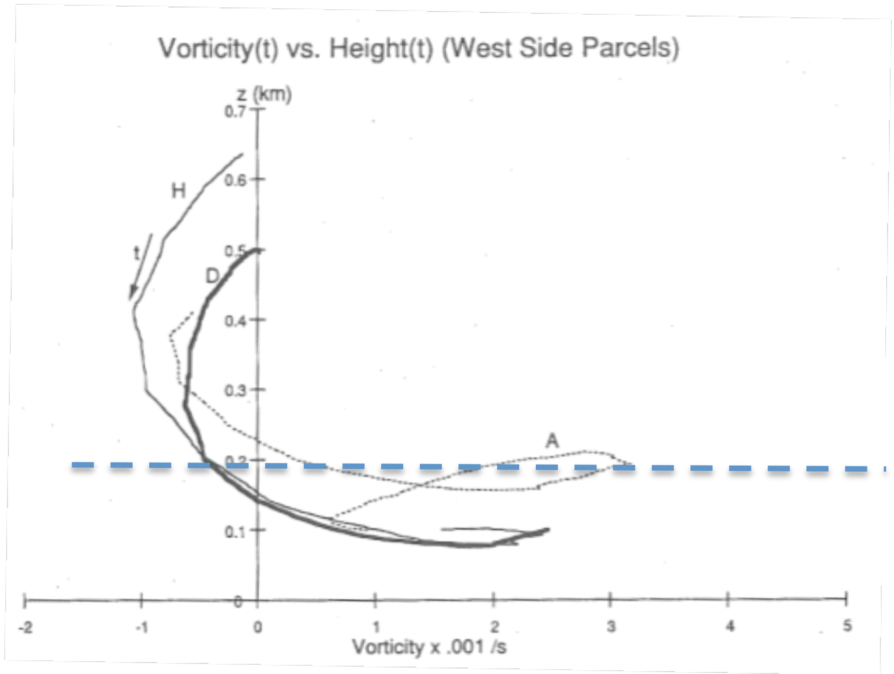
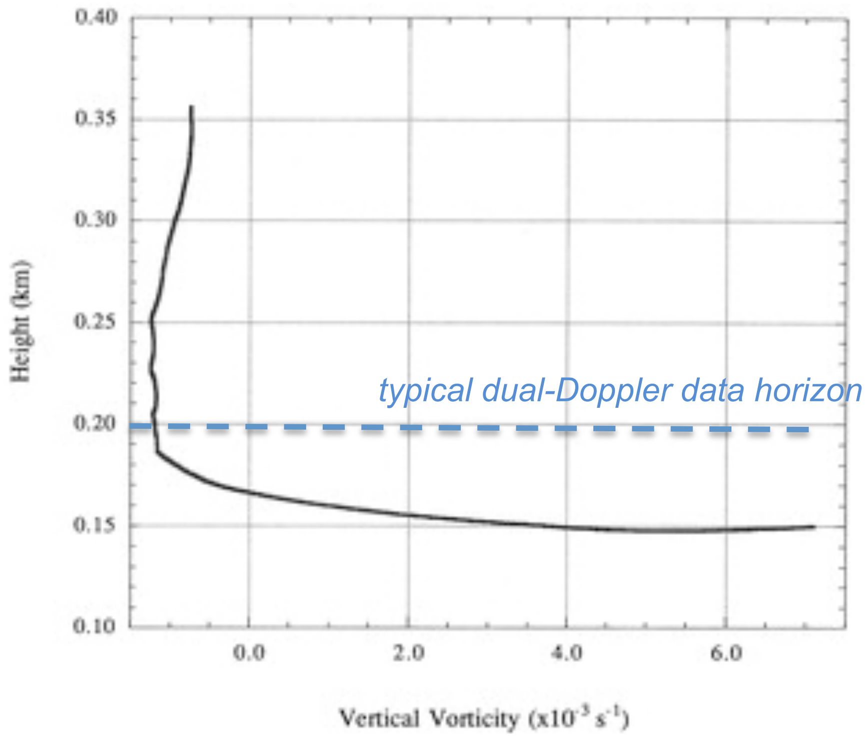


Davies-Jones & Brooks (1993)



Adlerman et al. (1999)

The development of low-level rotation

- Where things stand now
  - Still investigating the role of downdrafts, e.g., their thermodynamic characteristics, microphysics, etc.—several outstanding details yet to be fully understood (will say more at end of talk)

Relationship between storm-scale flow and tornado-scale (or at least sub-mesocyclone-scale) flow

