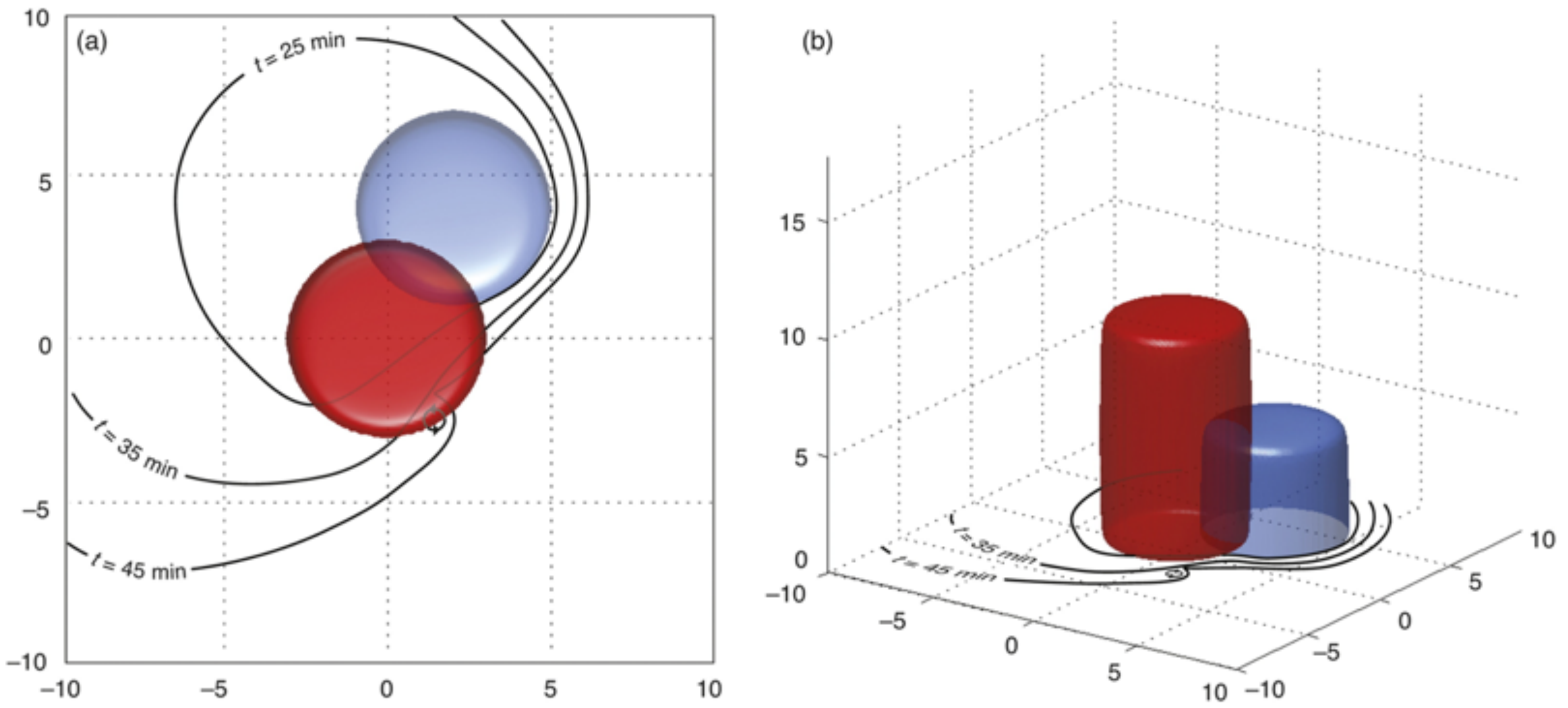
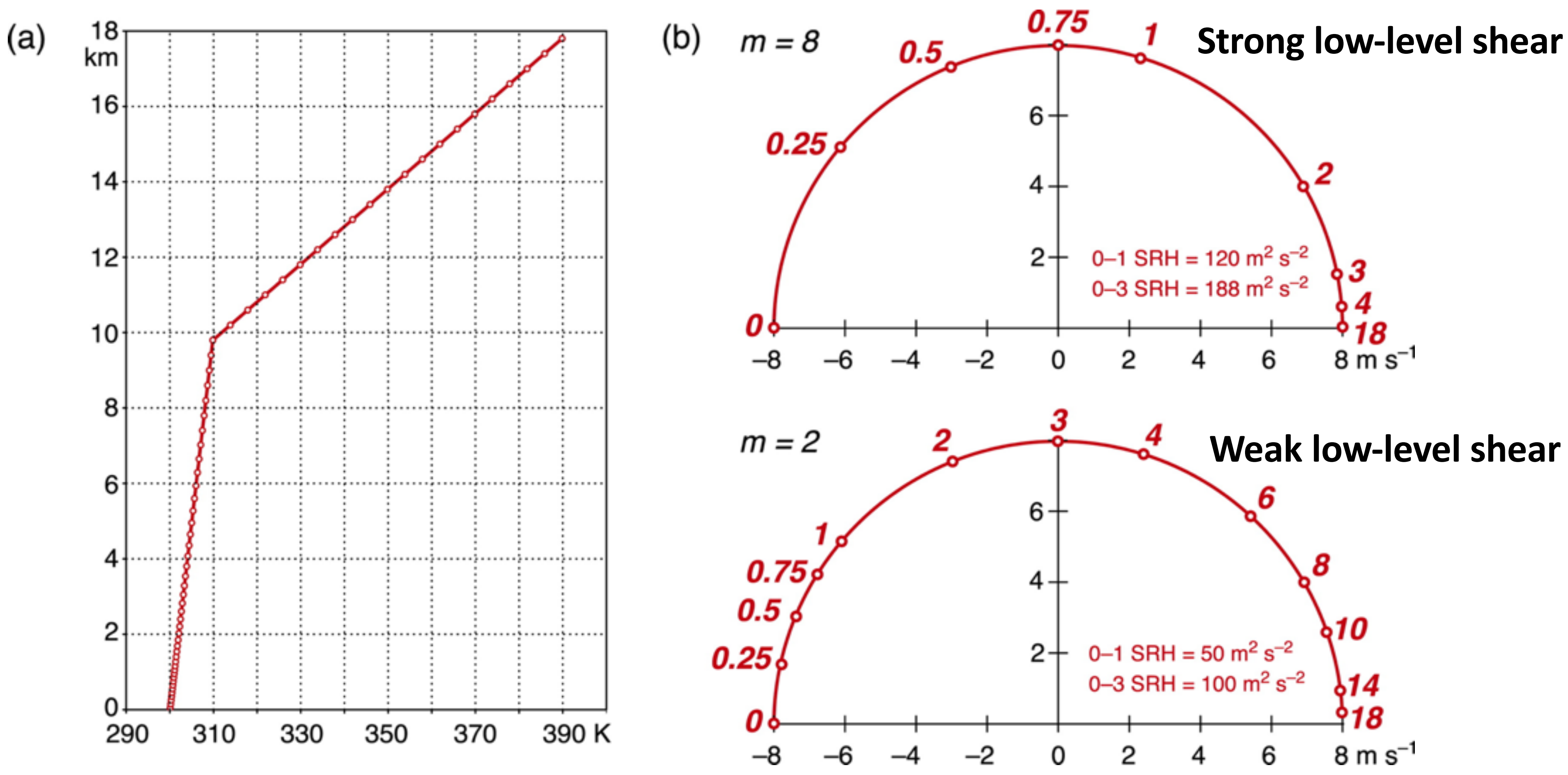
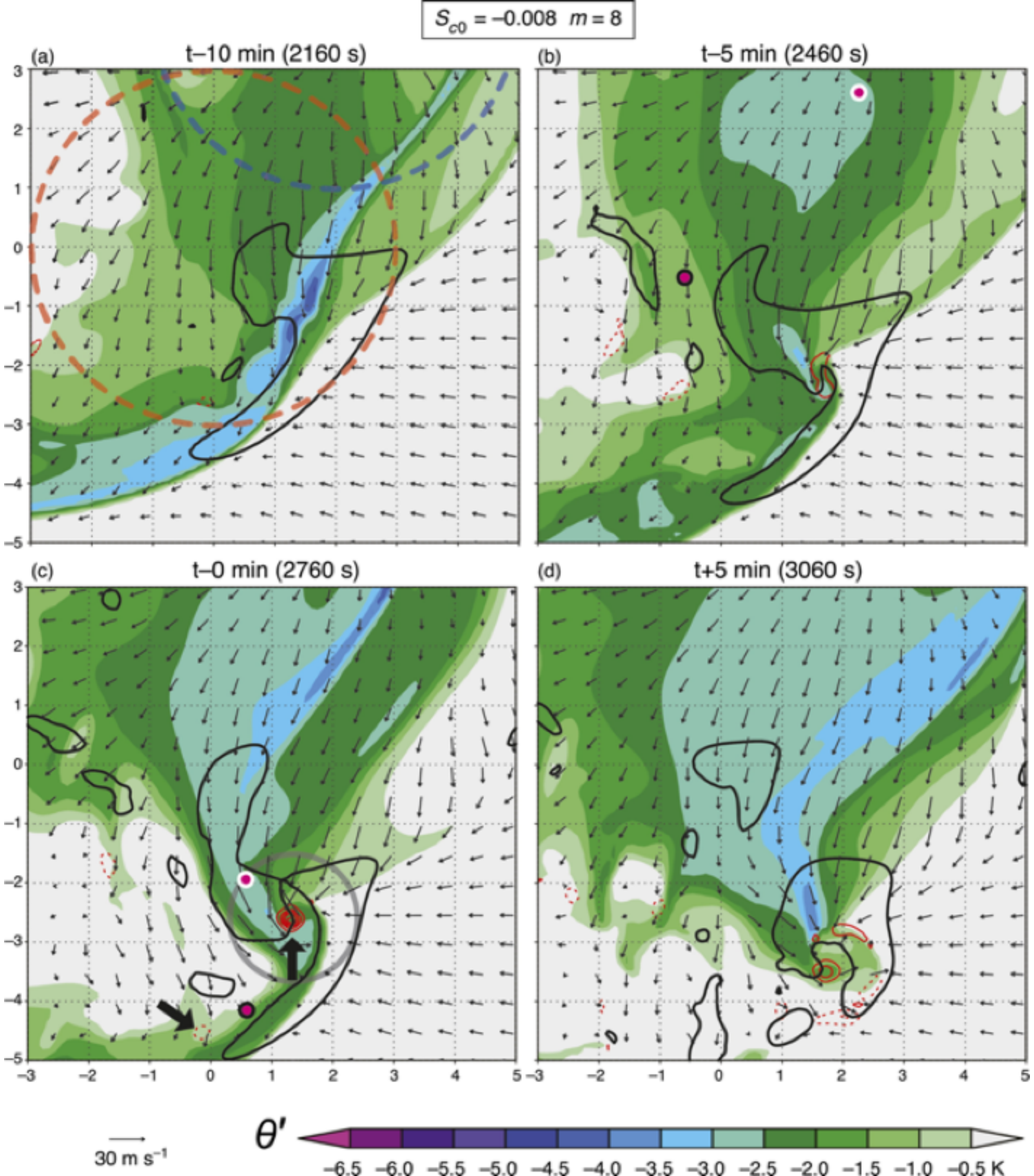
Markowski & Richardson (2014)

