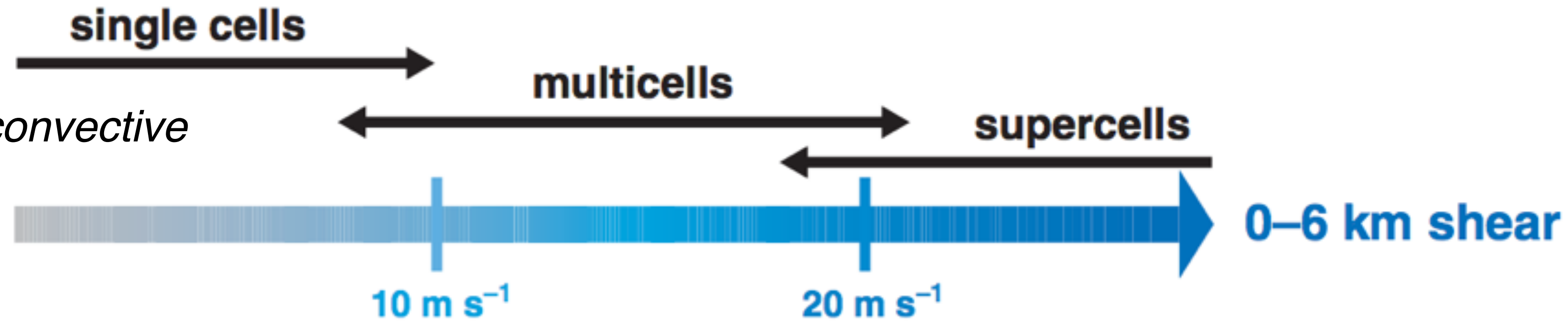
Discriminating Between Supercells and Non-supercell Thunderstorms

Desire to come up with fields that successfully discriminate between convective storm types.

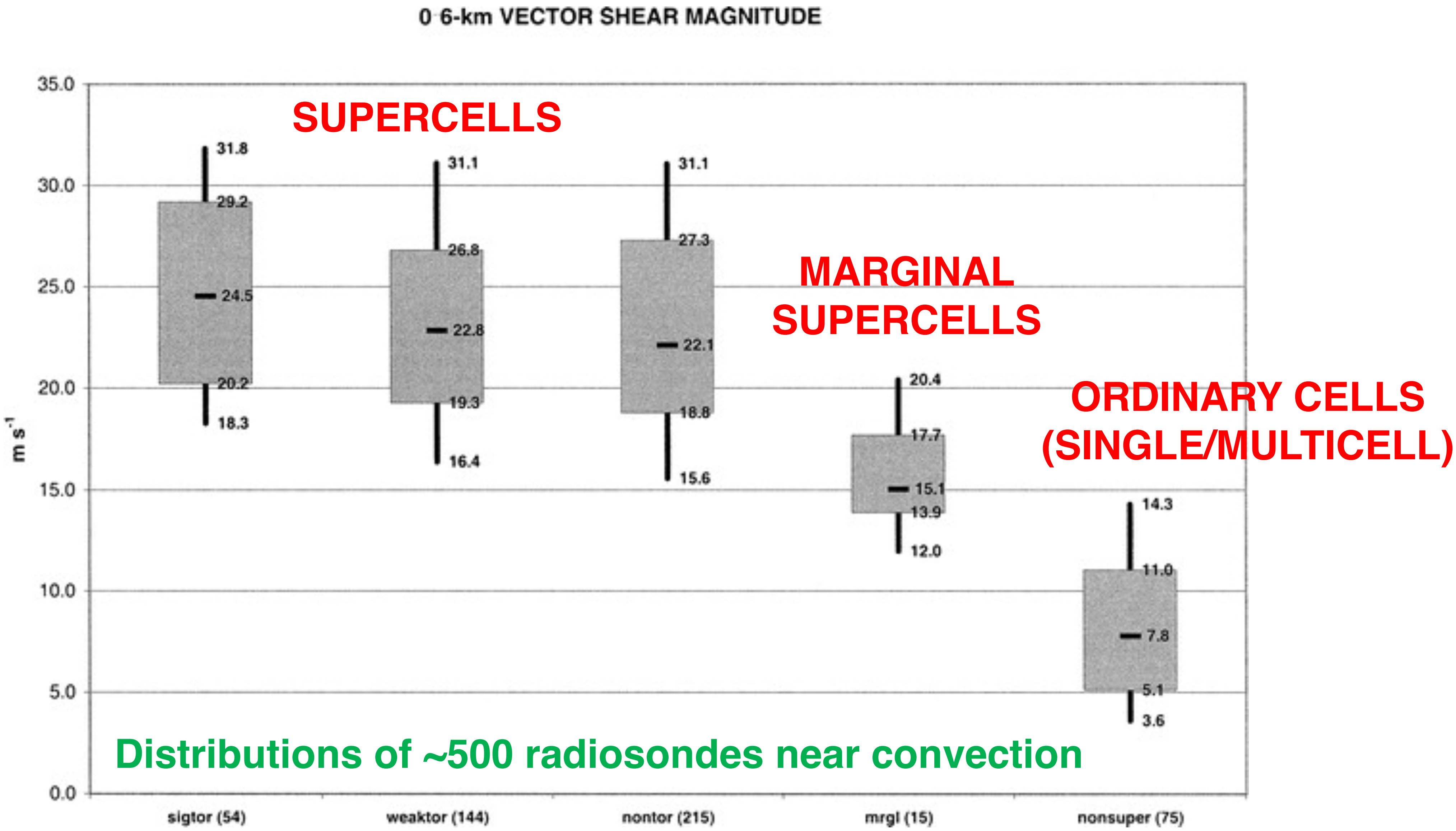
Of primary interest is supercells vs. non-supercells, since supercells produce large fraction of severe weather events (hail, tornadoes, intense wind gusts).

Spectrum of convective storm types



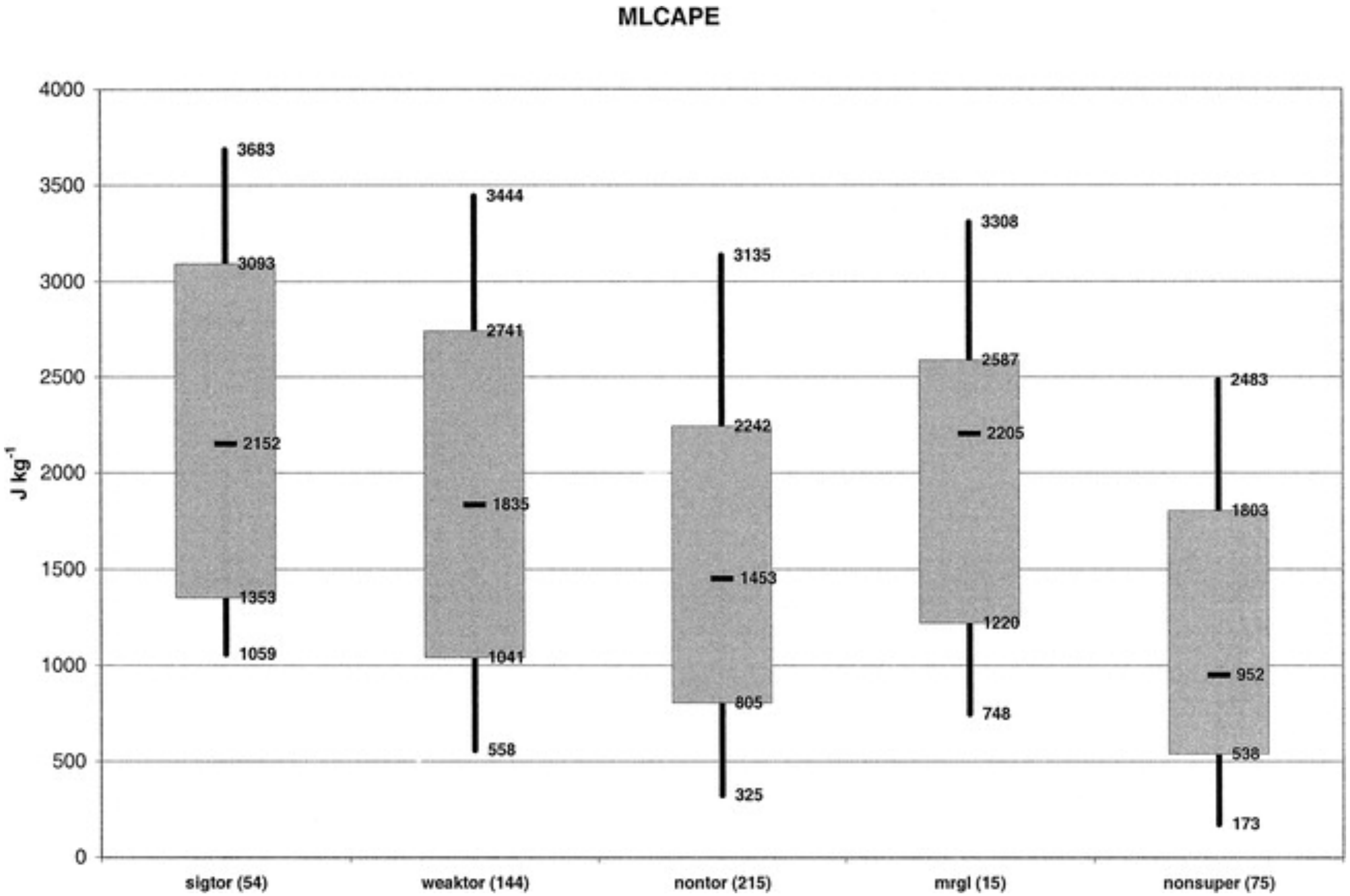
~20 kts ~40 kts

Discriminating Between Supercells and Non-supercell Thunderstorms



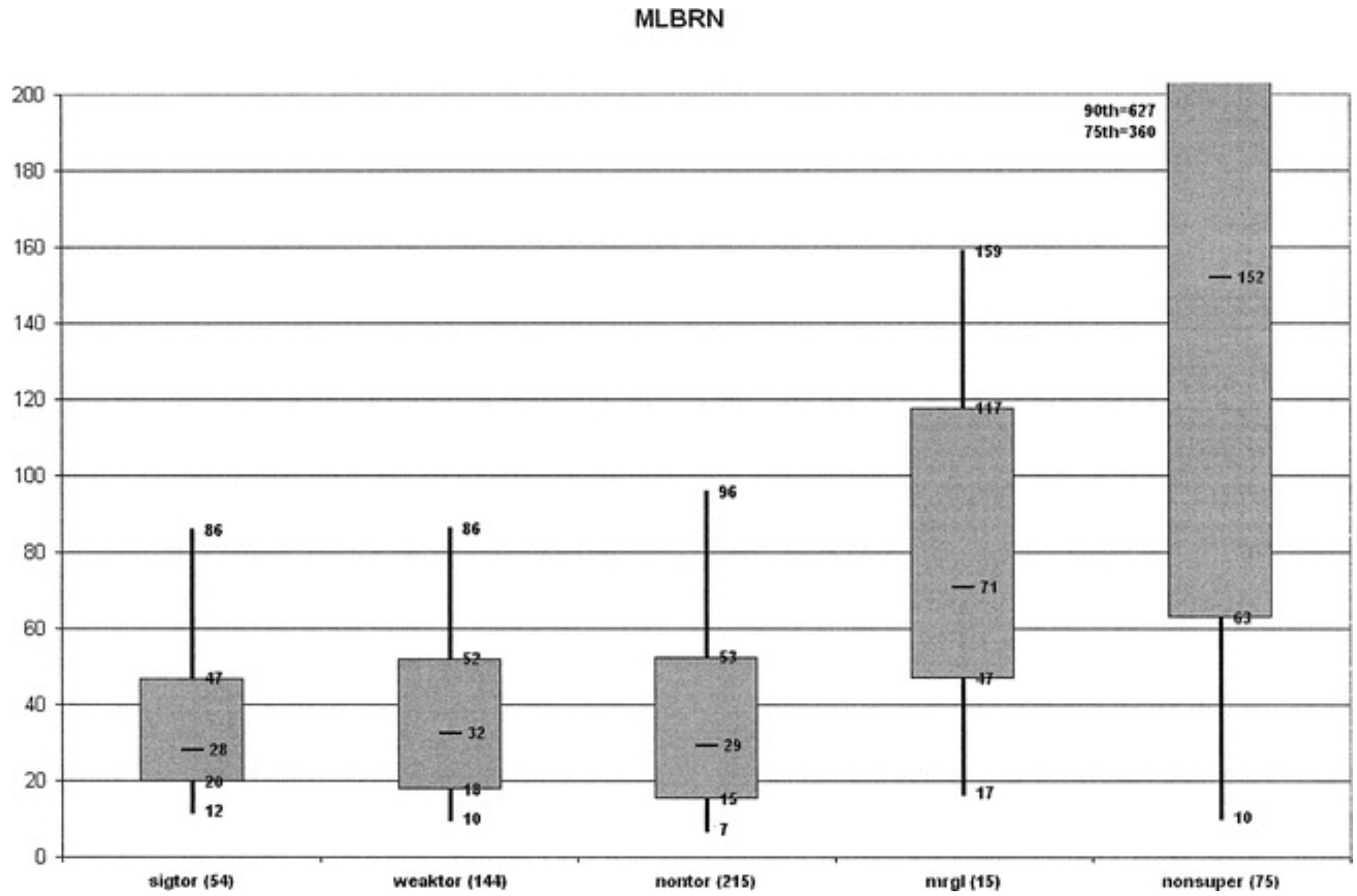
Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