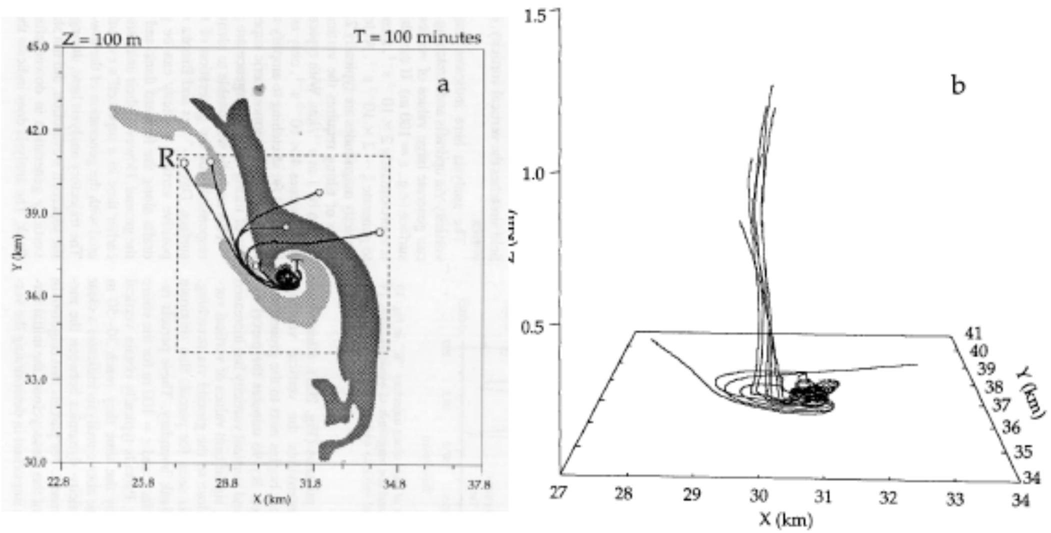
- Difficult to observe the storm scale, mesocyclone scale, and submesocyclone scale well simultaneously (at least prior to VORTEX2)

Simulation and Analysis of Tornado Development and Decay within a Three-Dimensional Supercell Thunderstorm

Louis J. Wicker* and Robert B. Wilhelmson

Department of Atmospheric Sciences and the National Center for Supercomputing Applications, University of Illinois, Urbana–Champaign, Illinois

J. Atmos. Sci., 1995



A Numerical Simulation of Cyclic Mesocyclogenesis

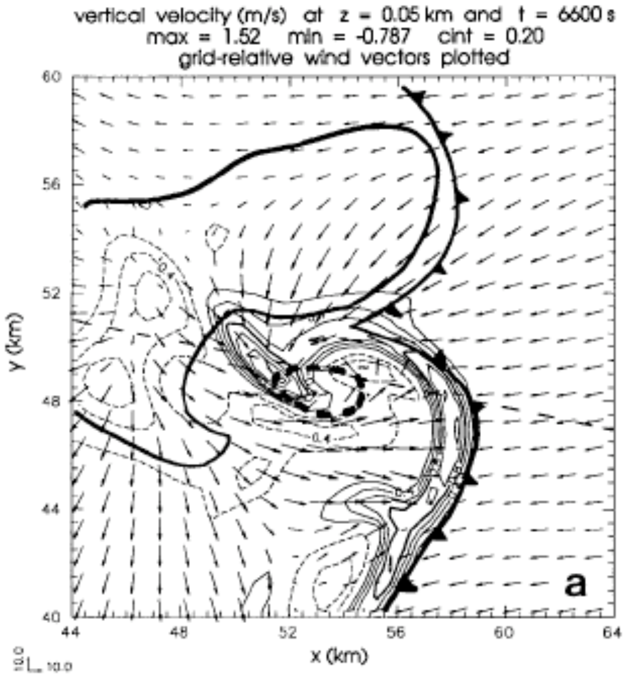
Edwin J. Adlerman and Kelvin K. Droegemeier

School of Meteorology and Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, Oklahoma

Robert Davies-Jones

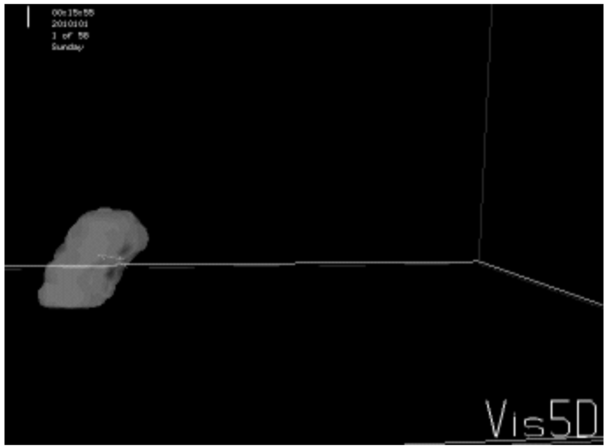
NOAA/National Severe Storms Laboratory, Norman, Oklahoma.