Dry simulations with CM1 – no moisture! ”Pseudo-storms”
Cylindrical heat source in homogeneous environment of vertical shear.
Heat sink imposed on northeastern flank of updraft at low-levels at 900s
Heat sink magnitude varied
Parcels maintain potential temperature outside of heat source/sink.

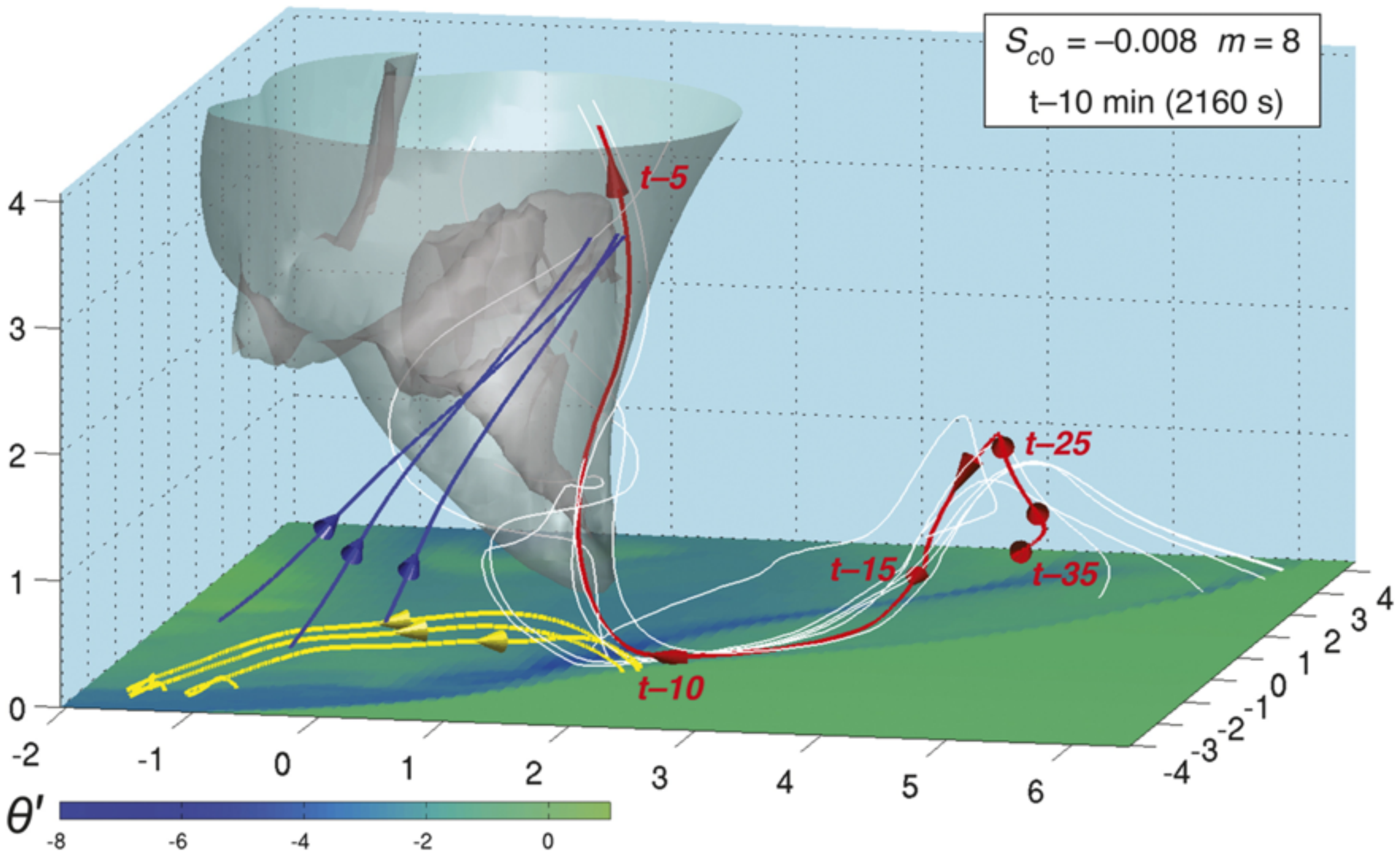


Semicircular hodograph





$S_{c0} = -0.008$ $m = 8$
(a)
t–10 min (2160 s)
(b)
t–5 min (2460 s)
(c)
t–0 min (2760 s)
(d)
t+5 min (3060 s)
30 m s^{-1}
θ'
−6.5 −6.0 −5.5 −5.0 −4.5 −4.0 −3.5 −3.0 −2.5 −2.0 −1.5 −1.0 −0.5 K



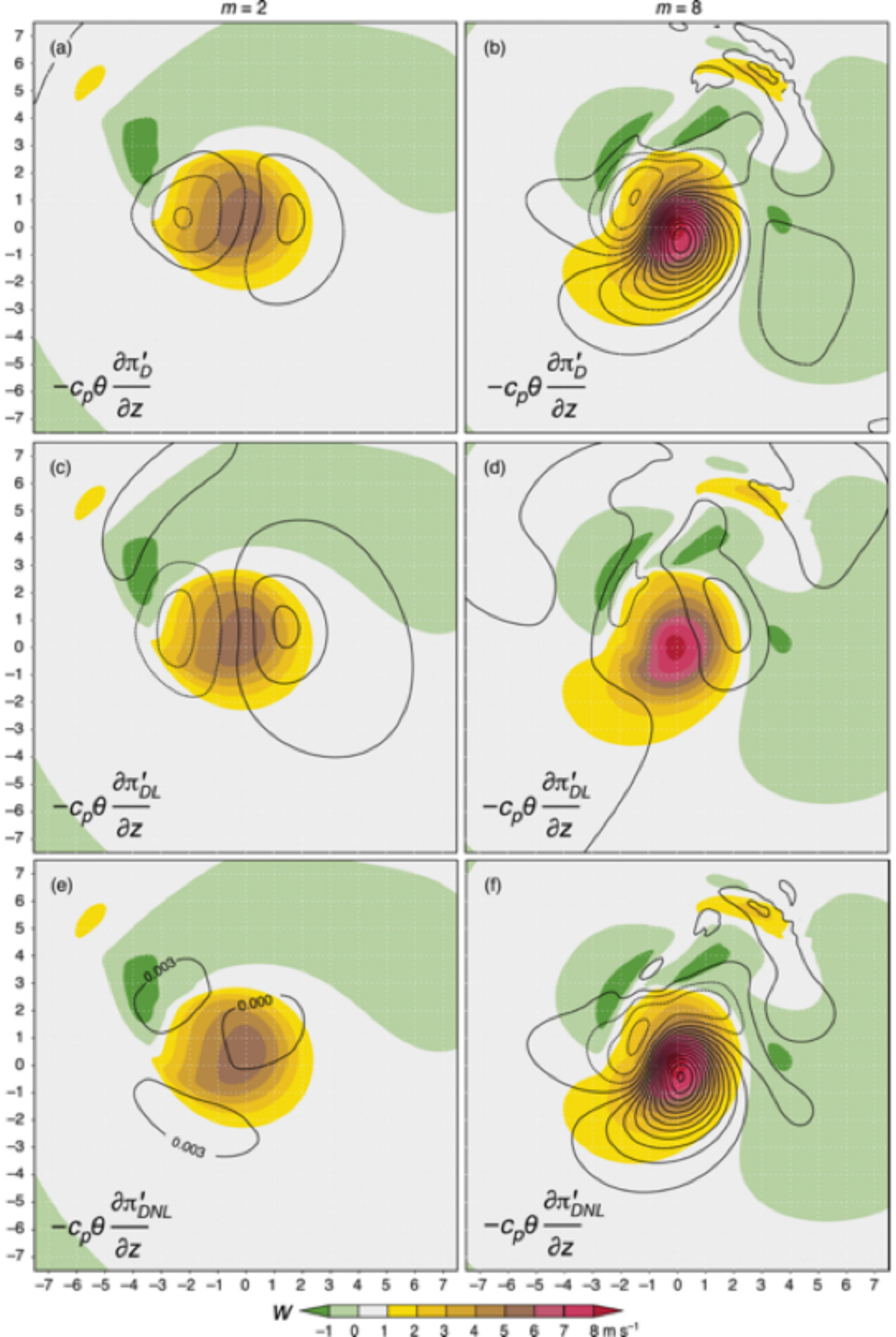
S_{c0} = −0.008 m = 8
t−10 min (2160 s)
t−5
t−10
t−15
t−25
t−35
θ′
-8
-6
-4
-2
0

Large difference in low-level dynamic lifting!

Stronger low-level shear produces VPPGF which is 5 times stronger than weak low-level shear case.

This difference due to large difference in vertical gradient of vertical vorticity in the 0 – 1 km layer.

Base of the mid-level mesocyclone lowered as the environmental shear increased.