Discriminating Between Supercells and Non-supercell Thunderstorms



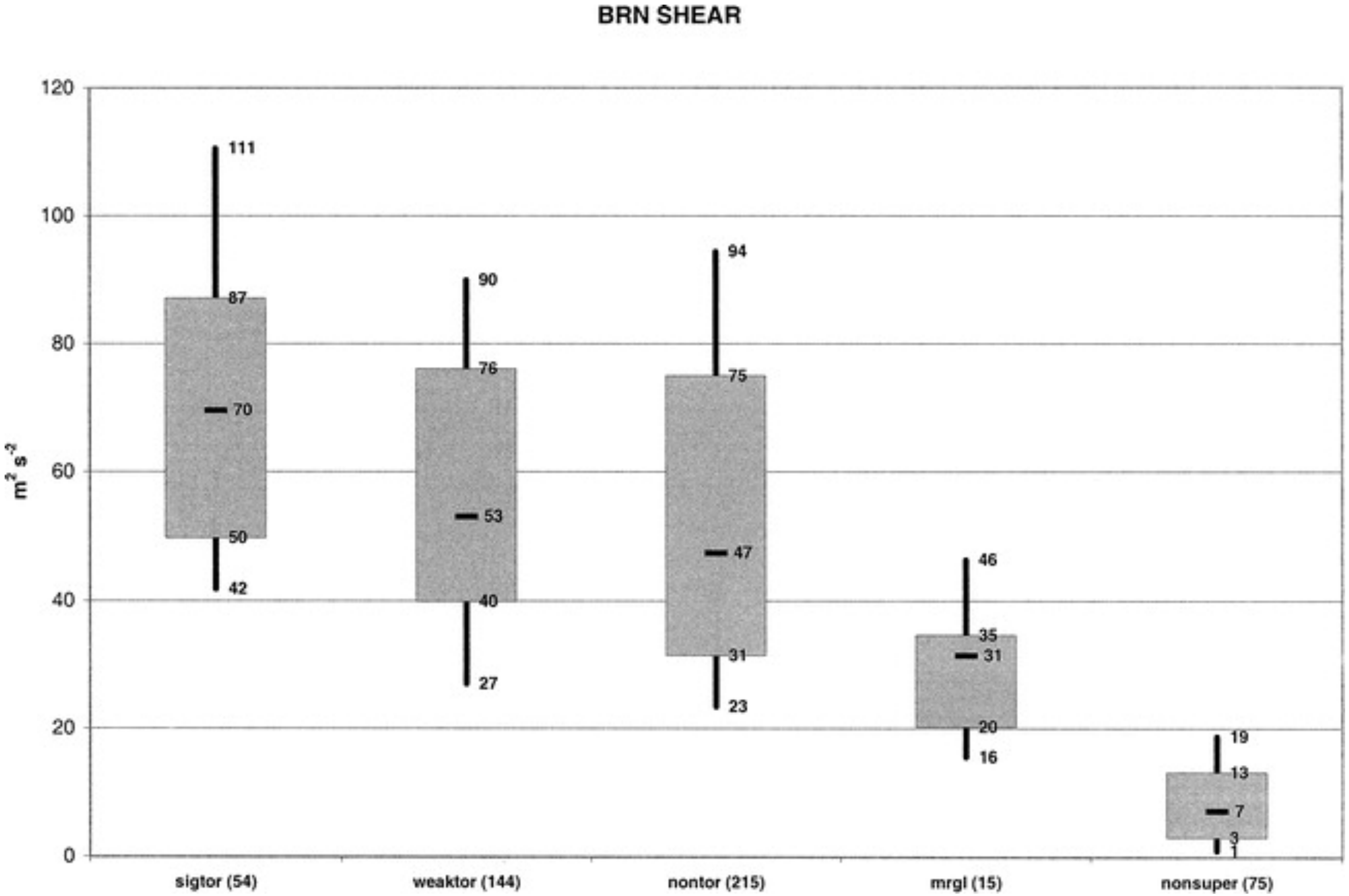
Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

Discriminating Between Supercells and Non-supercell Thunderstorms



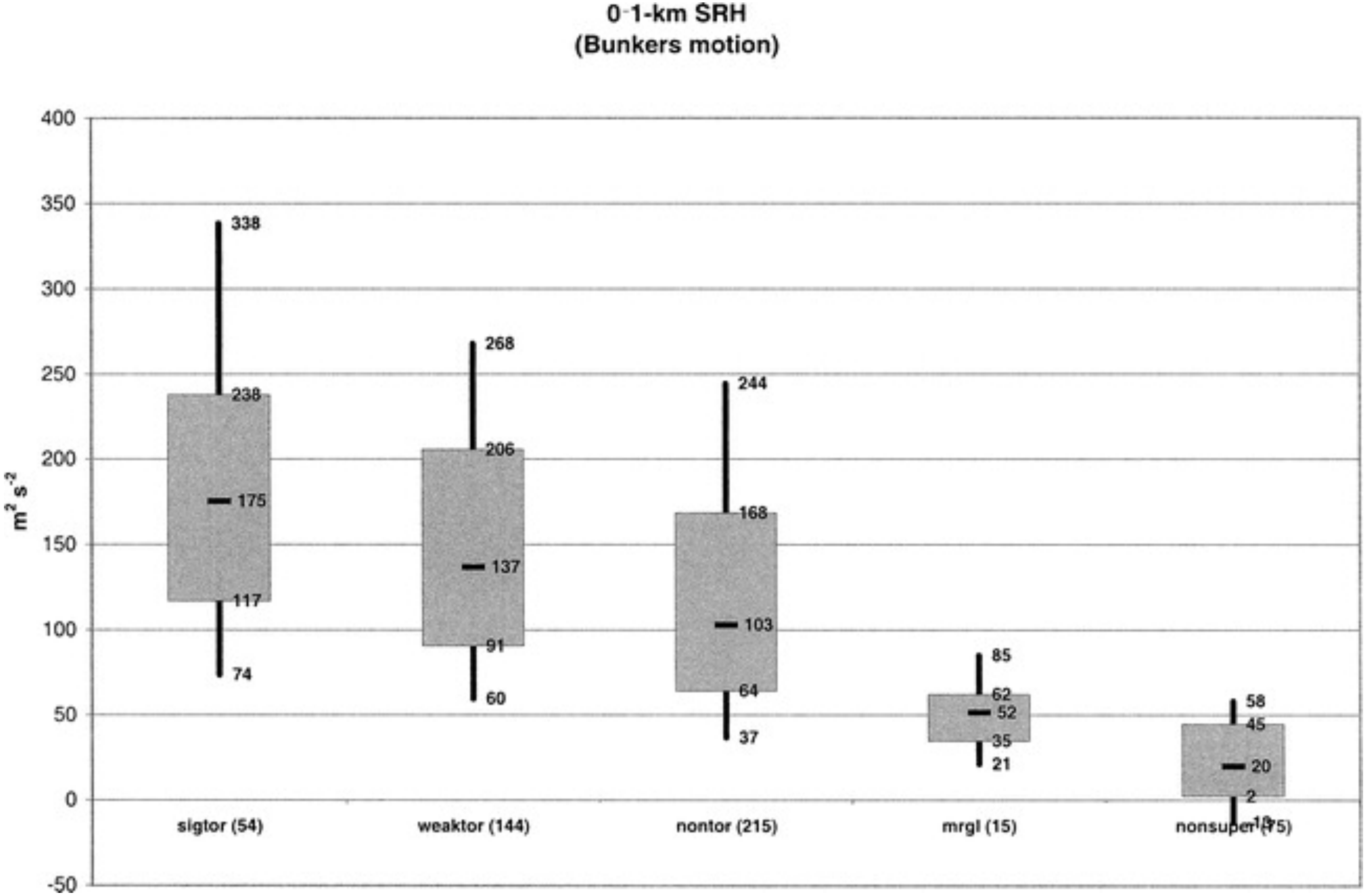
Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

Discriminating Between Supercells and Non-supercell Thunderstorms



Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

Discriminating Between Supercells and Non-supercell Thunderstorms



Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

Potential vorticity conservation to diagnose mid-level rotation

For conservative variable, in inviscid flow, Ertel's potential vorticity is conserved:

Absolute vorticity

Conserved variable

Ertel's potential vorticity: $$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{(\boldsymbol{\omega}+f\mathbf{k})\cdot\nabla\lambda}{\rho}\right]=0$$

Assume vertical vorticity is zero initially, vorticity vector oriented **horizontally**.

If theta is conserved variable, theta gradient vector is oriented **vertically** (downward).

In this case, potential vorticity is **zero**, vortex lines are within theta surfaces for all time.

Potential vorticity conservation to diagnose mid-level rotation

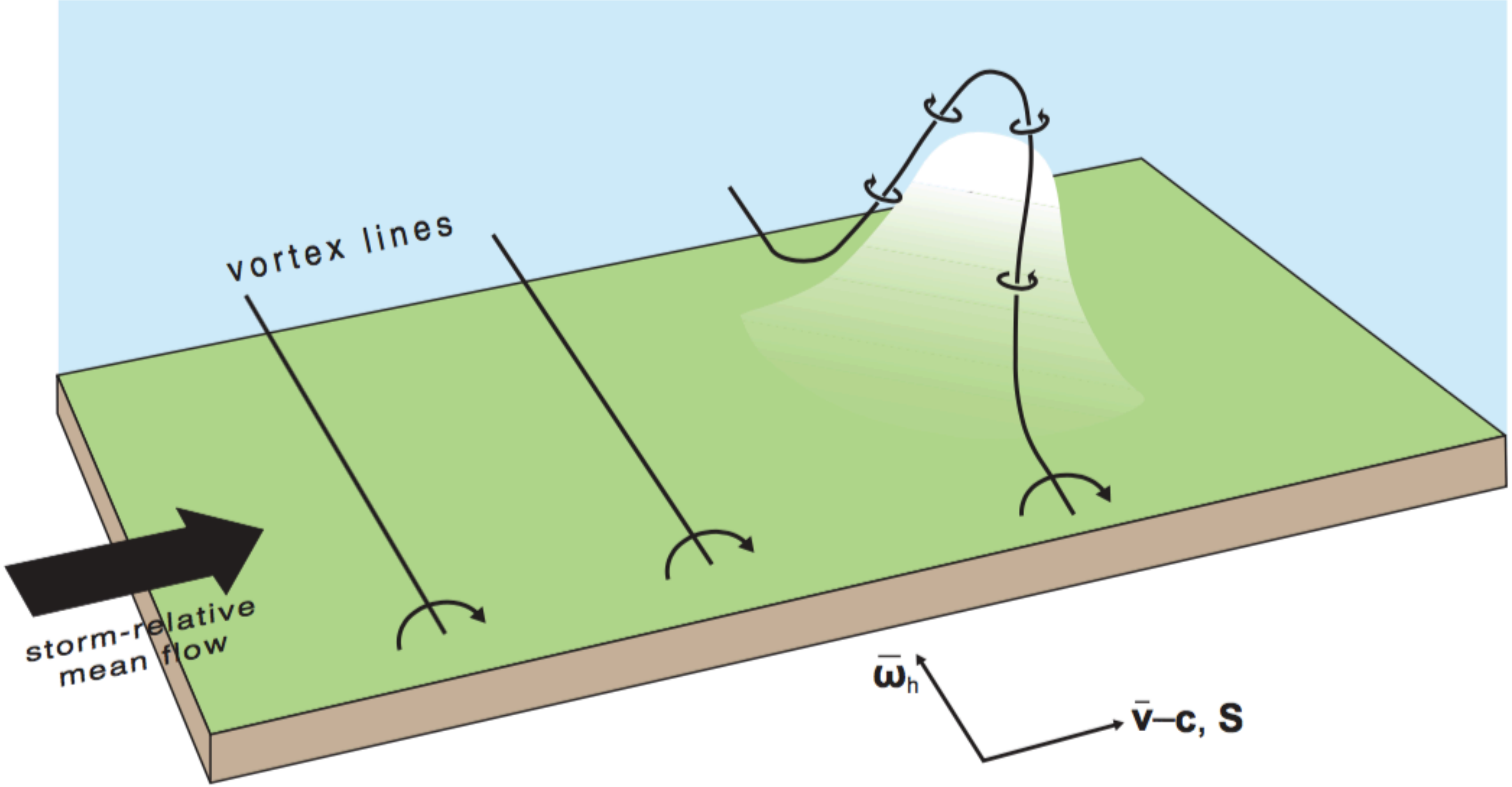
For generation of mid-level rotation, can use PV conservation. Neglecting Coriolis and using theta-e:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{\omega} \cdot \boldsymbol{\nabla}\theta_{\mathrm{e}}}{\rho}\right) = 0$$

As before, **vorticity and theta-e gradient are roughly perpendicular**, so PV should remain near zero for all time.