J. Atmos. Sci., 1999

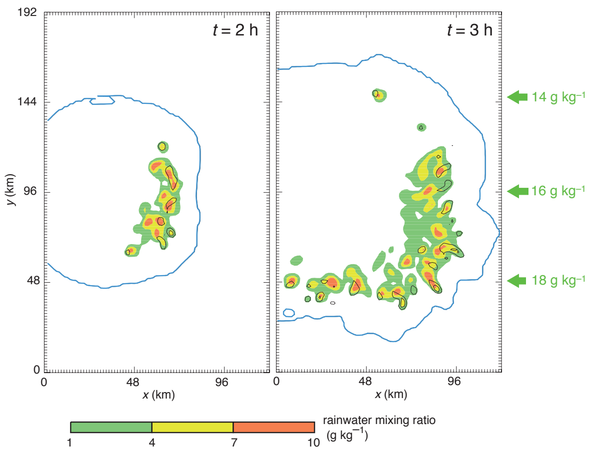


Apologies

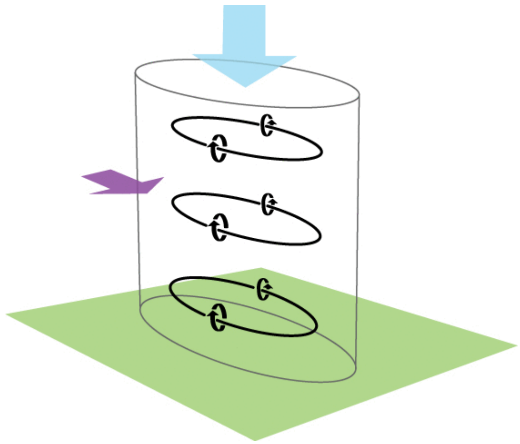
- Countless other studies unmentioned
  - Storm electrification—too hard to observe 4D electric fields and airflow through entire storm (e.g., Mansell et al. 2002, 2005; Gilmore & Wicker 2002)
  - Horizontal heterogeneity—models are crucial for assessing the influence of heterogeneity by virtue of the ability to do a "control run" without heterogeneity (e.g., Atkins et al. 1999; Richardson et al. 2007; Ziegler et al. 2010)
  - "Toy" simulations, i.e., those with a highly idealized design (e.g., Walko 1993; Trapp & Fiedler 1993; Straka et al. 2007, etc.)



Simulated storm with lightning (courtesy of Ted Mansell)



MCS in a heterogeneous environment (courtesy of Yvette Richardson)



Evolution of vorticity rings in a "toy" simulation by Straka et al. (2007)

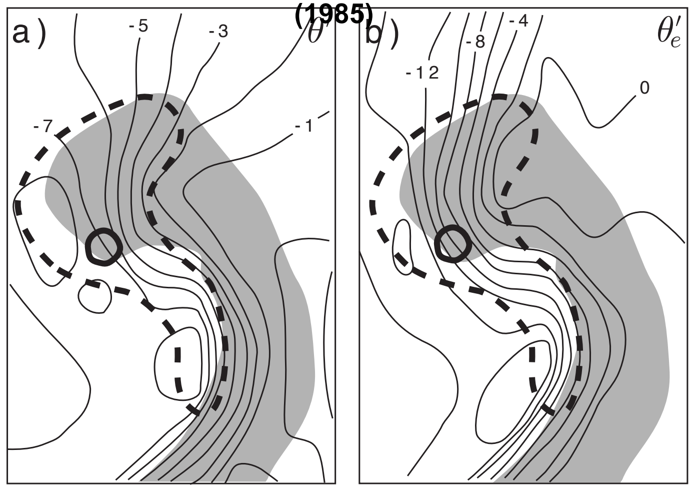
What have we learned from observations that we would not yet know from simulations?

Thermodynamic characteristics of supercell outflow

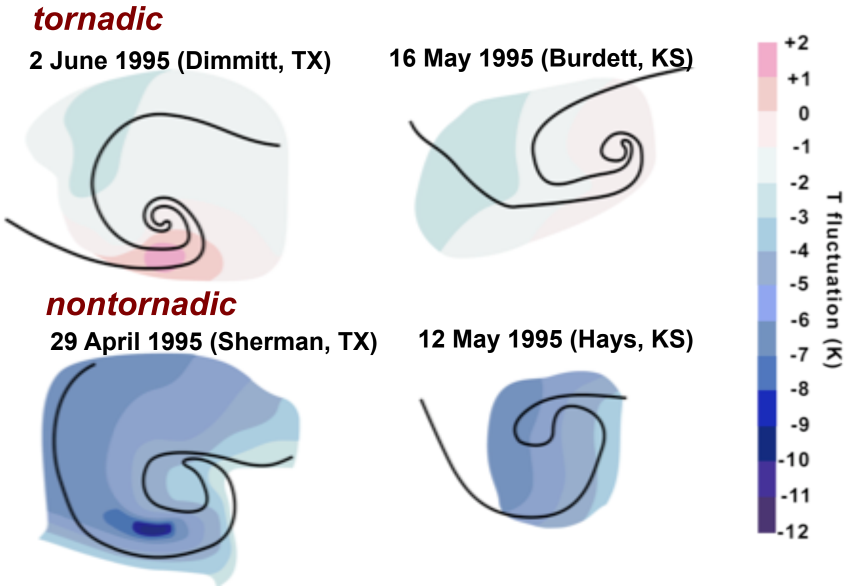
- Outflow is warmer (both in the FFD and RFD) in many observed supercells than in simulated storms (at least those that were reported in the literature in the 1970s–90s), especially in tornadic supercells (Markowski et al. 2002; Shabbott & Markowski 2008; Grzych et al. 2007; Hirth et al. 2008).