Circulation analysis

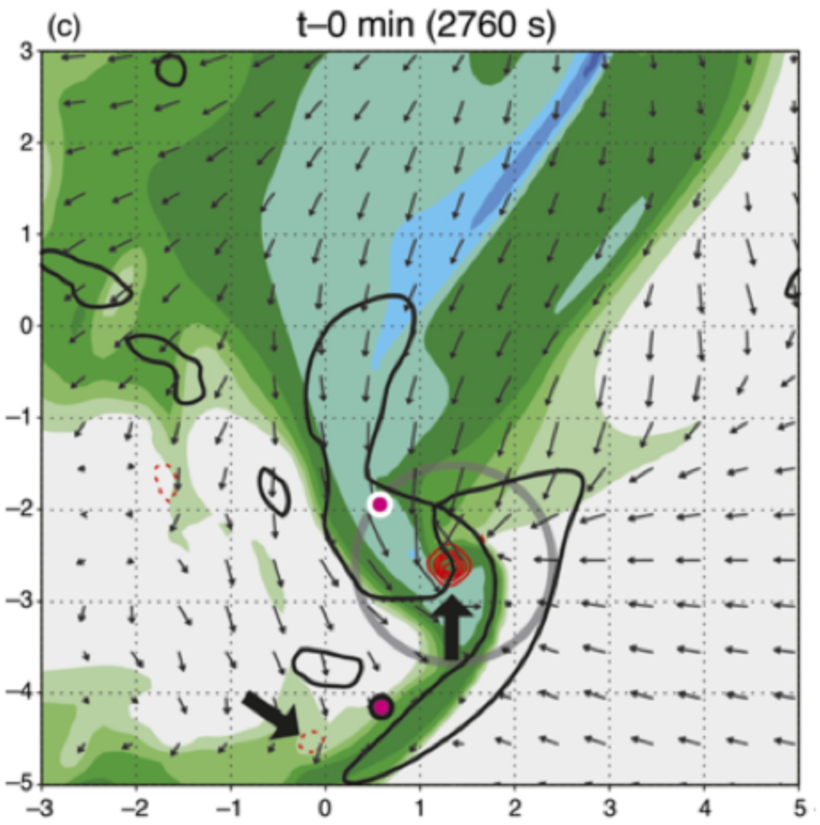
Circulation around material circuit can only change in time due to baroclinic effects (and earth's rotation, which we can neglect):

$$C = \oint \mathbf{v} \cdot \mathrm{d}\mathbf{l}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -\oint \frac{\mathrm{d}p}{\rho} - 2\Omega \frac{\mathrm{d}A_e}{\mathrm{d}t}$$

Baroclinic term

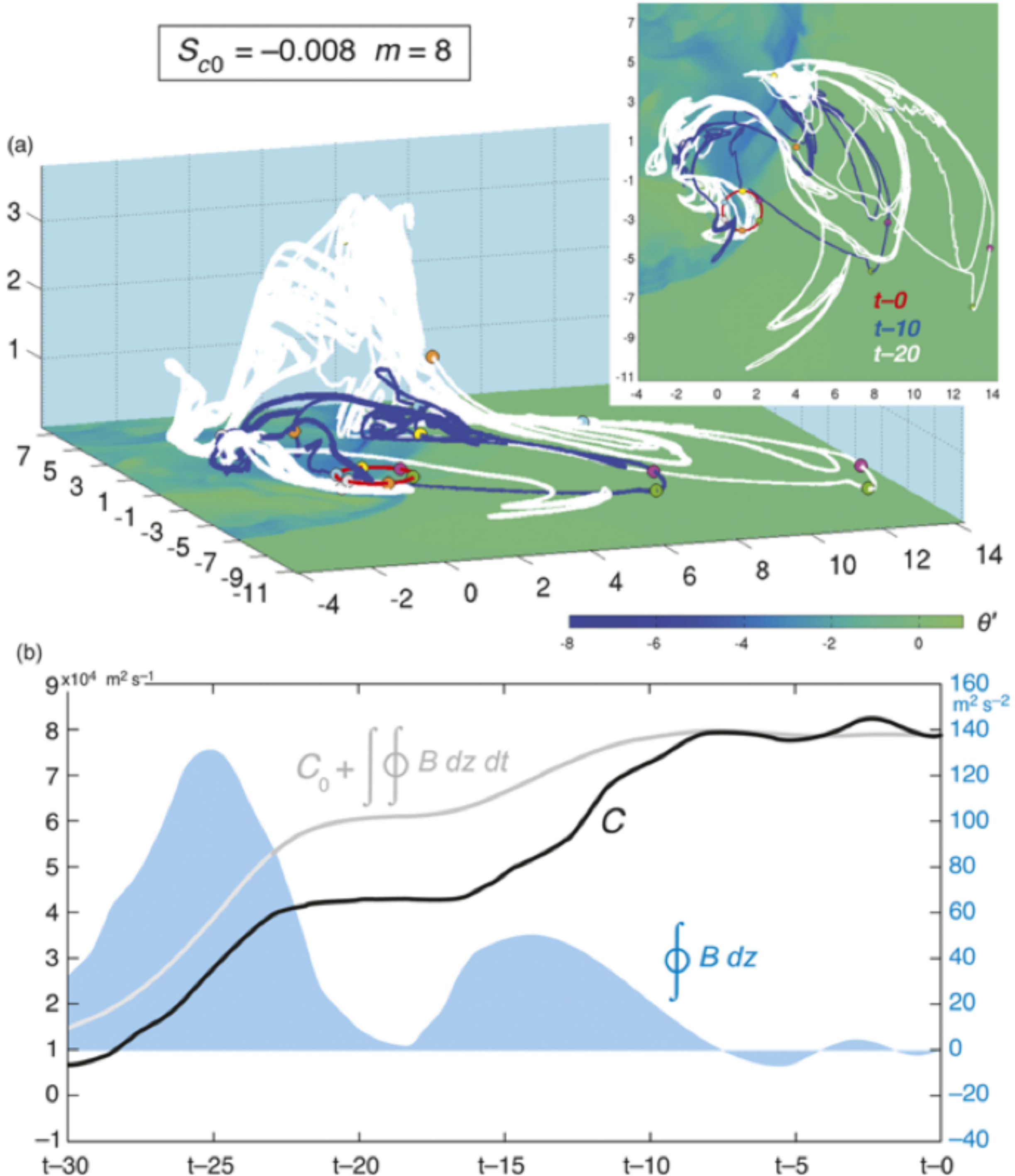
Bjerknes' circulation theorem



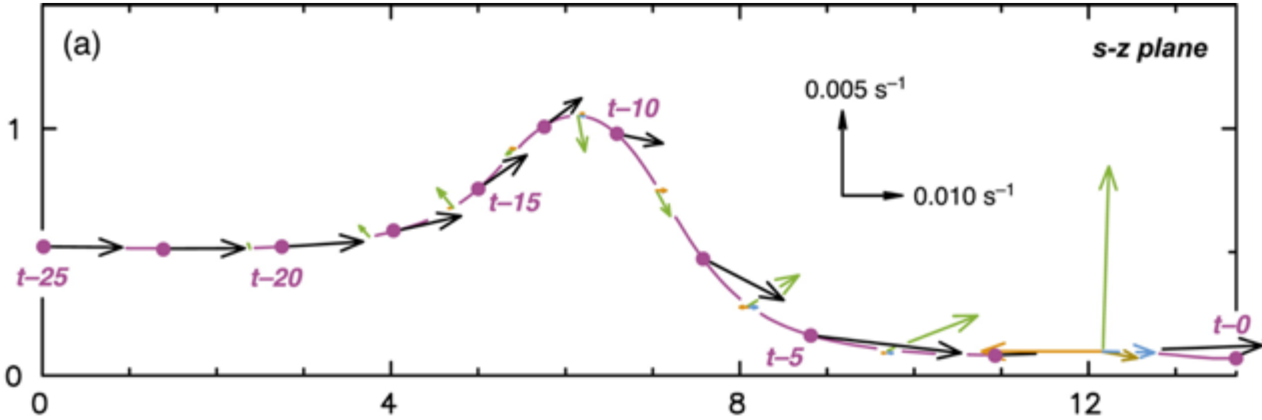
Circulation computed along material circuit tracked backward in time initially centered on maximum near-ground vorticity.