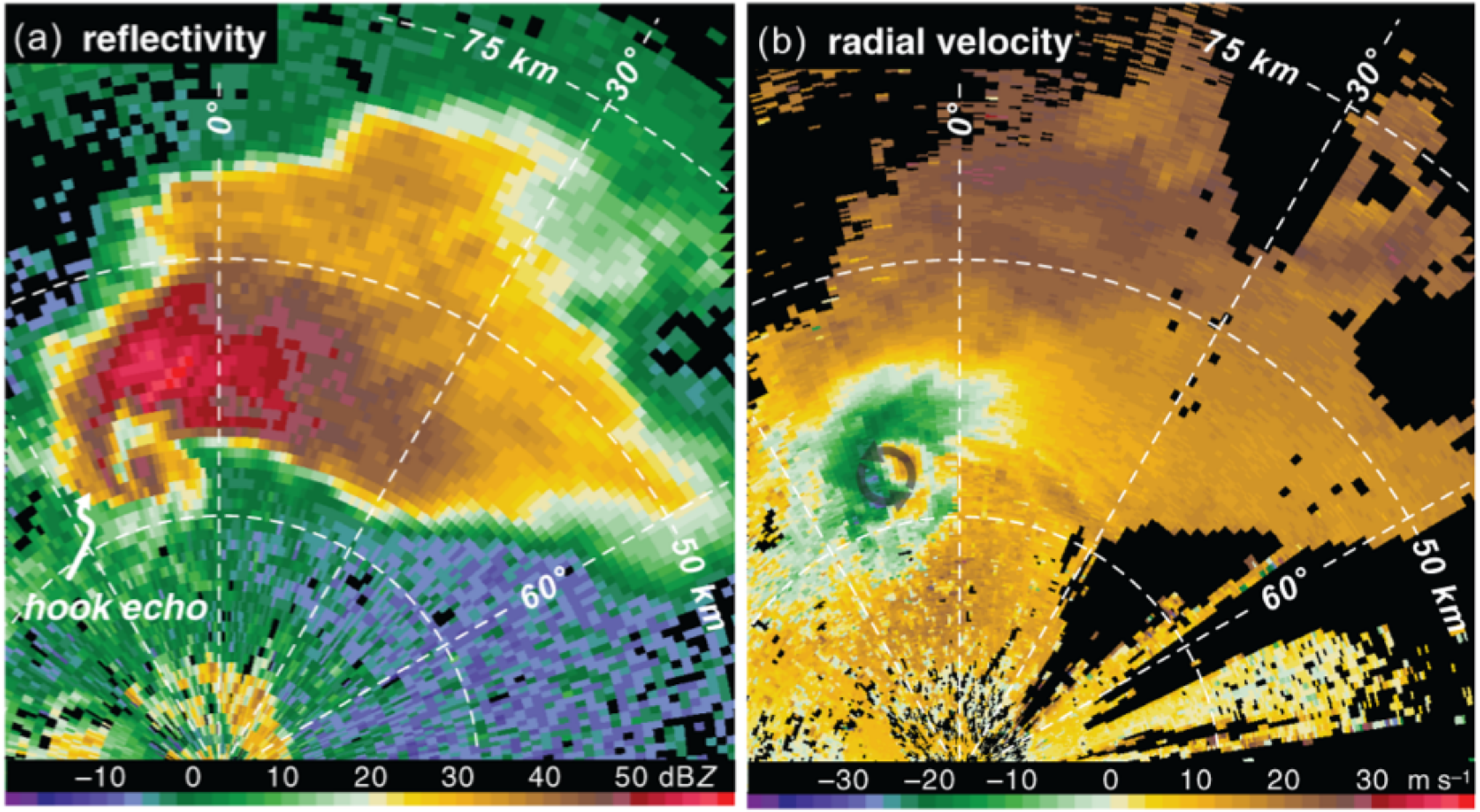
In a thunderstorm, theta-e surfaces bulge upward within the updraft, so vorticity vector (indicated by vortex lines) must do the same…

Potential vorticity conservation to diagnose mid-level rotation



Rotating updraft (mesocyclone) diagnosed from radar

Mesocyclone is defining feature of a supercell thunderstorm!



Propagation of supercells

If we substitute, (mean + perturbation) for u, v, w (e.g., $u = \bar{u} + u'$), we can write p' as,

$$p' \propto \underbrace{e_{ij}'^2 - \frac{1}{2}|\boldsymbol{\omega}'|^2}_{\text{nonlinear dynamic pressure perturbation}} \underbrace{+2\left(\frac{\partial w'}{\partial x}\frac{\partial \overline{u}}{\partial z} + \frac{\partial w'}{\partial y}\frac{\partial \overline{v}}{\partial z}\right)}_{\text{linear dynamic pressure perturbation}} \underbrace{-\frac{\partial B}{\partial z}}_{\text{buoyancy pressure perturbation}} \quad (2.137)$$

Where the linear dynamic pressure perturbation (**$p_{D,L}$**) can be written as,

$$2\left(\frac{\partial w'}{\partial x}\frac{\partial \overline{u}}{\partial z} + \frac{\partial w'}{\partial y}\frac{\partial \overline{v}}{\partial z}\right) = 2\mathbf{S} \cdot \boldsymbol{\nabla}_{\mathrm{h}} w'$$

Propagation of supercells

Can rewrite previous p' equation as…

Fluid extension terms associated with deformation

$$p' \propto \underbrace{\underbrace{\left[\left(\frac{\partial u'}{\partial x}\right)^2 + \left(\frac{\partial v'}{\partial y}\right)^2 + \left(\frac{\partial w'}{\partial z}\right)^2\right]}_{\text{fluid extension terms}} + 2\left(\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} + \frac{\partial w'}{\partial x}\frac{\partial u'}{\partial z} + \frac{\partial w'}{\partial y}\frac{\partial v'}{\partial z}\right)}_{\text{nonlinear dynamic pressure perturbation, } p'_{\mathrm{dnl}}} \underbrace{+2\mathbf{S}\cdot\nabla_{\mathrm{h}} w'}_{\text{linear dynamic pressure perturbation, } p'_{\mathrm{dl}}} \underbrace{-\frac{\partial B}{\partial z}}_{\text{buoyancy pressure term, } p'_{\mathrm{b}}} .$$

Propagation of supercells

Assume **deformation** can be neglected within strongly rotating updraft,

$$\frac{\partial v'}{\partial x} + \frac{\partial u'}{\partial y} = \frac{\partial w'}{\partial y} + \frac{\partial v'}{\partial z} = \frac{\partial w'}{\partial x} + \frac{\partial u'}{\partial z} = 0$$

Which implies, $\frac{\partial v'}{\partial x} = -\frac{\partial u'}{\partial y} \qquad \frac{\partial w'}{\partial y} = -\frac{\partial v'}{\partial z} \qquad \frac{\partial w'}{\partial x} = -\frac{\partial u'}{\partial z}$

Assume **horizontal vorticity** is also negligible,

$$\frac{\partial w'}{\partial y} - \frac{\partial v'}{\partial z} = \frac{\partial u'}{\partial z} - \frac{\partial w'}{\partial x} = 0$$

Which implies,

$$\frac{\partial w'}{\partial y} = \frac{\partial v'}{\partial z} \qquad \frac{\partial u'}{\partial z} = \frac{\partial w'}{\partial x}$$

Propagation of supercells

Together, this means that,

$$\frac{\partial u'}{\partial z} = \frac{\partial v'}{\partial z} = \frac{\partial w'}{\partial x} = \frac{\partial w'}{\partial y} = 0$$

Which eliminates two terms associated with the nonlinear dynamic pressure perturbation:

$$p' \propto \underbrace{\underbrace{\left[\left(\frac{\partial u'}{\partial x}\right)^2 + \left(\frac{\partial v'}{\partial y}\right)^2 + \left(\frac{\partial w'}{\partial z}\right)^2\right]}_{\text{fluid extension terms}} + 2\left(\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} + \cancel{\frac{\partial w'}{\partial x}\frac{\partial u'}{\partial z}} + \cancel{\frac{\partial w'}{\partial y}\frac{\partial v'}{\partial z}}\right)}_{\text{nonlinear dynamic pressure perturbation, } p'_{\mathrm{dnl}}}$$

Propagation of supercells

The last term can be written as,

$$
\begin{aligned}
2\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} &= -\frac{1}{2}\left(-\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} - 2\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} - \frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y}\right) \\
&= -\frac{1}{2}\left(\frac{\partial v'}{\partial x}\frac{\partial v'}{\partial x} - 2\frac{\partial v'}{\partial x}\frac{\partial u'}{\partial y} + \frac{\partial u'}{\partial y}\frac{\partial u'}{\partial y}\right) \\
&= -\frac{1}{2}\left(\frac{\partial v'}{\partial x} - \frac{\partial u'}{\partial y}\right)^2 \\
&= -\frac{1}{2}\zeta'^2 \qquad (8.23)
\end{aligned}
$$

Propagation of supercells

Which means the pressure perturbation equation can be written as,

$$p' \propto \underbrace{\underbrace{\cancel{\left[\left(\frac{\partial u'}{\partial x}\right)^2+\left(\frac{\partial v'}{\partial y}\right)^2+\left(\frac{\partial w'}{\partial z}\right)^2\right]}}_{\text{fluid extension terms}} \underbrace{-\frac{1}{2}\zeta'^2}_{\text{spin term}}}_{\text{nonlinear dynamic pressure perturbation, } p'_{\mathrm{dnl}}}$$

$$+ \underbrace{2\mathbf{S}\cdot\nabla_{\mathrm{h}} w'}_{\substack{\text{linear dynamic pressure}\\ \text{perturbation, } p'_{\mathrm{dl}}}} \quad \underbrace{\cancel{-\frac{\partial B}{\partial z}}}_{\text{buoyancy pressure perturbation, } p'_{\mathrm{b}}}. \tag{8.24}$$

Focus on dynamic forcing and neglect fluid extension terms…

Propagation of supercells

Focus on contribution to vertical acceleration (dw/dt) from these two terms…

$$-\frac{\partial p'_{\mathrm{d}}}{\partial z} \propto \underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}} \quad \underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_{\mathrm{h}}w'}_{\text{linear dynamic forcing}},$$

In supercells, contribution to dw/dt from dp_d/dz has **same order of magnitude** as buoyancy forcing!

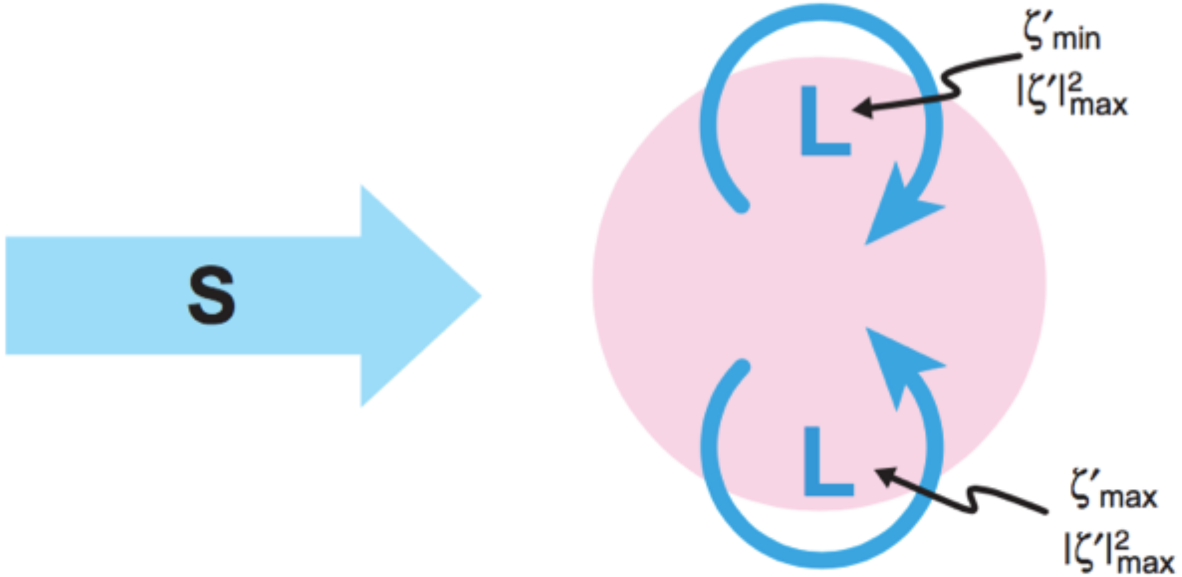
$$\frac{dw}{dt} = \underbrace{-C_p\bar{\theta}_v\frac{\partial \pi_{dn}}{\partial z}}_{\text{Dynamic forcing}} + \underbrace{\left[-C_p\bar{\theta}_v\frac{\partial \pi_b}{\partial z} + B\right]}_{\text{Buoyancy forcing}}$$

Propagation of supercells

$$-\frac{\partial p'_{\mathrm{d}}}{\partial z} \propto \boxed{\underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}}} \underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_{\mathrm{h}}w'}_{\text{linear dynamic forcing}},$$

crosswise vorticity

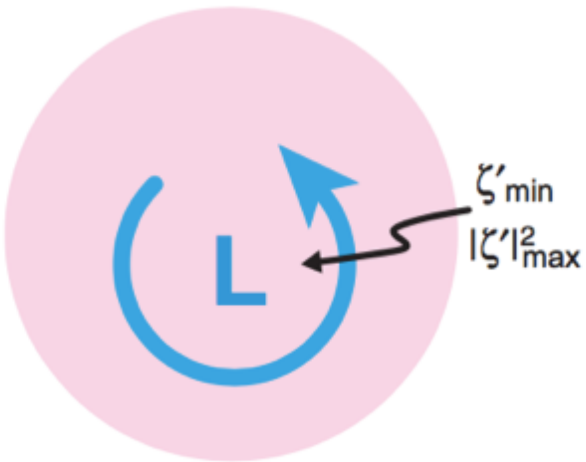
(w' and ζ' uncorrelated)