- Reasons for outflow being too cold in past simulations:
  - Kessler microphysics (the presence of large hail usually leads to weaker outflow)
  - the artificial cooling at the lower boundary in the KW model at grid points within outflow
  - exclusion of radiative transfer (cloud shading tends to weaken forward-flank baroclinity)

Simulation with Del City sounding, adapted from Rotunno & Klemp (1985)



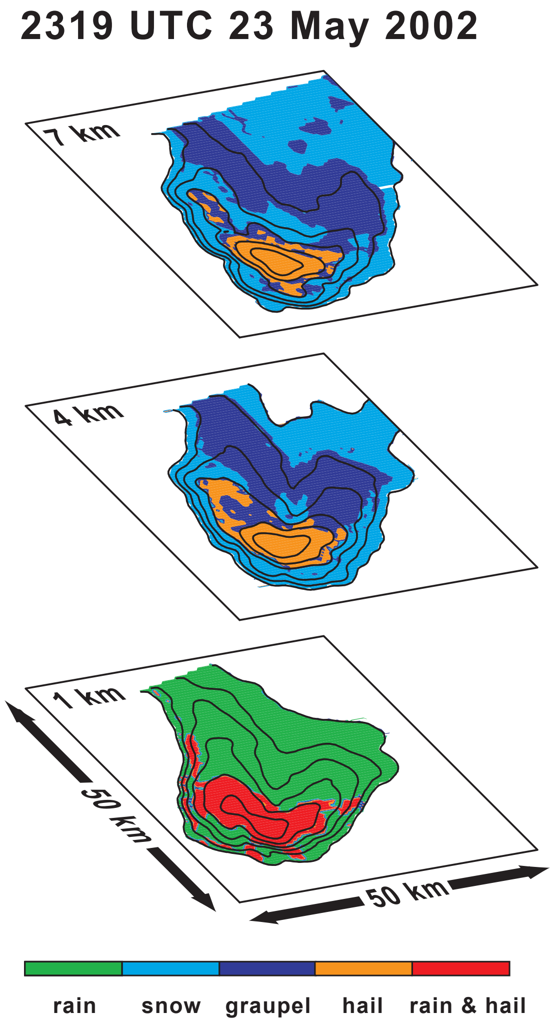
VORTEX1 analyses derived from mobile mesonet observations, adapted from Markowski et al. (2002)



Microphysical properties of supercells

- The body of polarimetric radar observations continues to grow.

- Active research (pertaining to supercells/ tornadoes) going in two directions:
  - Warning improvement (e.g., detection of large hail at the surface or tornado debris)
    - Kumjian & Ryzhkov (2008); Kumjian et al. (2010), etc.
  - Hydrometeor retrieval for the purposes of increasing our understanding of the degree to which the microphysical characteristics of supercells vary from storm to storm, or within one storm as a function of time (new understanding could perhaps later be used, in conjunction with the information about the sounding, to deduce the likely range of outflow temperatures)
    - Van Den Broeke et al. (2008), Frame et al. (2009), etc.



Frame et al. (2009)

Microphysical properties of supercells

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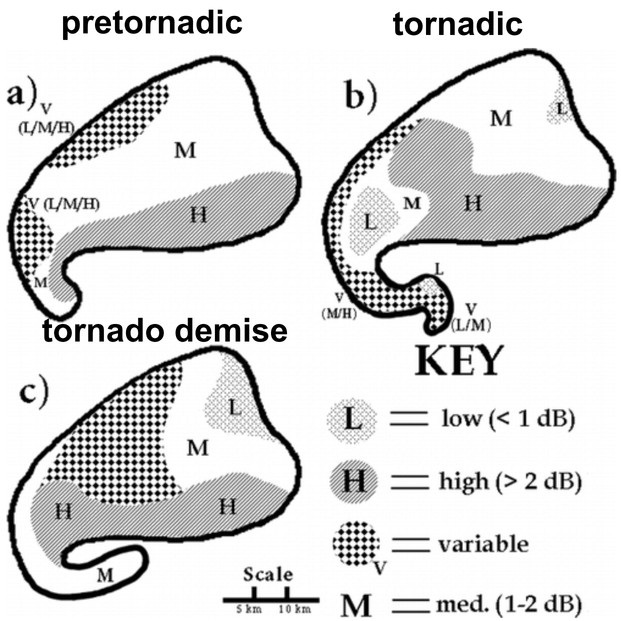
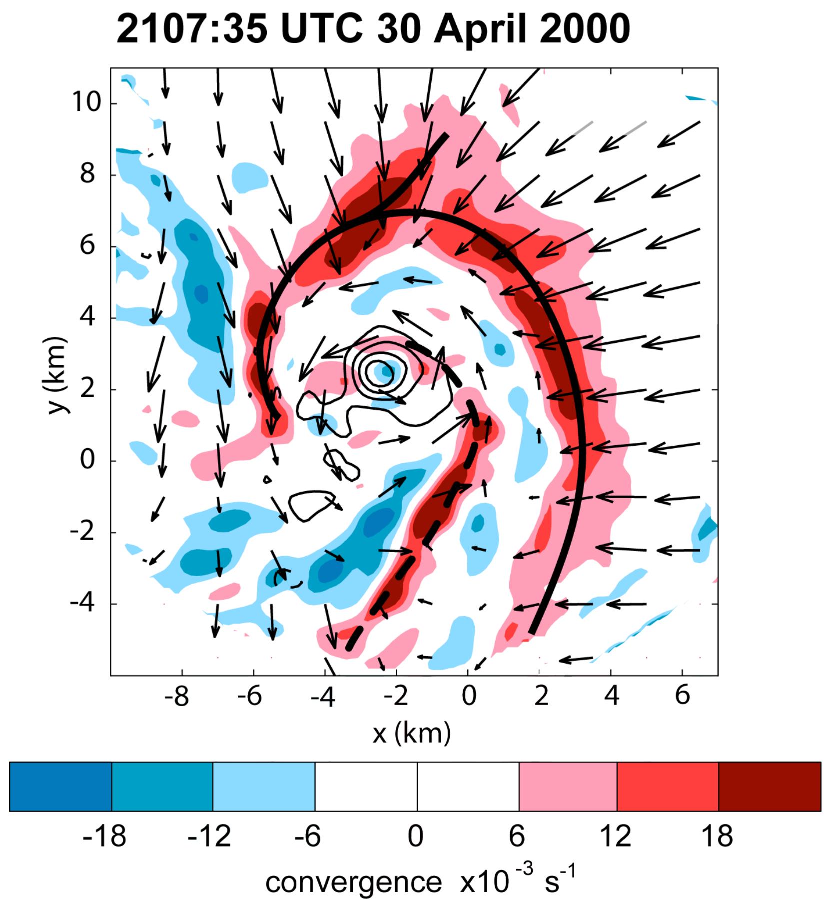
Evolution of Z_{DR}