Circulation analysis

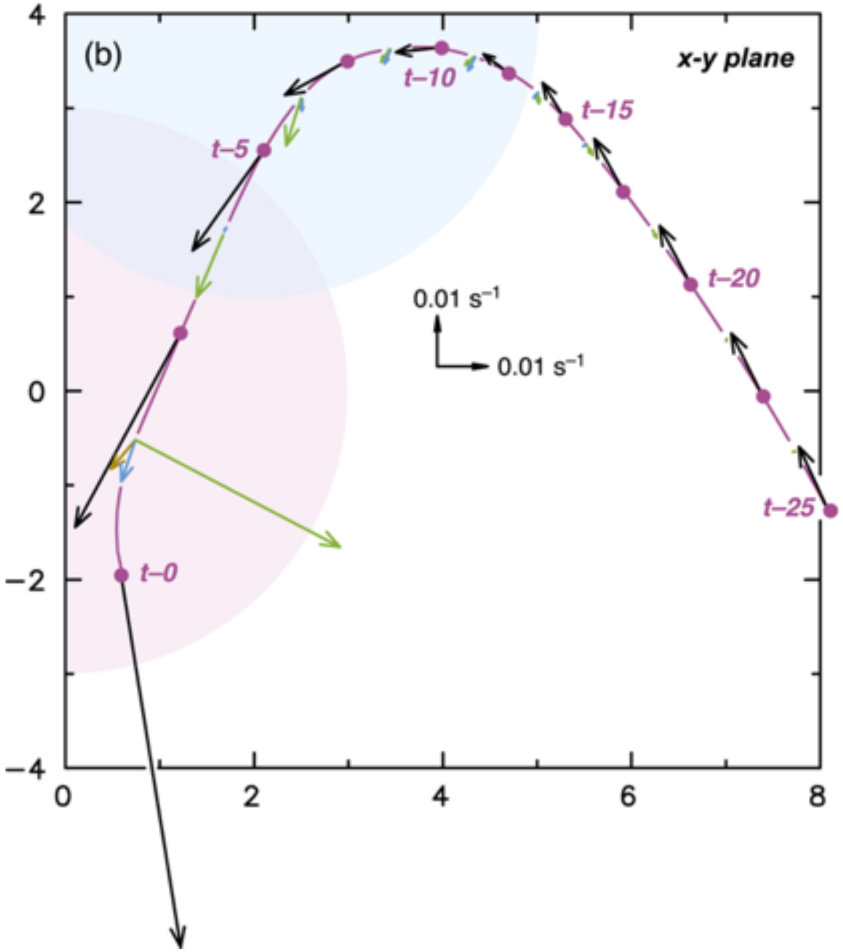
Almost all of circulation increase due to baroclinic effects – environmental vorticity does not play a significant role in near-surface vertical vorticity.



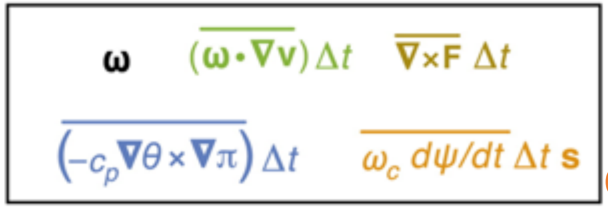
Vorticity forcing analysis



Development of cyclonic vertical vorticity along a trajectory associated with a downdraft