Elevated pressure minima produces upward nonlinear VPPGF on flanks of storm below vort max. **Leads to *storm splitting***

streamwise vorticity

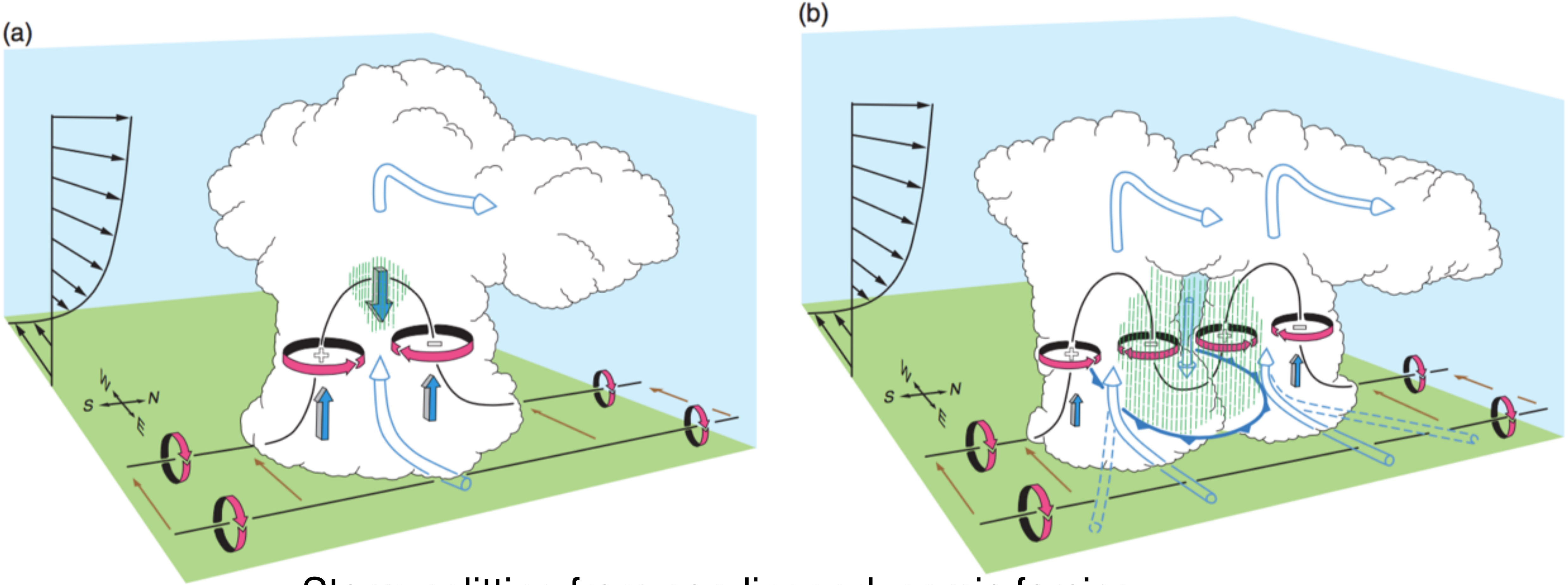
(w' and ζ' highly correlated)



Cannot generate storm splitting

Propagation of supercells

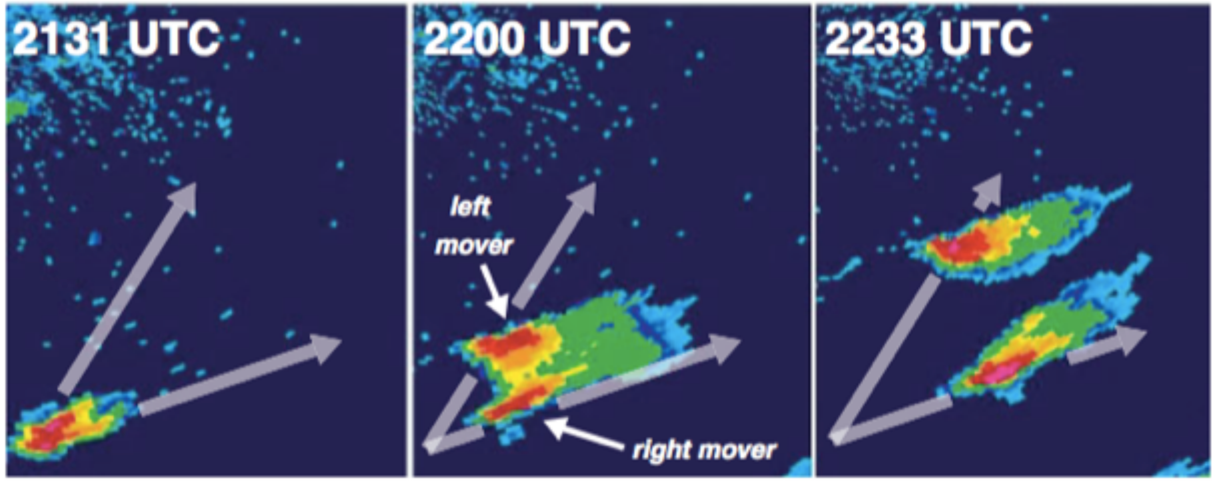
$$-\frac{\partial p_{\mathrm{d}}'}{\partial z} \propto \boxed{\underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}}} \underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_{\mathrm{h}}w'}_{\text{linear dynamic forcing}},$$

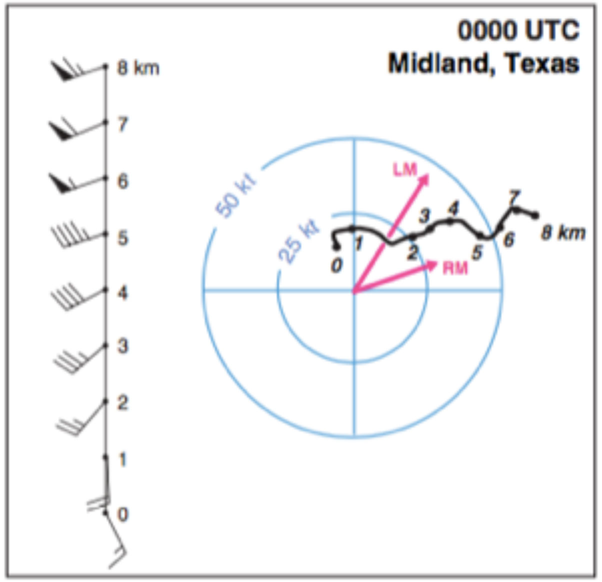


Storm splitting from non-linear dynamic forcing

Propagation of supercells

$$-\frac{\partial p'_{\mathrm{d}}}{\partial z} \propto \boxed{\underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}}} \underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_{\mathrm{h}} w'}_{\text{linear dynamic forcing}},$$





Splitting due to non-linear dynamic forcing only occurs when vorticity ingested is **crosswise**, meaning hodograph is straight.

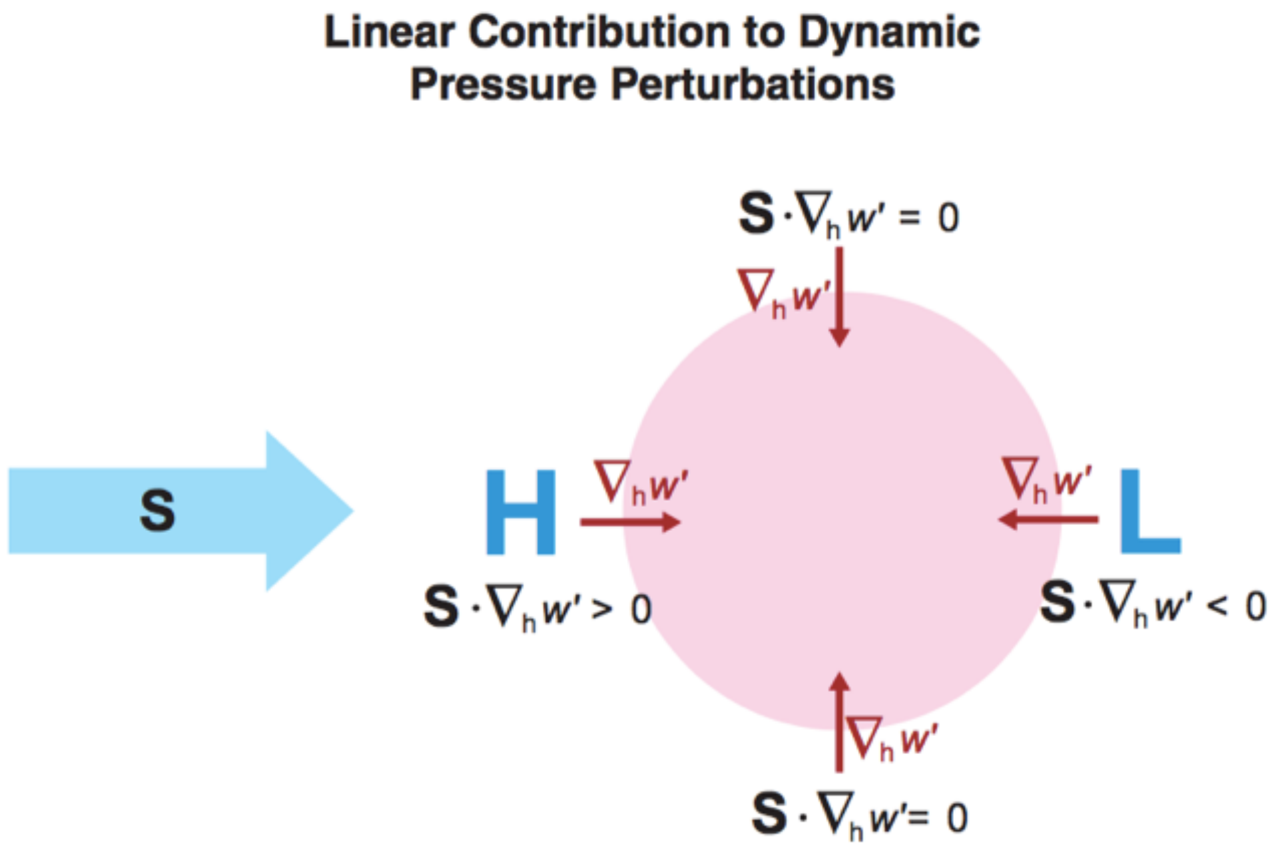
In this case, motion will initially be on-hodograph, so ingested vorticity will be **crosswise** (no SRH area).

Following split, propagation occurs, and ingested vorticity is partially **streamwise**, resulting in net positive vorticity.

As long as crosswise component exists, lateral updraft propagation can continue.

Propagation of supercells

$$-\frac{\partial p'_d}{\partial z} \propto \underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}} \boxed{\underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_h w',}_{\text{linear dynamic forcing}}}$$

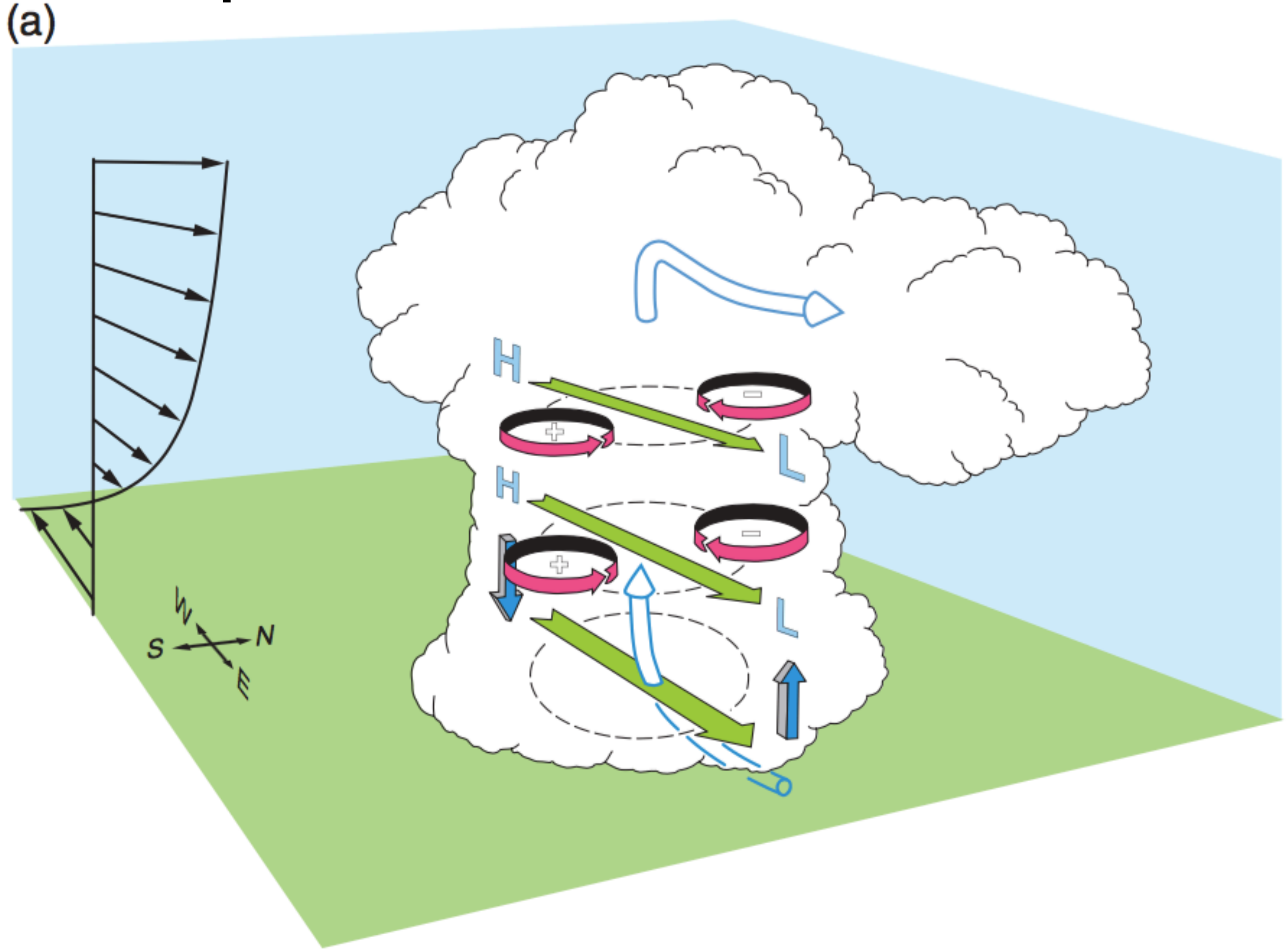


As previously discussed, **linear dynamic forcing** produces high/low pressure couplets up/down shear of an updraft.