Van Den Broeke et al. (2008)

Dual-Doppler studies comparing tornadic mesocyclone attributes to nontornadic mesocyclone attributes

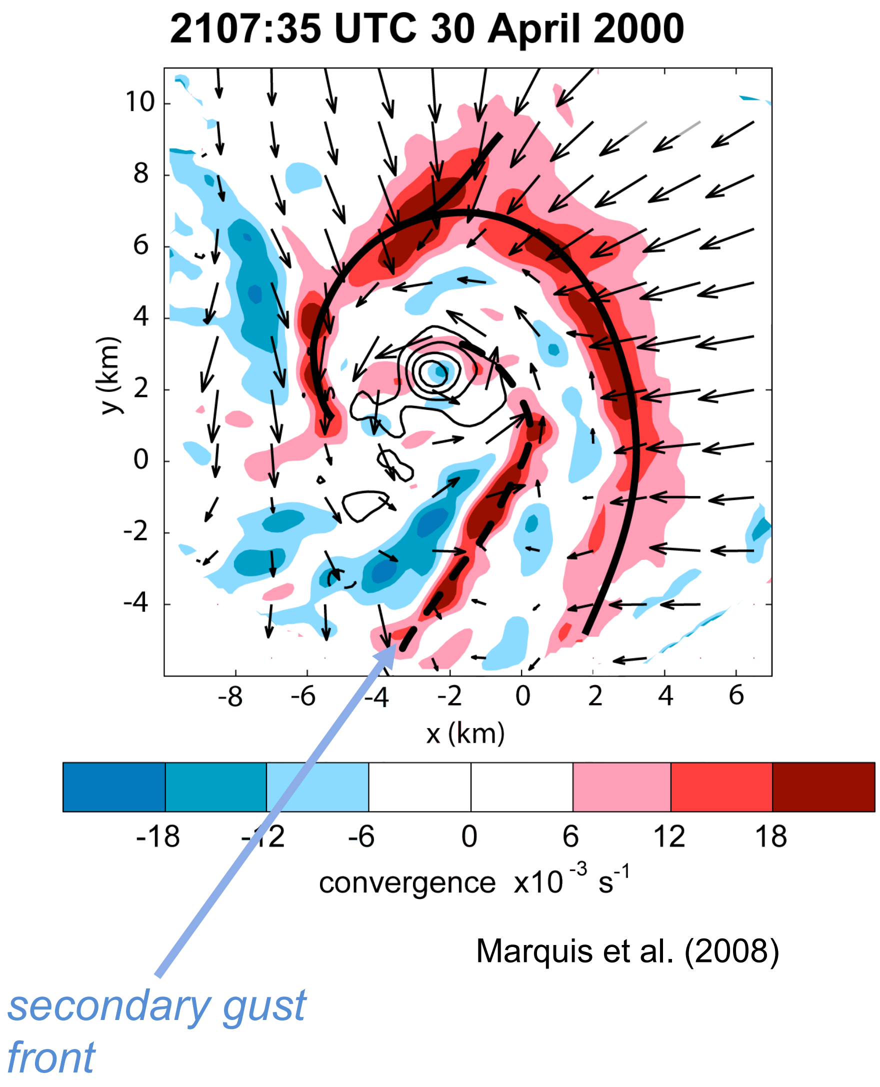
- Simulations are unsuitable because they do not resolve the tornado, at least in the large parameter-space studies that would need to be conducted in order to make generalizations about the attributes (it's dangerous to use grid-scale vorticity as a proxy for tornado/no-tornado in a simulation that can't resolve a tornado)



Marquis et al. (2008)

Dual-Doppler studies comparing tornadic mesocyclone attributes to nontornadic mesocyclone attributes