Projection into streamwise direction

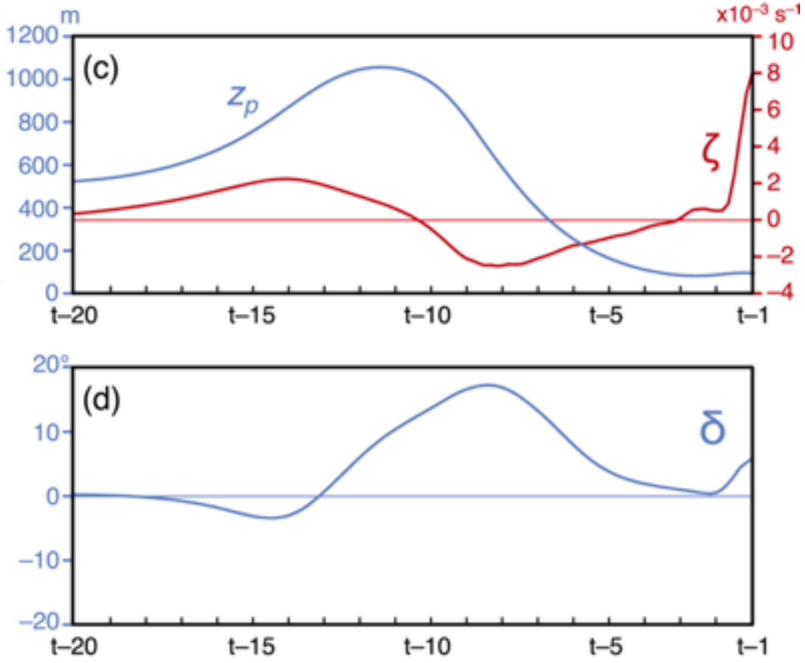


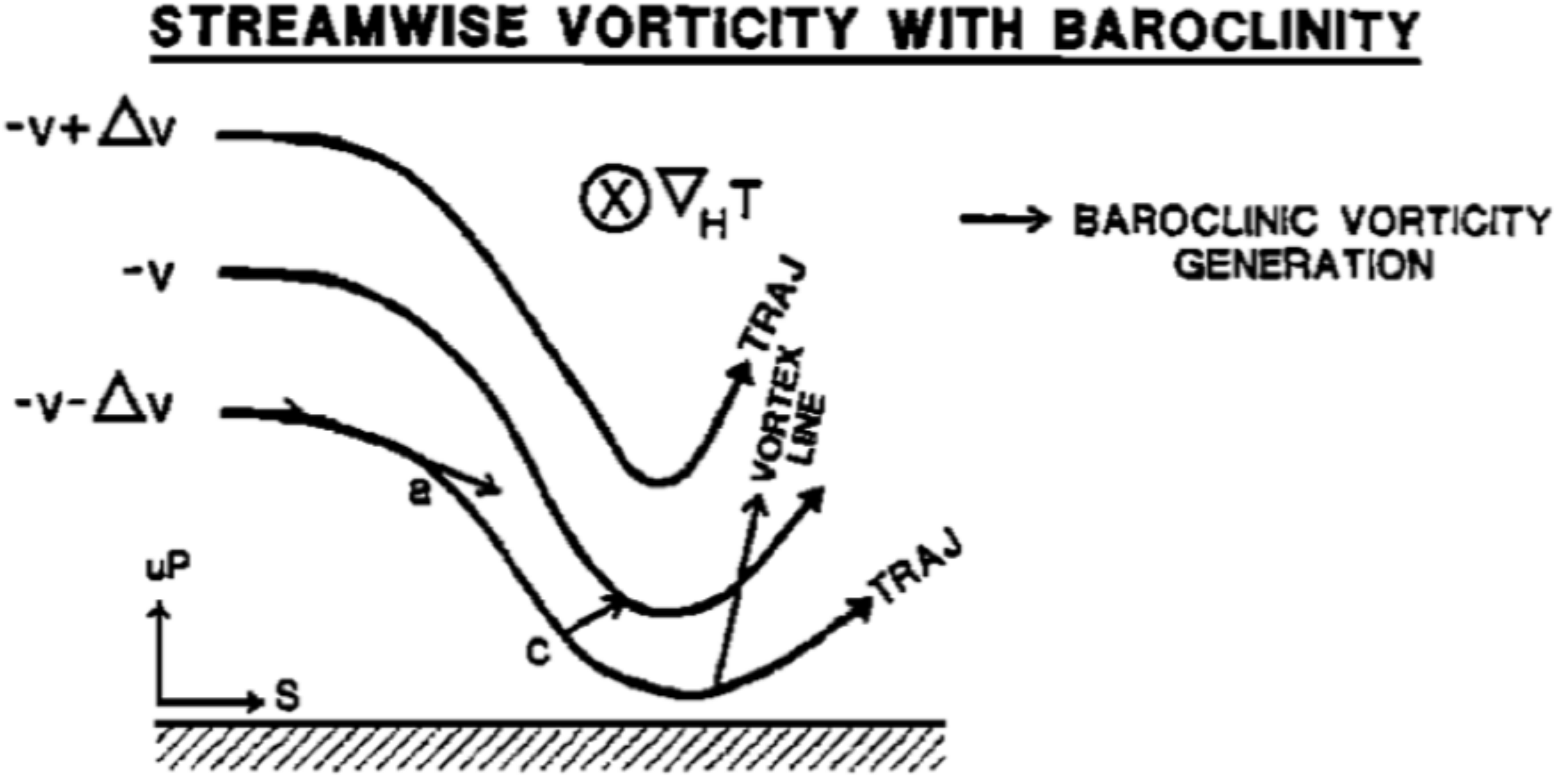
Barotropic

Baroclinic

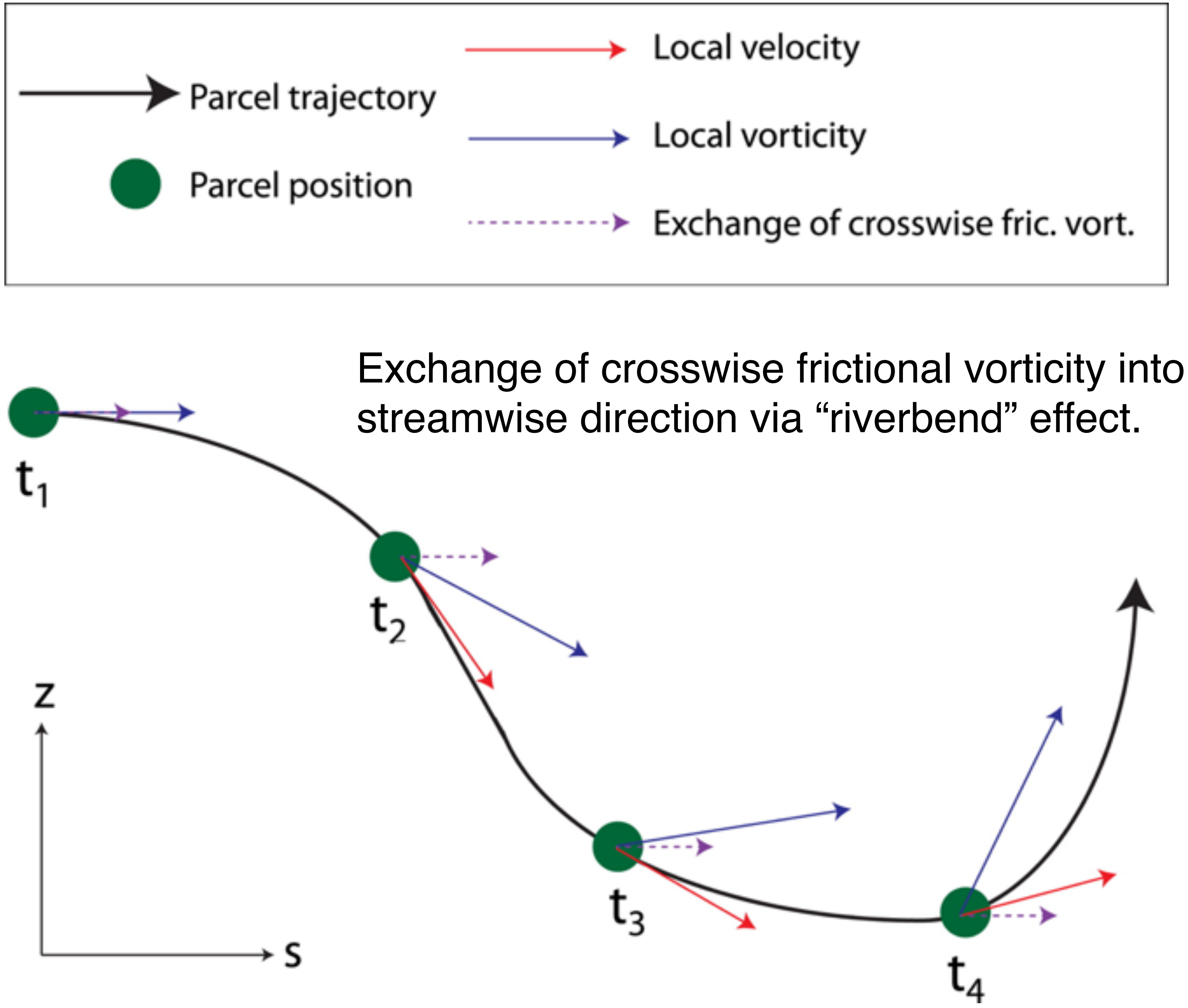
Turbulent

Crosswise > Streamwise





From Davies-Jones (1993): “Horizontal southward vorticity is being generated continually by the baroclinic effect (which introduces slippage between the fluid and vortex lines)” “…a combination of tilting and baroclinic generation causes the vorticity of parcels to change from anticyclonic to cyclonic while still descending.”



Exchange of crosswise frictional vorticity into streamwise direction via “riverbend” effect.