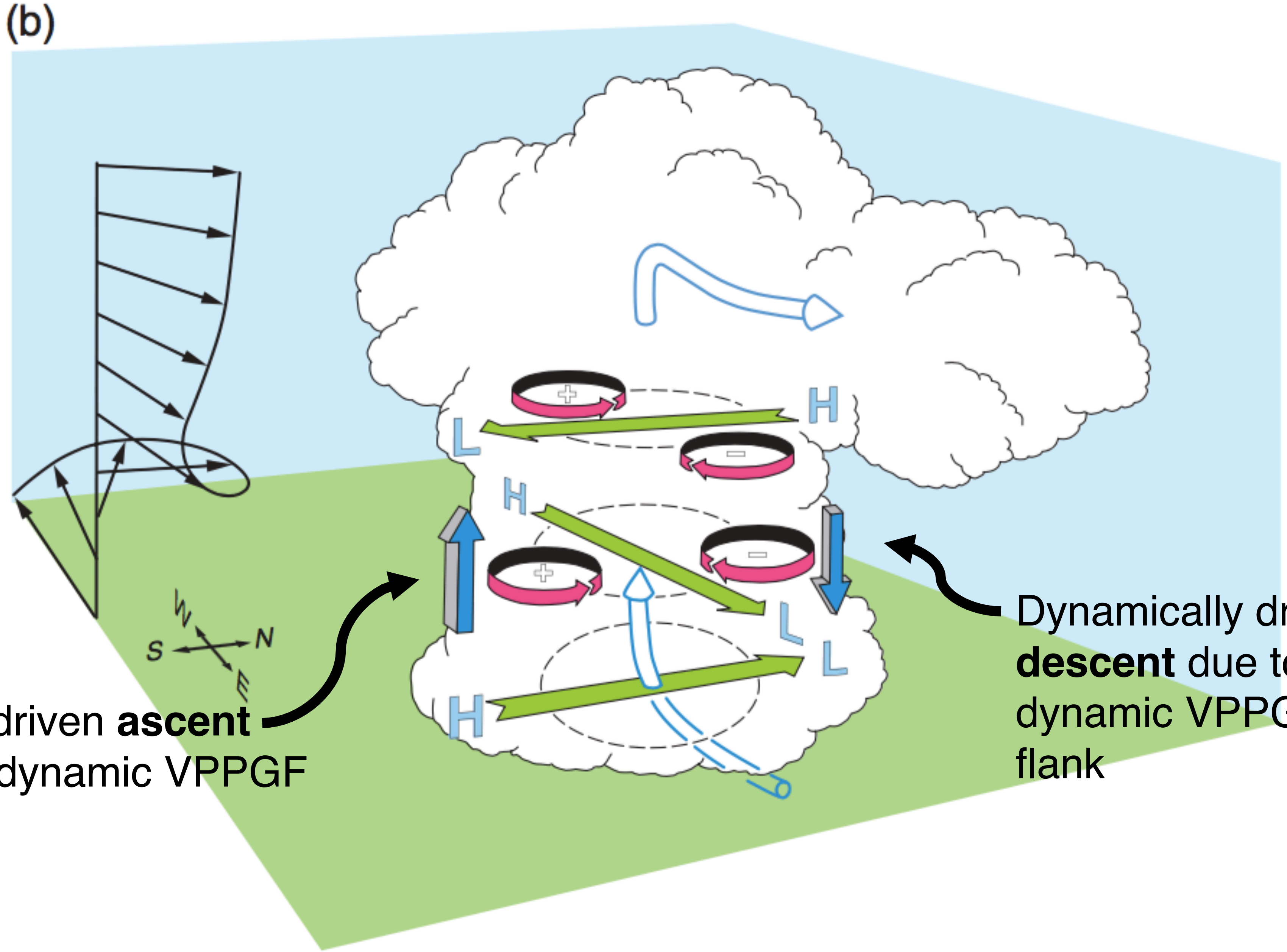
For **straight hodograph**, these are vertically stacked, no propagation can occur.

For **curved hodograph**, high/low couplets are arranged such that new updrafts can be forced along flanks of storm.

Updraft in unidirectional shear



Updraft in vertically-varying shear

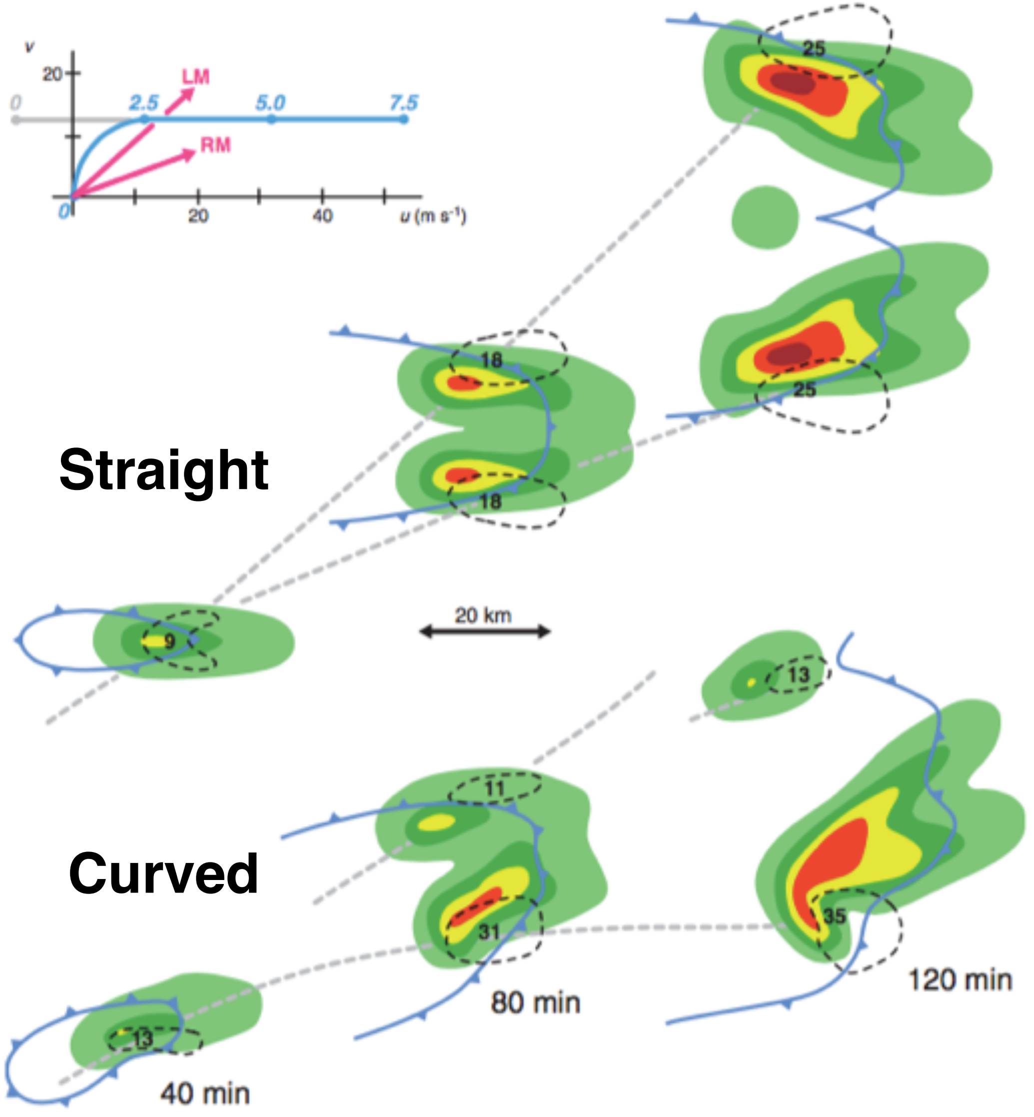


Dynamically driven **ascent** due to linear dynamic VPPGF on right flank

Dynamically driven **descent** due to linear dynamic VPPGF on left flank

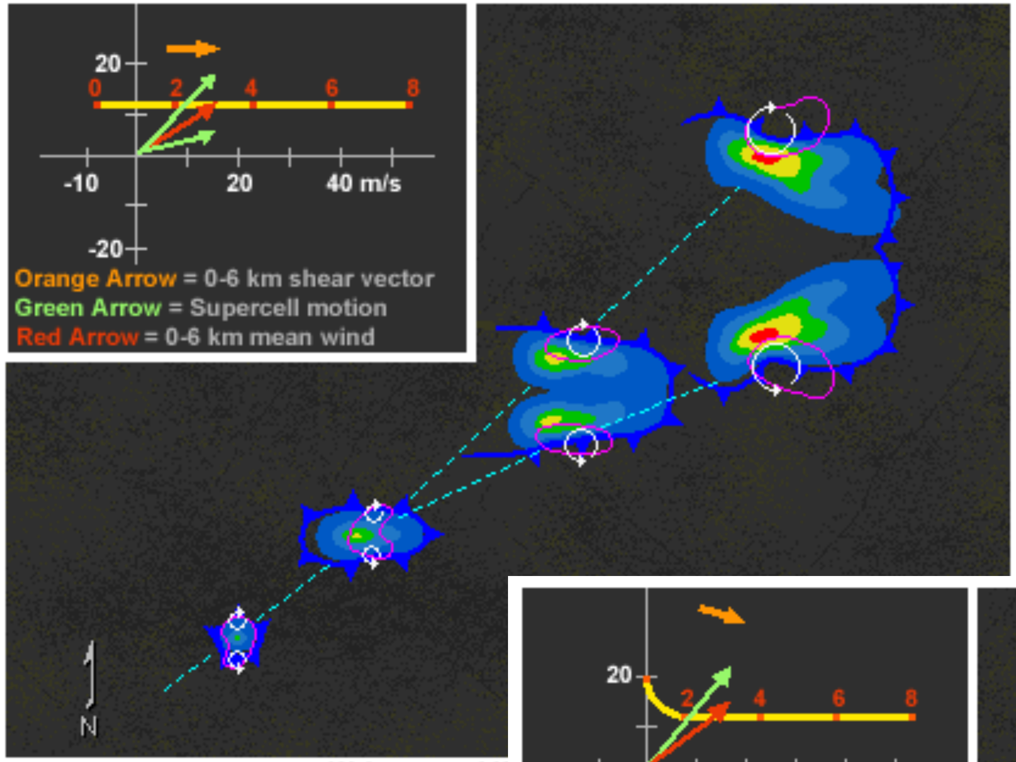
Propagation of supercells

$$-\frac{\partial p'_d}{\partial z} \propto \underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}} \quad \boxed{\underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_h w'}_{\text{linear dynamic forcing}},}$$

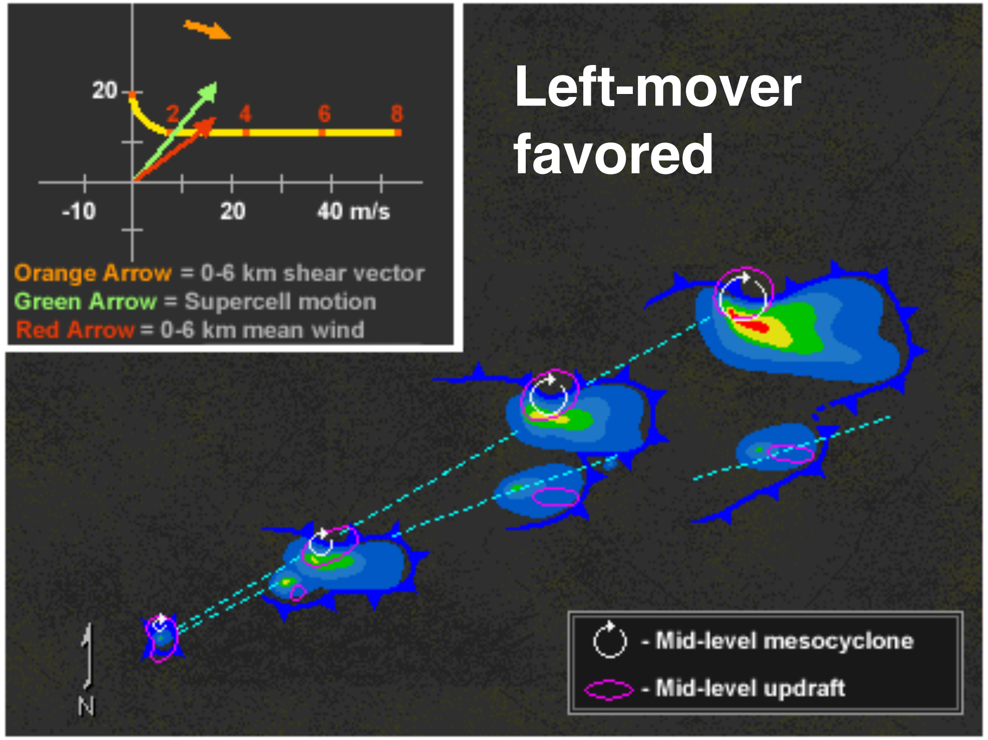


Unidirectional shear vector leads to storm splitting, moving to left and right of deep-layer shear vector.