- Where things presently stand
  - Growing body of dual-Doppler observations of nontornadic and tornadic mesocyclones and surrounding wind fields (VORTEX2 and other projects); Δx~100–300 m, Δt~1–2 min
  - Incomplete list of topics of interest:
    - Role of secondary rear-flank gust fronts, which are observed in many tornadic supercells just prior to tornadogenesis and while tornadoes are ongoing
    - Differences in trajectories of tornadic and nontornadic mesocyclones (and vorticity forcings along those trajectories)
    - Differences in angular momentum of tornadic and nontornadic mesocyclones (do nontornadic mesocyclones tend to have less in general, or is that they have insufficient convergence of that angular momentum?)
    - Role of descending reflectivity cores (DRCs), which appear to trigger tornadogenesis in some storms



Marquis et al. (2008)

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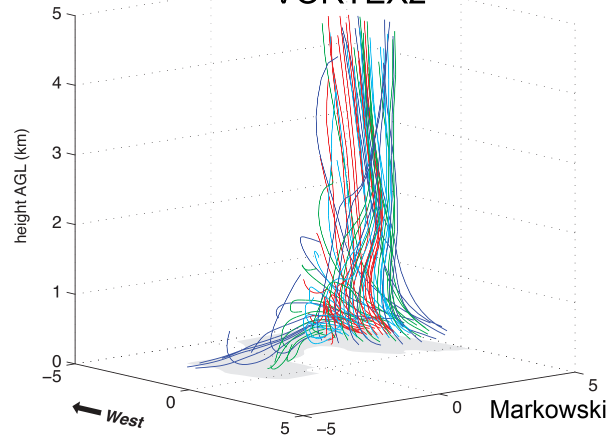
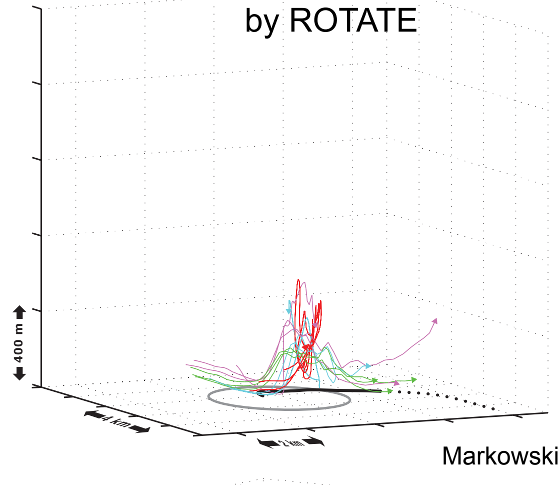
Forward trajectories originating in the 5 June 2009 **tornadic** mesocyclone intercepted by VORTEX2



Markowski et al. (2012)

Forward trajectories originating in the 12 June 2004 **nontornadic** mesocyclone intercepted by ROTATE



Markowski et al. (2011)

Dual-Doppler studies comparing tornadic mesocyclone attributes to nontornadic mesocyclone attributes

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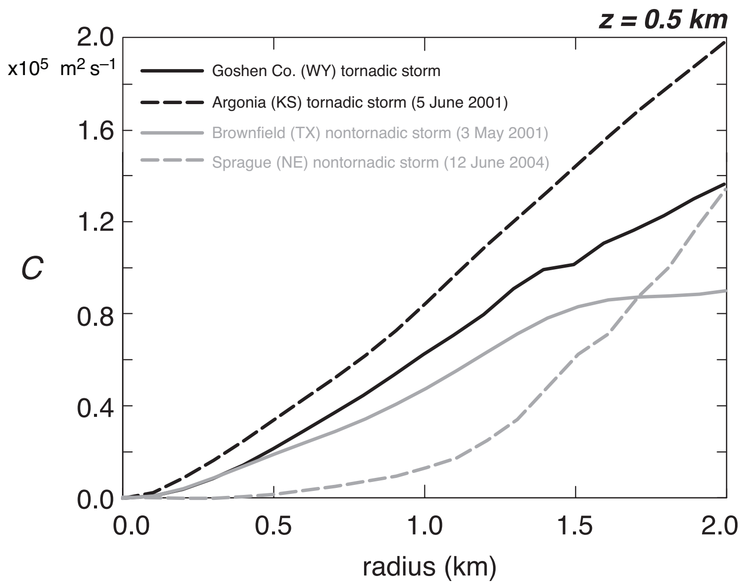

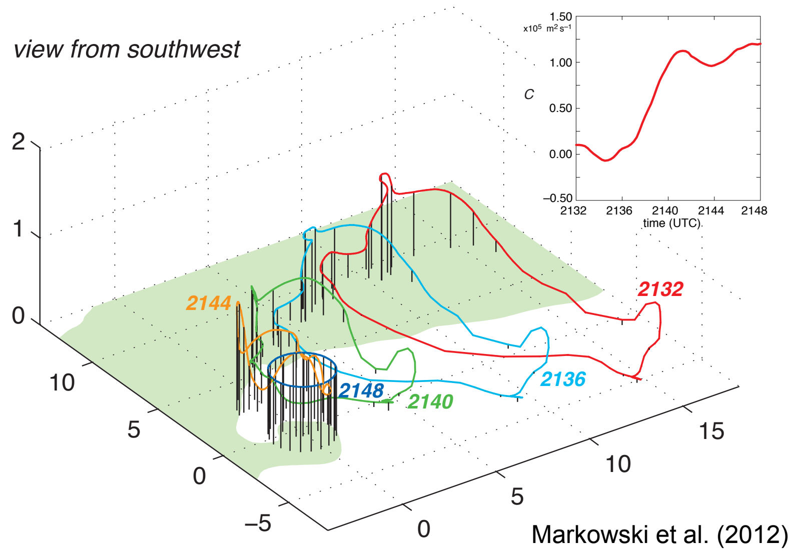

Markowski et al. (2012)