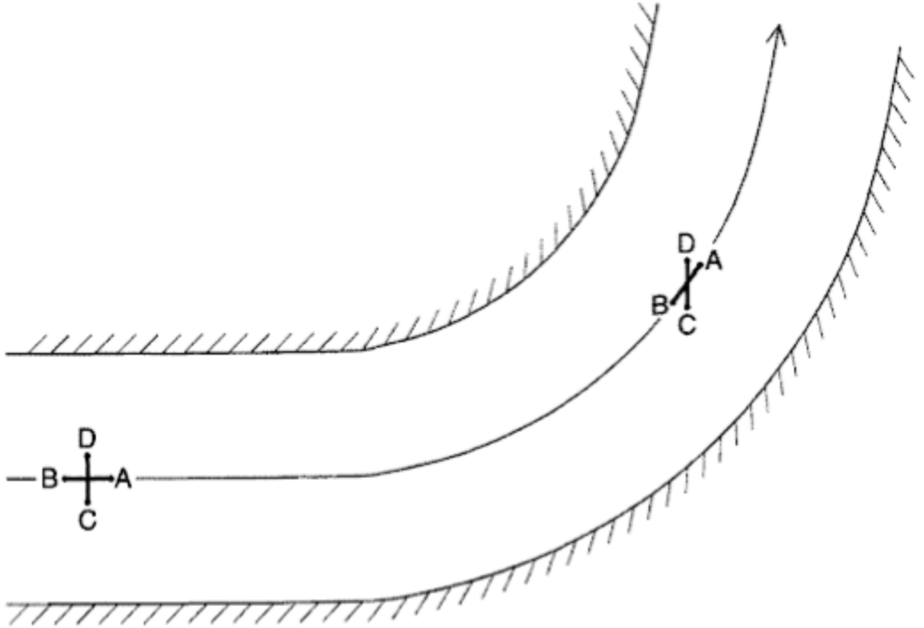


FIG. 5.15. Diagram of flow around a river bend, demonstrating the development of streamwise vorticity. Upstream of the bend the flow is parallel with speed shear (crosswise vorticity) owing to friction at the river bottom. Consider the fluid cross ABCD with arm AB along a streamline and CD along a vortex line. Since flow around the bend generates no vertical vorticity to a first approximation, the arms of the cross must rotate in opposite directions. Thus the vortex line CD turns toward the streamwise direction AB.

Roberts et al. (2016): The role of surface draft in tornadogenesis within an idealized supercell simulation

Stronger heat sink / cold pool

Larger cyclonic circulation
Negative buoyancy reduces vertical accelerations
Circulation displaced from strongest dynamic lifting

Weaker low-level shear

Dynamic VPPGF field substantially weaker
Circulation rich-air also more negatively buoyant