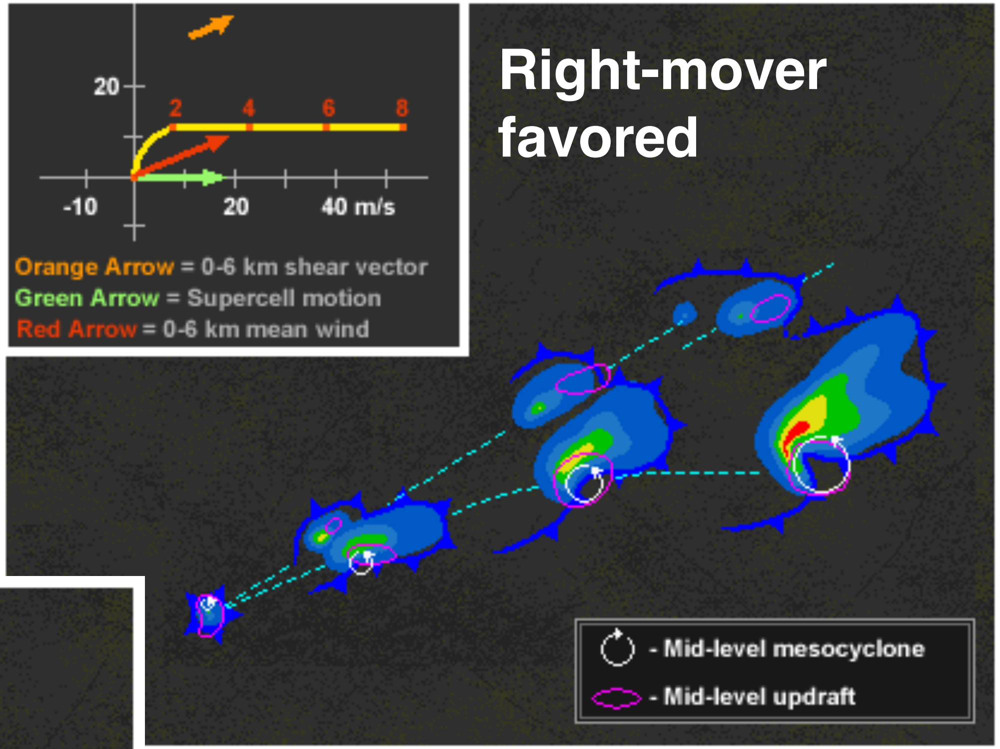
In case of **directionally-varying shear vector** (turning clockwise with height), downward-directed linear dynamic forcing on left flank may completely **suppress left-split** from developing.



Weisman and K

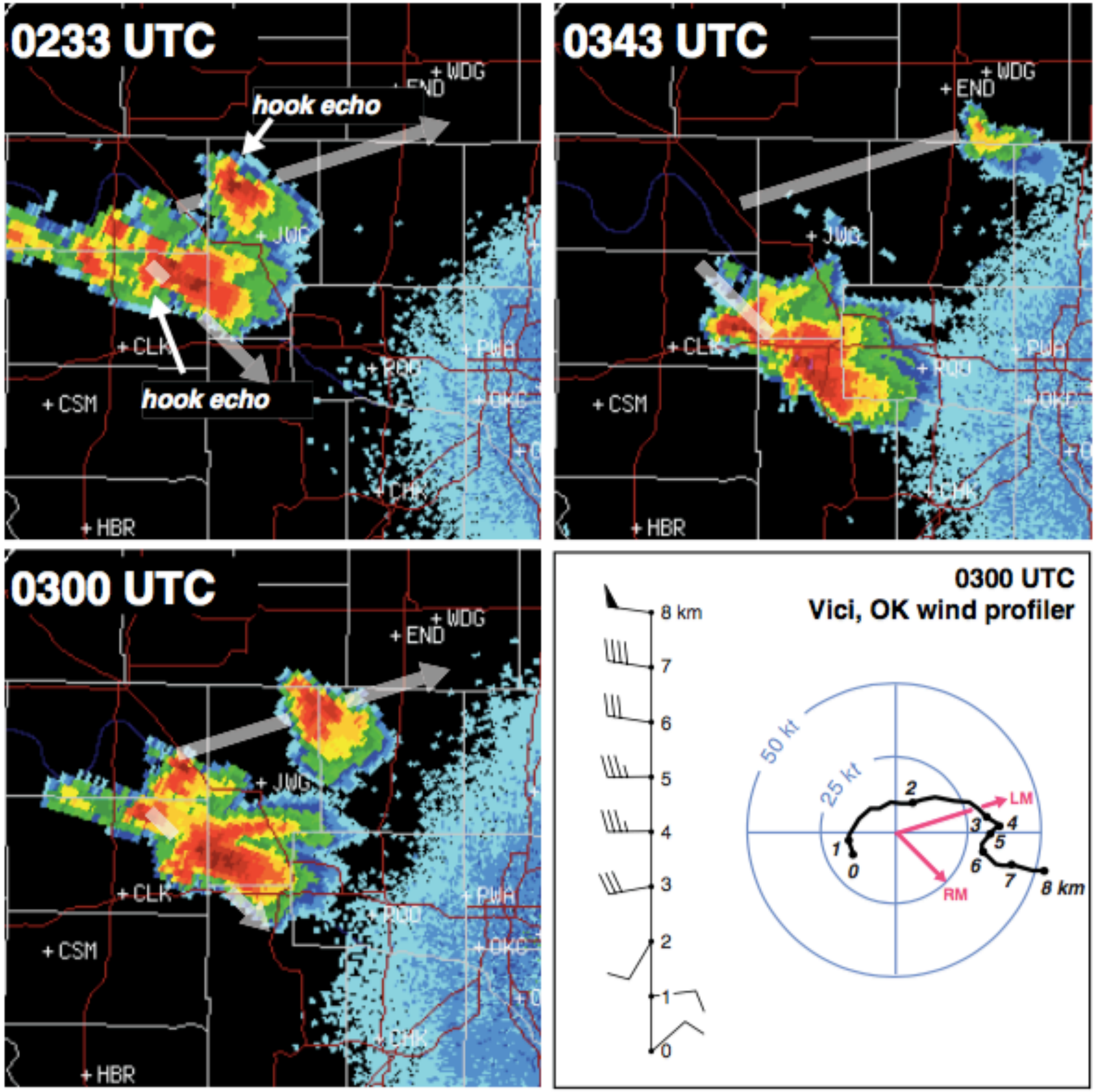


Weisman and Klemp, Ray, Ed., 1986 / The COMET Program



Weisman and Klemp, Ray, Ed., 1986 / The COMET Program

Propagation of supercells



Propagation of supercells

$$-\frac{\partial p_{\mathrm{d}}'}{\partial z} \propto \underbrace{\frac{1}{2}\frac{\partial \zeta'^2}{\partial z}}_{\text{nonlinear dynamic forcing}} \underbrace{-2\frac{\partial}{\partial z}\mathbf{S}\cdot\nabla_{\mathrm{h}} w',}_{\text{linear dynamic forcing}}$$

Summary

For **straight hodograph**, nonlinear forcing leads to storm splitting, resulting in lateral propagation.

For **curved hodograph**, linear forcing leads to lateral storm propagation. Left-moving storm suppressed for clockwise turning shear vector.

Table 8.1 Comparison of the properties of supercells in environments with nearly straight hodographs and with strongly curved hodographs that turn clockwise with height. It is assumed that the environments have roughly similar CAPE and vertical wind shear. (From Davies-Jones *et al.* [2001].)

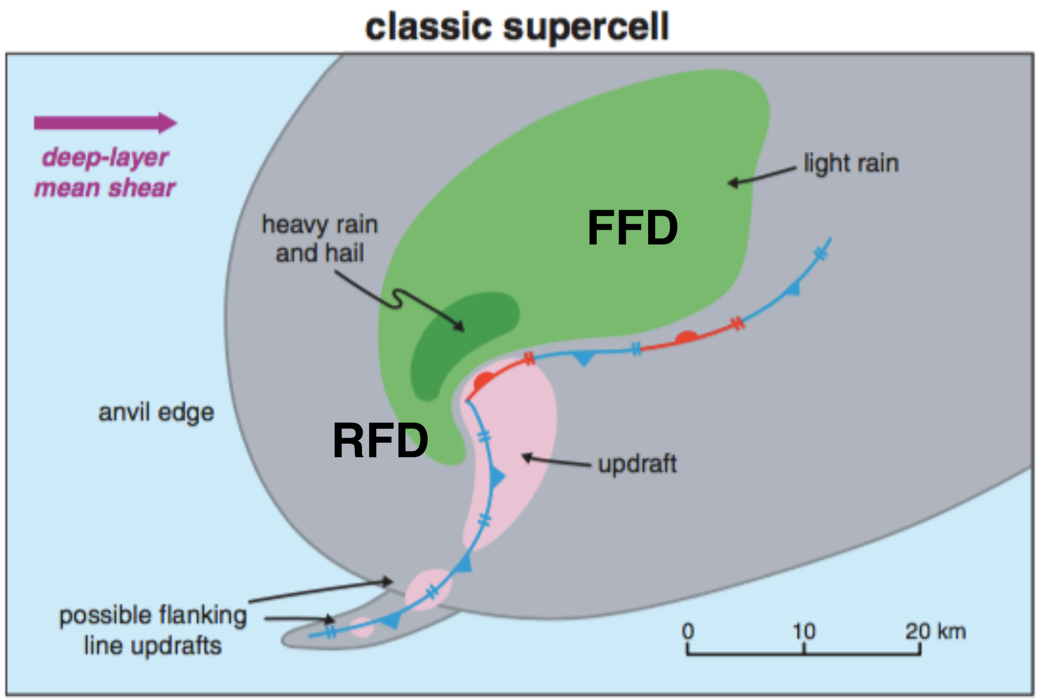
Property	(Nearly) straight hodograph	Strongly curved hodograph
Symmetry of left and right movers	Yes (for straight hodograph, neglecting f)	No
Net updraft rotation in initial storm	No	Yes
Cyclonic vortex in initial storm	On the right side of the updraft	In strong updraft
Anticyclonic vortex in initial storm	On the left side of the updraft	In downdraft or weak updraft
Storm splitting	Highly significant	Insignificant or absent
Time to first mesocyclone	Slower	Faster
Low and midlevel mesocyclone intensity	Generally less intense	Generally more intense
Mesoanticyclone	In left mover	Generally absent
Maximum updraft strength	Weaker	Stronger
Direction of low-level environmental vorticity versus baroclinically generated horizontal vorticity	Very different (roughly orthogonal)	In roughly same direction
Lateral updraft propagation	Via nonlinear dynamic forcing	Via linear dynamic forcing