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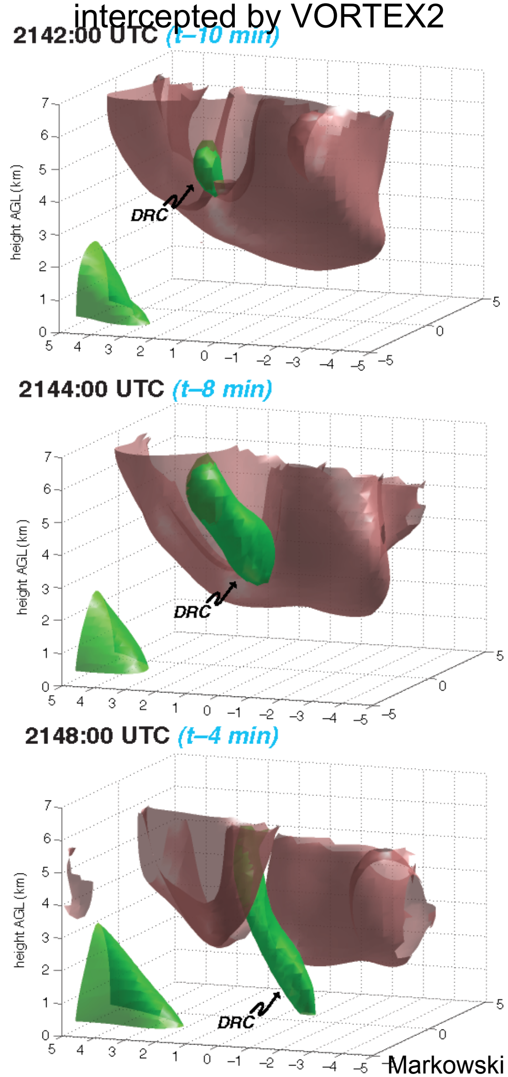
DRC that immediately preceded tornadogenesis in the 5 June 2009 supercell intercepted by VORTEX2



Markowski et al. (2012)

Not an all-inclusive list!

Trends in numerical simulations

- Resolution continues to increase
- Studies can include lots of simulations (the days of the single "production-run" simulation written-up in a journal article are probably over)
- Increasing sophistication of microphysics parameterizations (even some triple-moment schemes are now in use; some investigators are using bin scheme to look at sensitivity of storms to aerosols)
- Inclusion of additional physics previously excluded (e.g., surface momentum flux, surface heat flux, radiative transfer?)
  - It was easy to look past the neglect of surface friction, radiation, ice physics, etc. in the early-day simulations at coarse resolution that were just exploring the fundamentals (e.g., mesocyclogenesis, updraft propagation).
  - But it's not as easy to look past the exclusion of these effects in today's "high-resolution" simulations, because the goal is of one of today's "high-resolution" simulations is presumably to investigate fine-scale processes and such processes are quite likely sensitive to many of the previously neglected physical processes.

what is considered "high-resolution" is constantly changing!

- Model users must not allow the complexity of their model to outstrip their ability to understand what is happening!

Trends in observations

- The body of dual-polarimetric observations and retrieved hydrometeor distributions (from WSR-88D and research radars) of supercells will continue to grow
- More in situ observations of microphysical properties of storms via next-generation of storm-penetration aircraft?
- Role of UAVs is uncertain
- Is there room for any more truck-borne Doppler radars on the U.S. Great Plains?

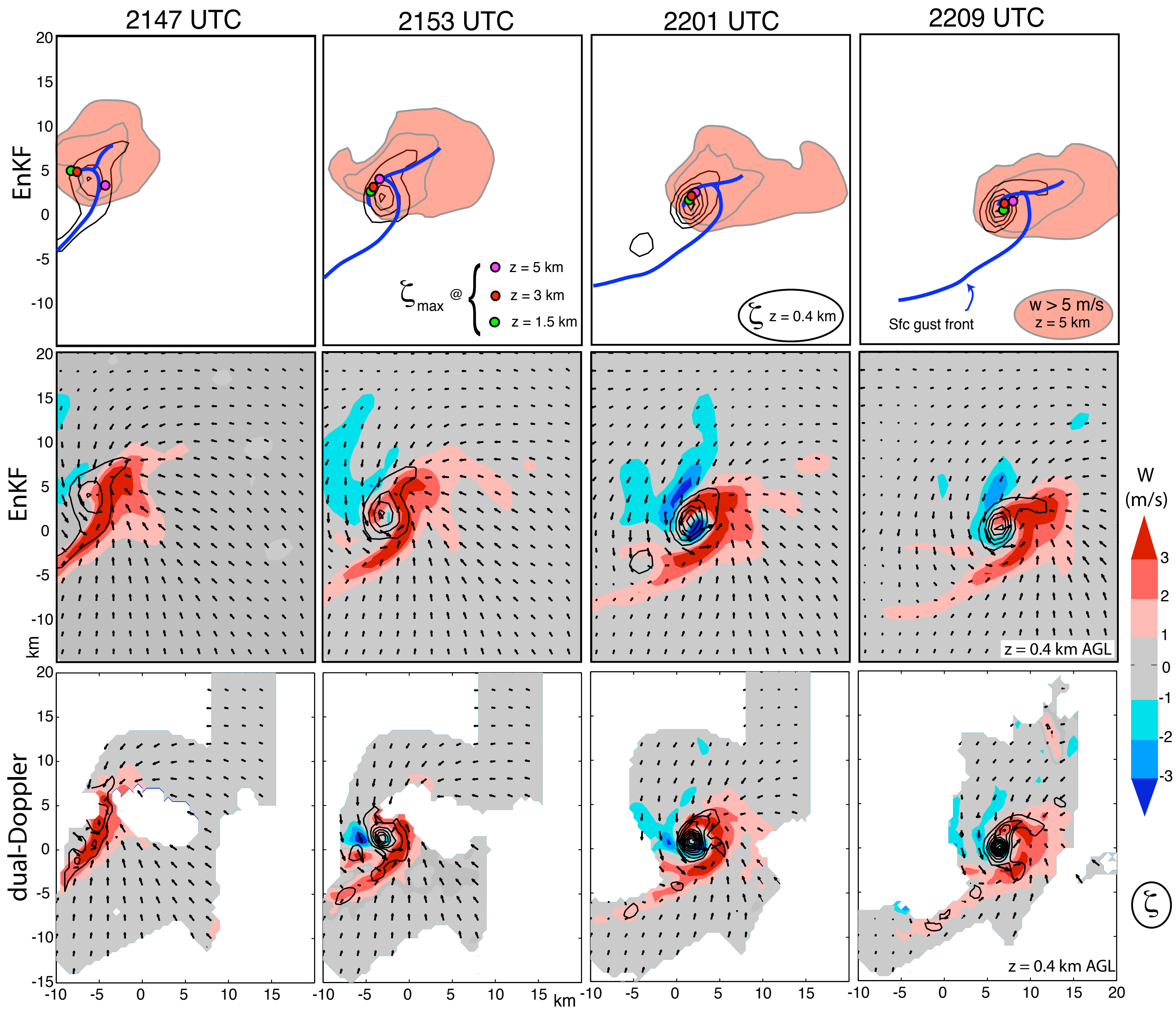
Future challenges—what do we need, and what roles will models and observations play?

- Tornadogenesis/maintenance
  - Winds in the lowest 100 m (this is where cyclonic vorticity grows most rapidly within downdraft parcels?) simulations essential
  - Rapid updates of 3D winds (needed for accurate trajectories in regions of large acceleration and rapid evolution) simulations essential
  - Microphysical and thermodynamic characteristics observations essential
    - How well will we be able to retrieve hydrometeor distributions from dual-pol radars?
    - What can we do about the sparseness of thermodynamic observations?

- Sensitivity of supercells to environment simulations and observations essential
  - Effects of terrain relatively unexplored
  - Effects of meso-gamma-scale heterogeneity (e.g., boundary layer rolls) on supercells only beginning to be unexplored
  - Effects of changing aerosol distributions
    - Do the microphysical characteristics of observed storms change in the same way as in simulated storms when the aerosol distribution changes?
  - Effects of storm interactions with mesoscale boundaries

Future challenges—what do we need, and what roles will models and observations play?

- **Data assimilation (DA)**—potential for observations and models to yield more than either alone (provided that the model's physics are credible)
- No good analyst or modeler should just consider observations or models these days
- Potential benefits
  - faster time-updates than typical dual-Doppler observations (therefore more accurate trajectories)
  - smoother derivatives (therefore more accurate vorticity forcings)
  - winds closer to the surface (dual-Doppler observations are rarely available below ~200 m AGL)
  - more accurate winds aloft (dual-Doppler retrievals of 3D winds are more error-prone at midlevels)
  - better handling of data voids (e.g., where ground clutter has contaminated observations)



EnKF analyses of the 5 June 2009 tornadic supercell intercepted by VORTEX2 courtesy of Jim Marquis (PS

Future challenges—what do we need, and what roles will models and observations play?

- **Data assimilation (DA)**—potential for observations and models to yield more than either alone (provided that the model's physics are credible)
- No good analyst or modeler should just consider observations or models these days
- Can DA analyses provide trustworthy information about the 3D thermodynamic characteristics of storms (particularly above ground) from relatively sparse in situ thermodynamic observations obtained at the surface?

For the foreseeable future, advances in our understanding will require both observations and simulations.

With respect to simulations, a "hierarchy" of simulations is likely to be most fruitful (i.e., both idealized and "case-study simulations," and this includes the analysis of storms using the latest data assimilation techniques).