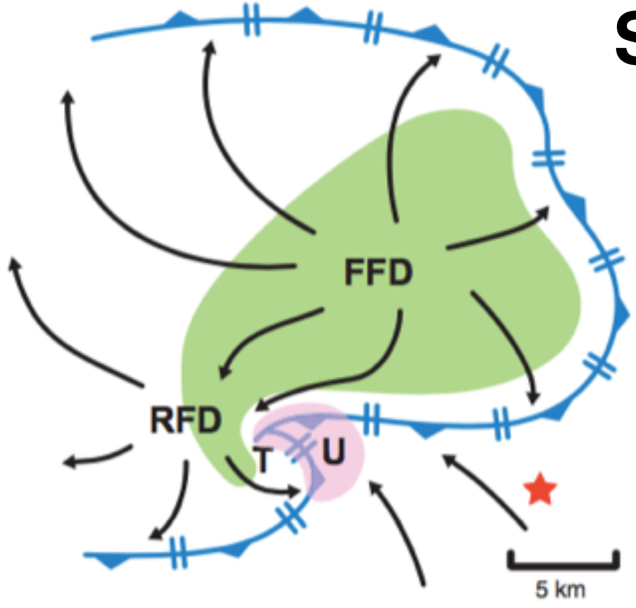
Supercell Structure

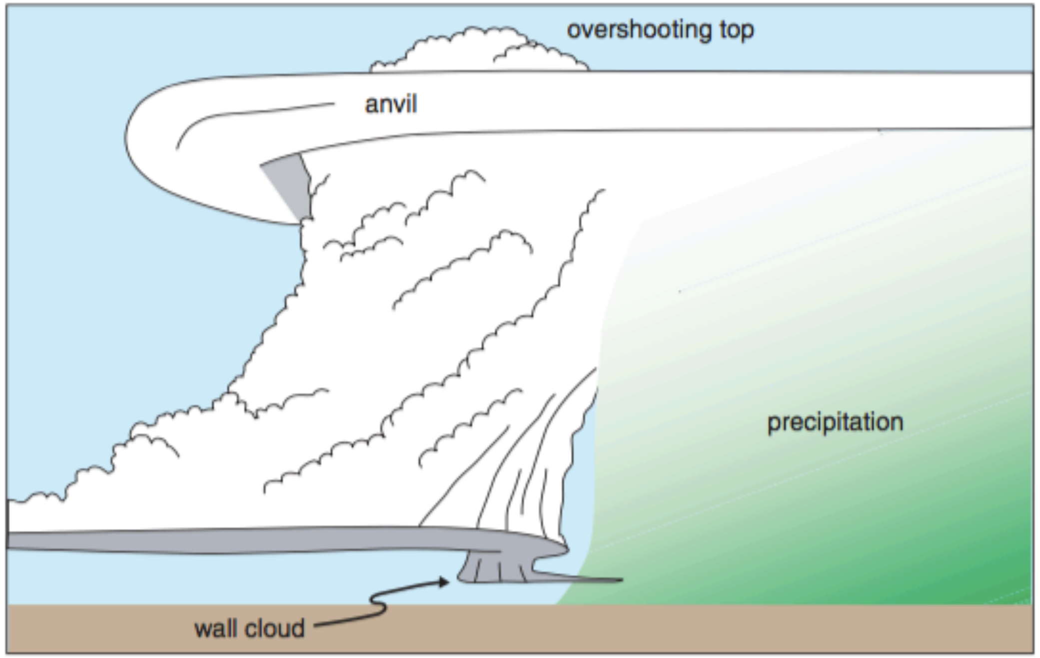
Two main downdrafts:

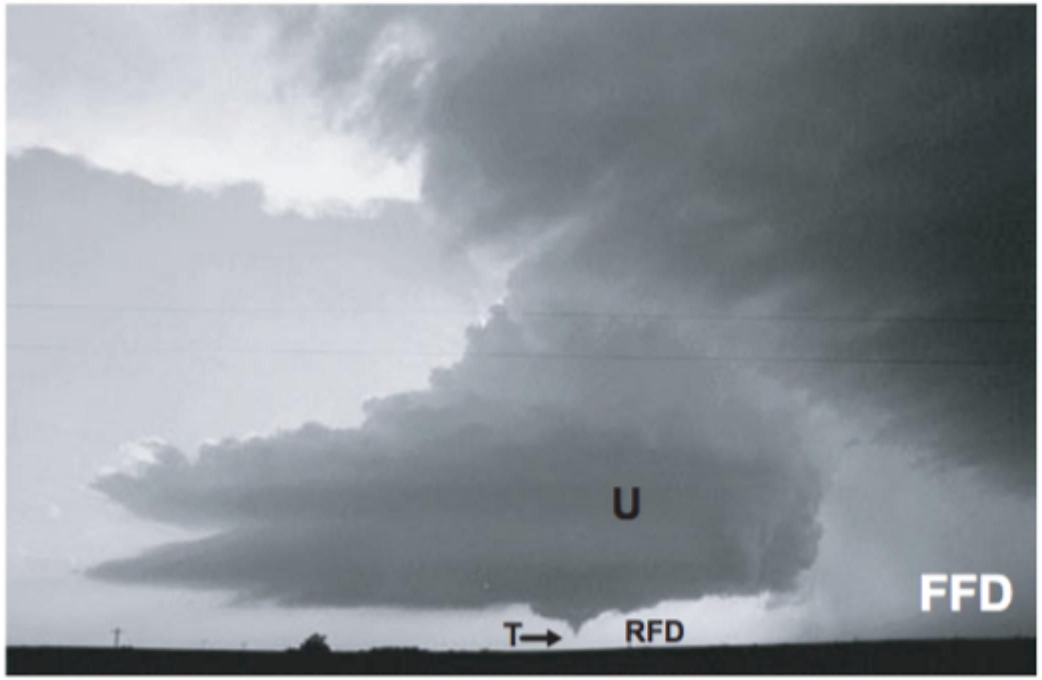
Forward-flank downdraft (**FFD**)

Rear-flank downdraft (**RFD**)

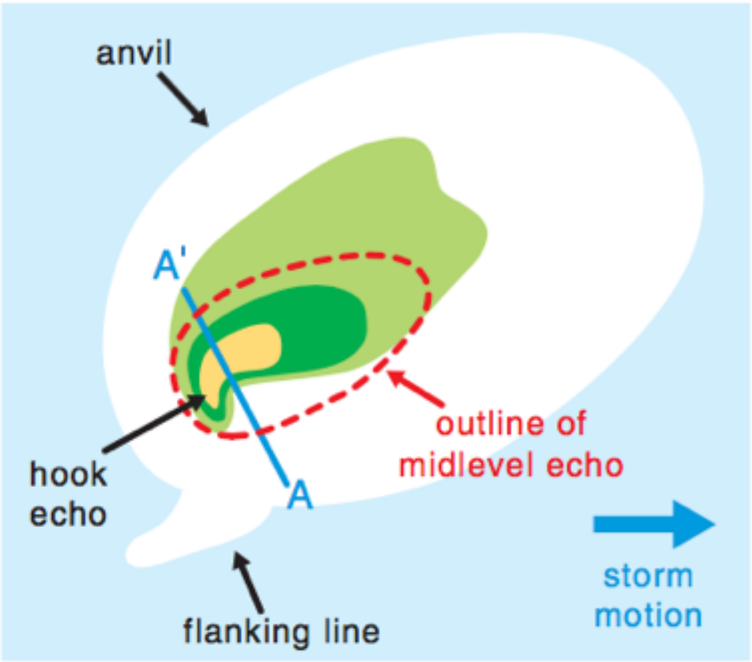


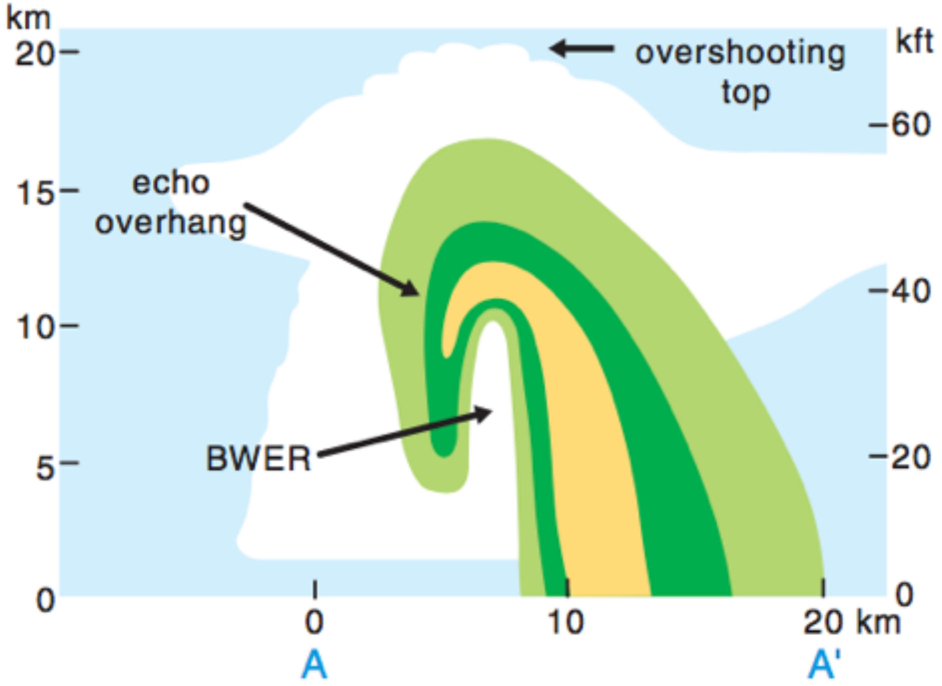


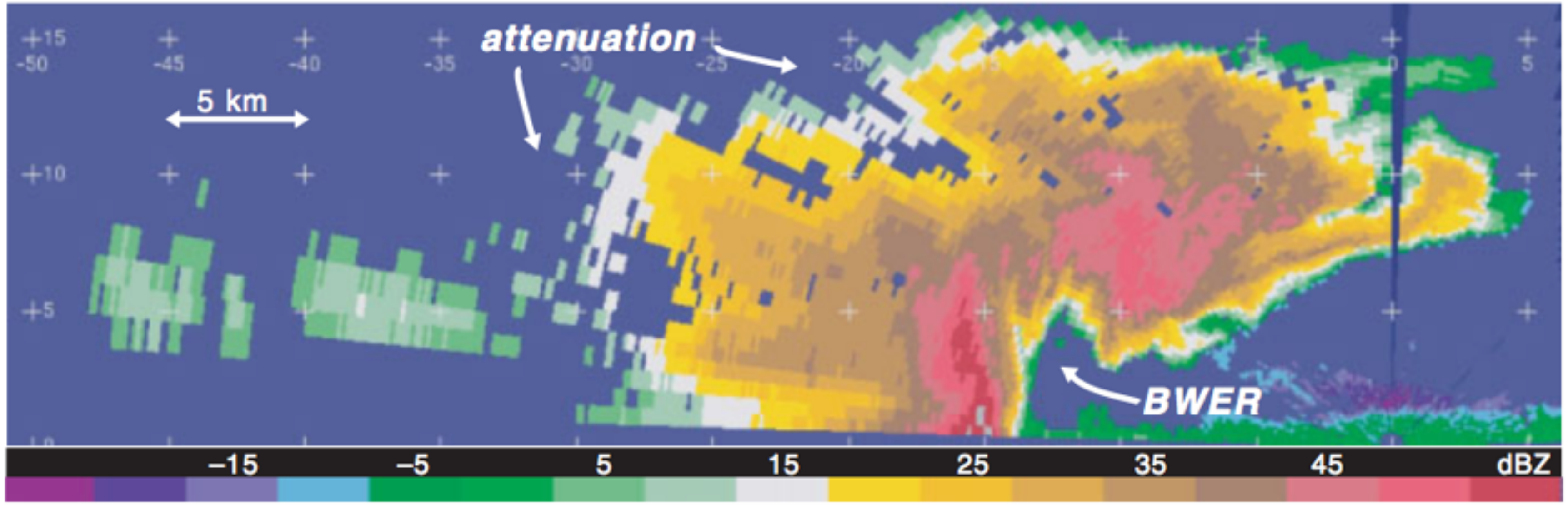


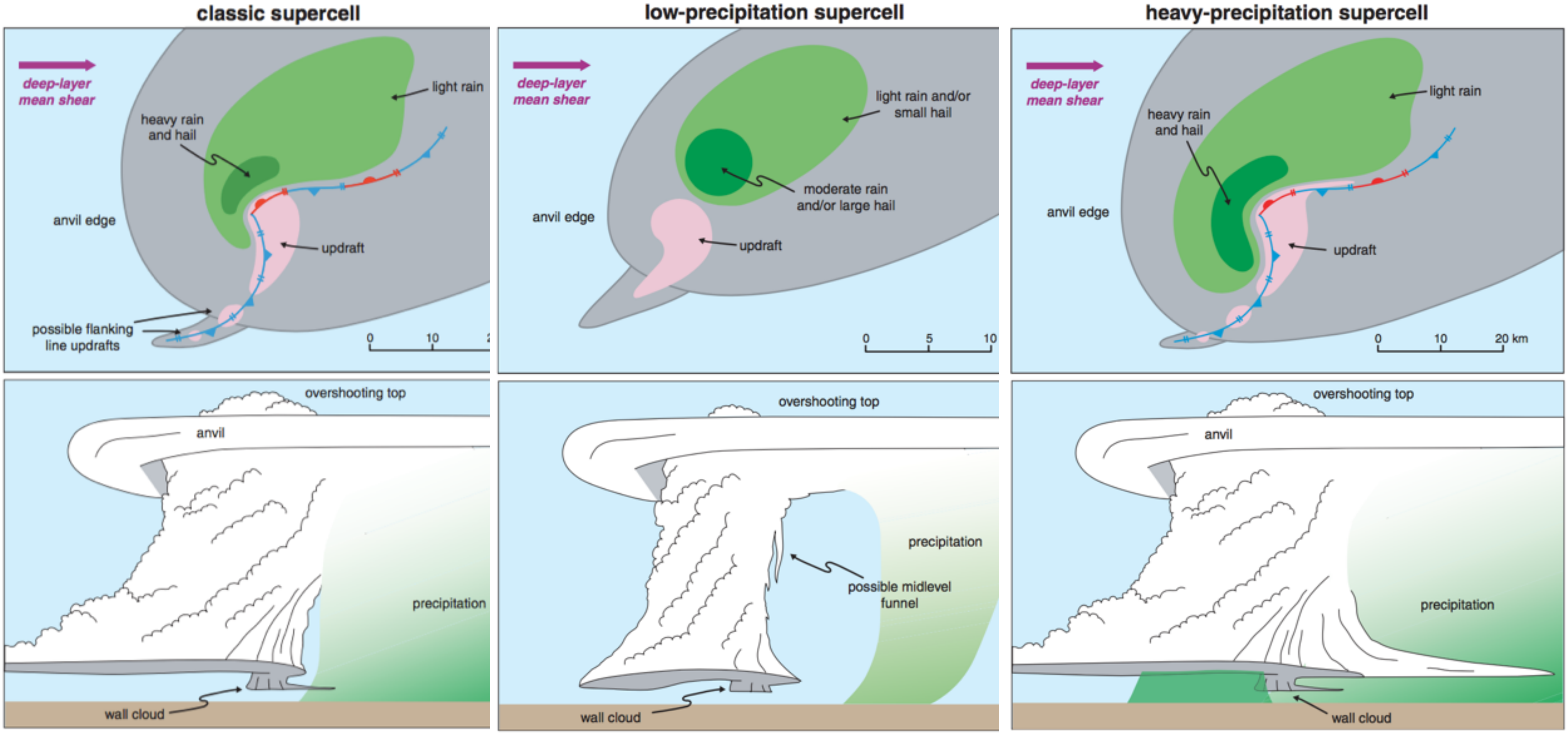


Supercell radar presentation









classic supercell
low-precipitation supercell
heavy-precipitation supercell
deep-layer
mean shear
light rain
heavy rain
and hail
anvil edge
updraft
possible flanking
line updrafts
0
10
light rain and/or
small hail
moderate rain
and/or large hail
5
20 km
overshooting top
anvil
precipitation
wall cloud
possible midlevel
funnel

Rasmussen and Straka (1998): *Variations in Supercell Morphology. Part I: Observations of the Role of Upper-Level Storm-Relative Flow*

Storm-relative environmental flow at anvil level stronger in LP storms.

This transports hydrometeors well away from the updraft, reducing the amount of precipitation that is reingested into the updraft.

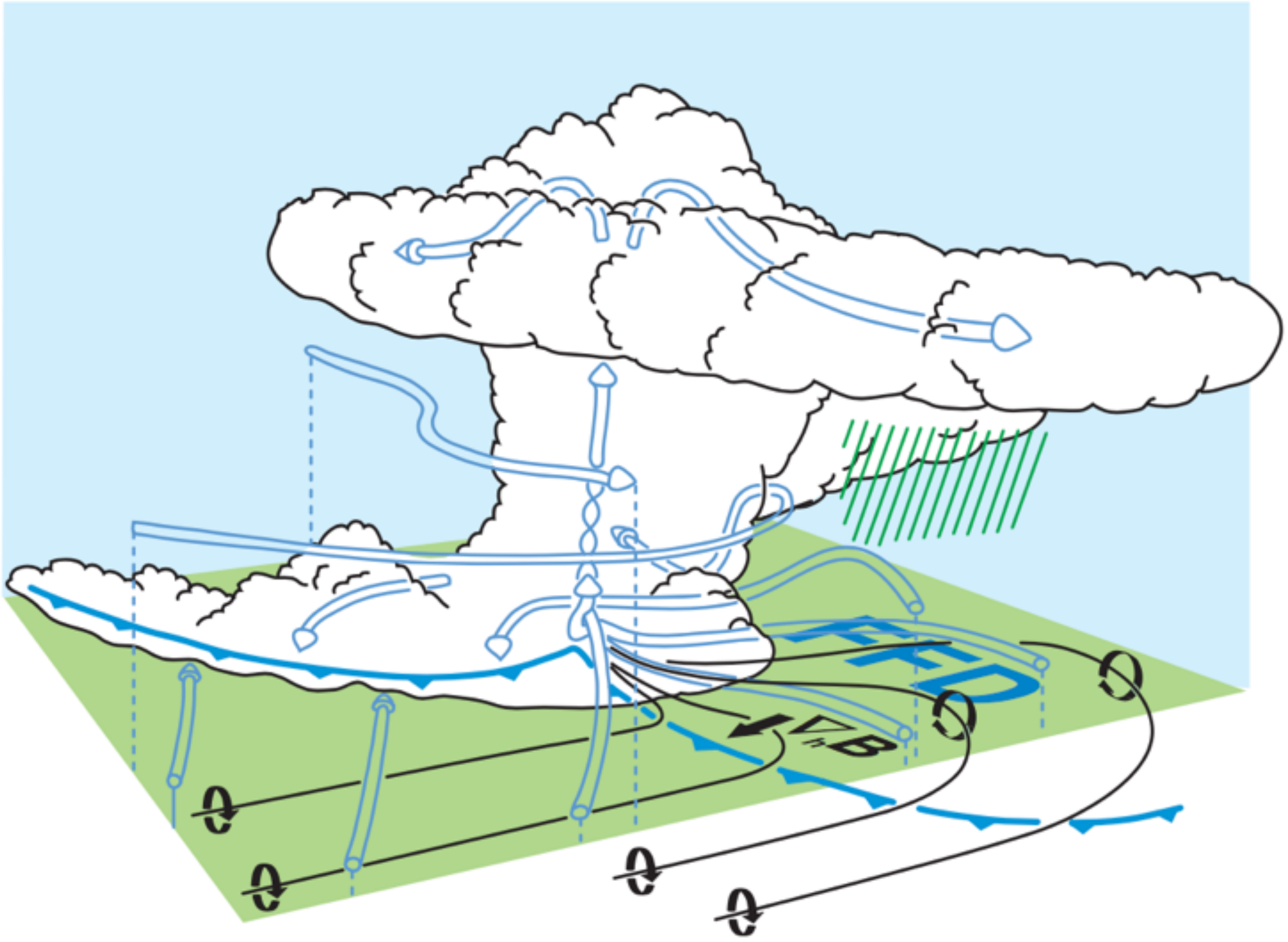
Upstream storms may precipitate within updrafts of downstream storms, leading to HP evolution.

Vertical vorticity generation by buoyancy gradients within supercells

Parcel trajectories often traverse buoyancy gradients within the FFD.

Horizontal buoyancy gradients in FFD can **increase** horizontal vorticity available for tilting into updraft, if *environmental and storm-generated vorticity are in same direction*.

Important for **low-level updraft rotation** following the development of surface cold pools.

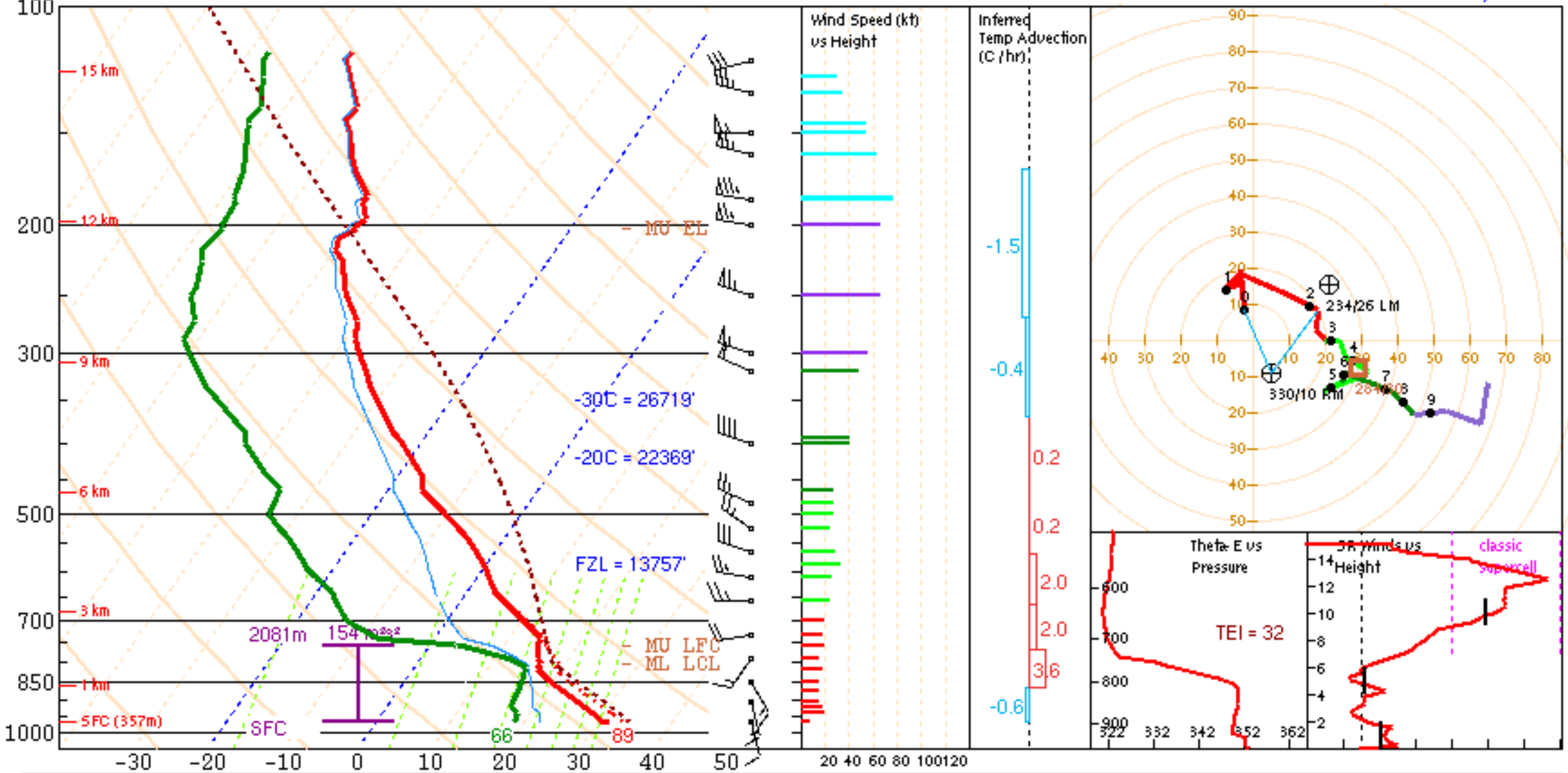


Review

Derivation of vertical momentum equation containing VPPGF and buoyancy.
Hydrostatic approximation – when does it hold?
Skew-T and hodograph basics – assessing environmental instability and wind shear
Buoyancy and virtual temperature
Parcel theory and its limitations
Origins of pressure perturbations
Buoyancy forcing vs. dynamic forcing
Linear and non-linear pressure perturbation terms – how do they differ
Processes responsible for changes to environmental sounding
Role of vertical wind shear in maintaining convection
Differences between three convective storm types
Favored areas of lifting along cold pool outflow boundary
Derivation of theoretical cold pool speed
Origins of updraft rotation – crosswise vs. streamwise vorticity
Usage of helicity
Supercell propagation

OUN 120530/0000 (Observed)

NOAA/NWS Storm Prediction Center
Norman, Oklahoma



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	2772	-7	1640m	-9	2081m	38783'
MIXED LAYER	2493	-26	1593m	-8	2443m	38783'
FCST SURFACE	2889	-0	1839m	-9	1948m	38783'
MU (968 mb)	2772	-7	1640m	-9	2081m	38783'

PW = 1.27 in | 3CAPE = 24 J/kg | WBZ = 9410' | WNDG = 0.3
K = 22 | DCAPE = 1339 J/kg | FZL = 13757' | ESP = 0.7
MidRH = 42% | DownT = 57 F | ConvT = 92F | MMP = 0.91
LowRH = 59% | MeanW = 13.9 g/kg | MaxT = 92F
SigSevere = 42425 m3/s3

Sfc-3km Agl Lapse Rate = 8.5 C/km
3-6km Agl Lapse Rate = 7.9 C/km
850-500mb Lapse Rate = 7.4 C/km
700-500mb Lapse Rate = 7.7 C/km

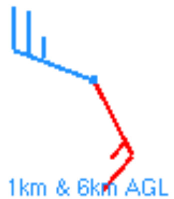
Supercell = 7.1
Left Supercell = 1.0
Sig Tor (CIN) = 0.6
Sig Tor (fixed) = 0.0
Sig Hail = 1.2

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	-22	7	164/16	159/26
SFC - 3 km	193	26	193/13	174/21
Eff Inflow Layer	154	20	175/15	165/24
SFC - 6 km		33	243/12	201/15
SFC - 8 km		51	253/13	210/15
Lower Half Storm Depth		33	242/12	201/15
Cloud Bearing Layer		67	280/27	259/22

BRN Shear = 40 m²/s²
4-6km SR Wind = 275/21 kt

.....Storm Motion Vectors.....
Bunkers Right = 330/10 kt
Bunkers Left = 234/26 kt

Corfidi Downshear = 295/59 kt
Corfidi Upshear = 305/36 kt



1km & 6km AGL Wind Barbs

* * * BEST GUESS PRECIP TYPE * * *

None.

Based on sfc temperature of 89.2 F.

SARS - Sounding Analogs

SUPERCELL		SGFNT HAIL	
00071001.LBF	NON	95062300.LBF	3.00
		04081000.DDC	3.00
		95062800.LBF	2.75
		92062700.AMA	2.75
		92060500.AMA	2.75
		06081000.BIS	2.75
		04082400.BIS	2.00
		02052800.MAF	1.75
(5 loose matches)		(222 loose matches)	
SARS: 40% TOR		SARS: 56% SIG	