Weaker heat sink / cold pool

Smallest baroclinic generation of vorticity, circulation weak

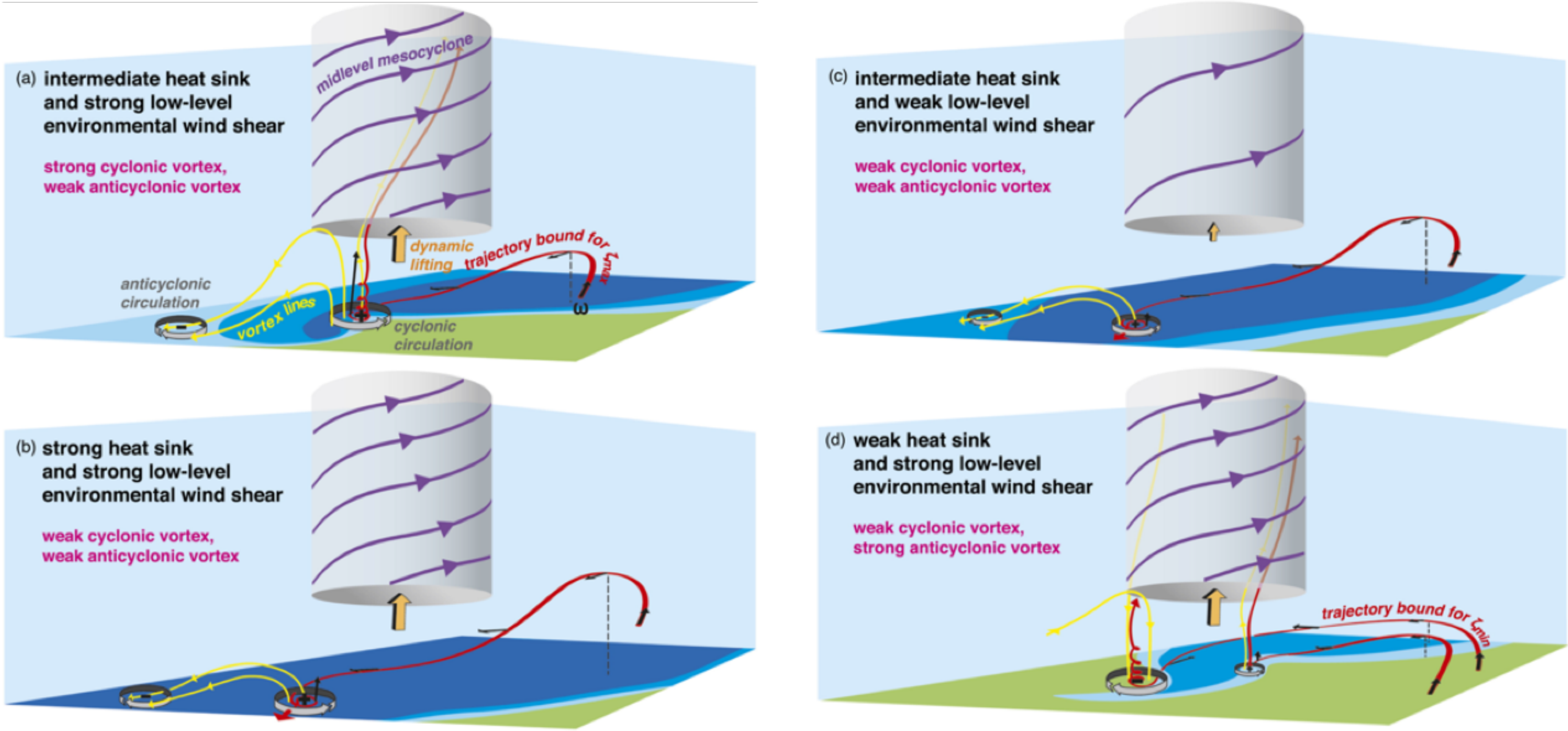
Summary

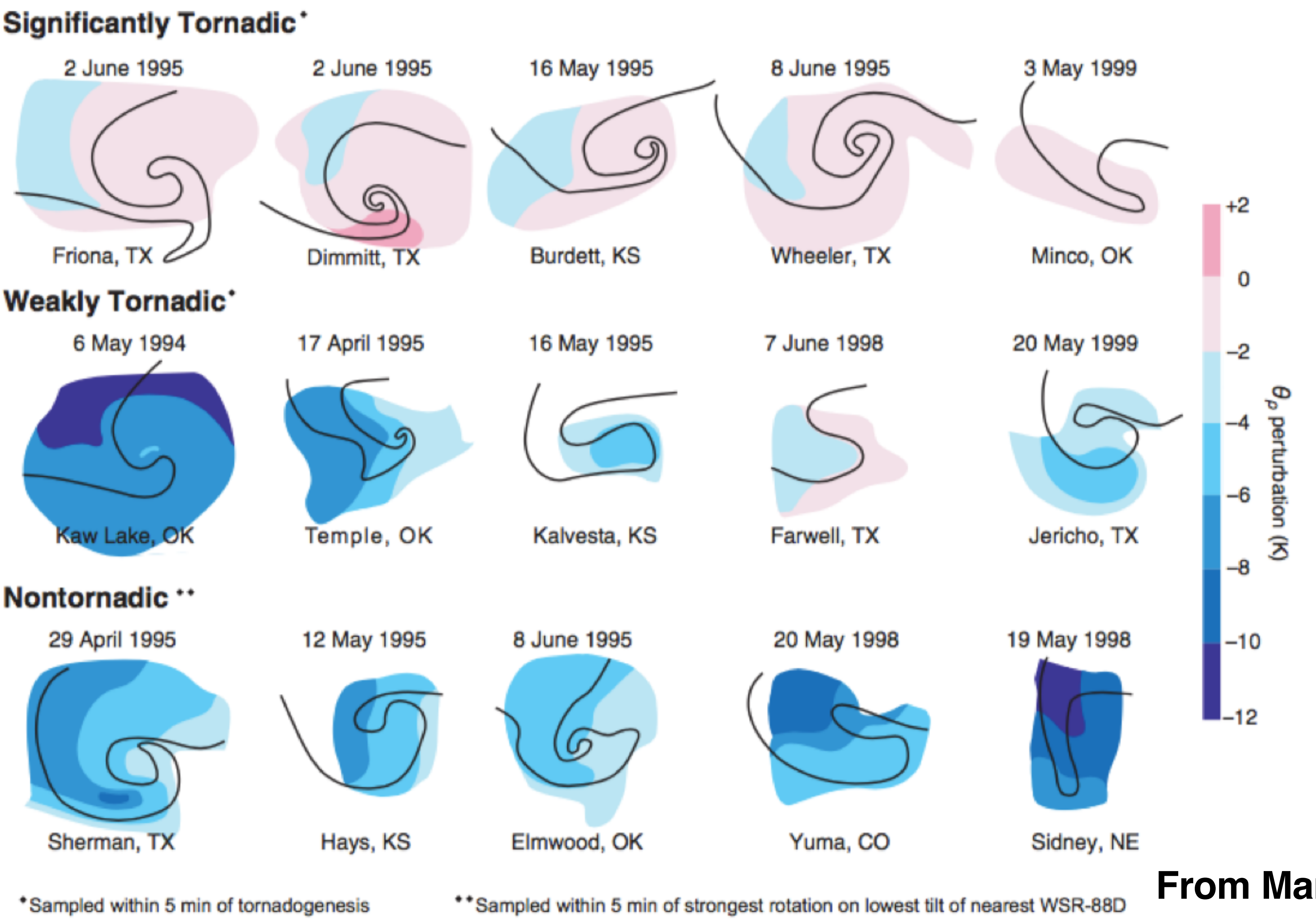
Development of near-surface vortex requires large near-surface stretching.

Need combination of large environmental shear to produce large VPPGF and modest cold pool buoyancy to colocate region of buoyancy-induced circulation and vertical stretching.

This colocation is extremely sensitive to buoyancy field, buoyancy gradients, and trajectories through region of negative buoyancy.

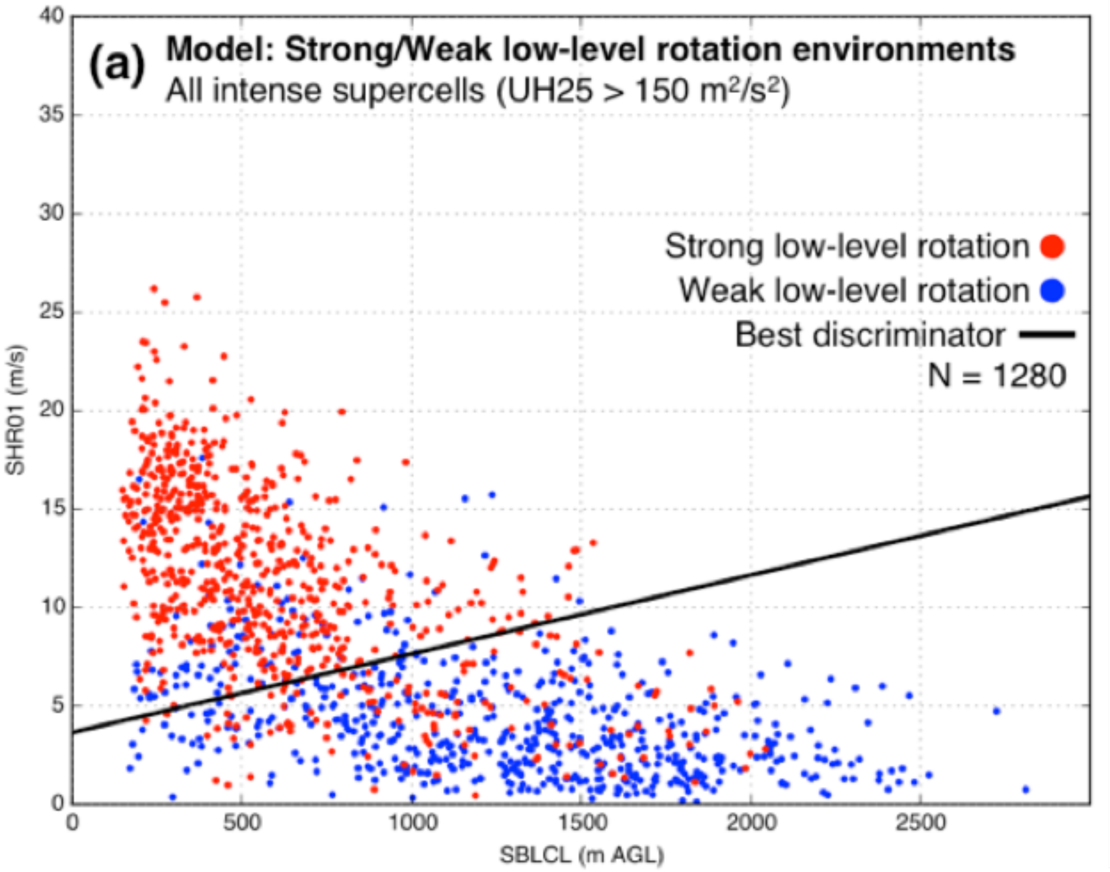
LCL height is often used as a proxy for potential cold pool strength…


(a) intermediate heat sink and strong low-level environmental wind shear
strong cyclonic vortex, weak anticyclonic vortex
midlevel mesocyclone
dynamic lifting
trajectory bound for ζ_{max}
anticyclonic circulation
vortex lines
cyclonic circulation
ω
(b) strong heat sink and strong low-level environmental wind shear
weak cyclonic vortex, weak anticyclonic vortex
(c) intermediate heat sink and weak low-level environmental wind shear
weak cyclonic vortex, weak anticyclonic vortex
(d) weak heat sink and strong low-level environmental wind shear
weak cyclonic vortex, strong anticyclonic vortex
trajectory bound for ζ_{min}



From Markowski et al. 2002

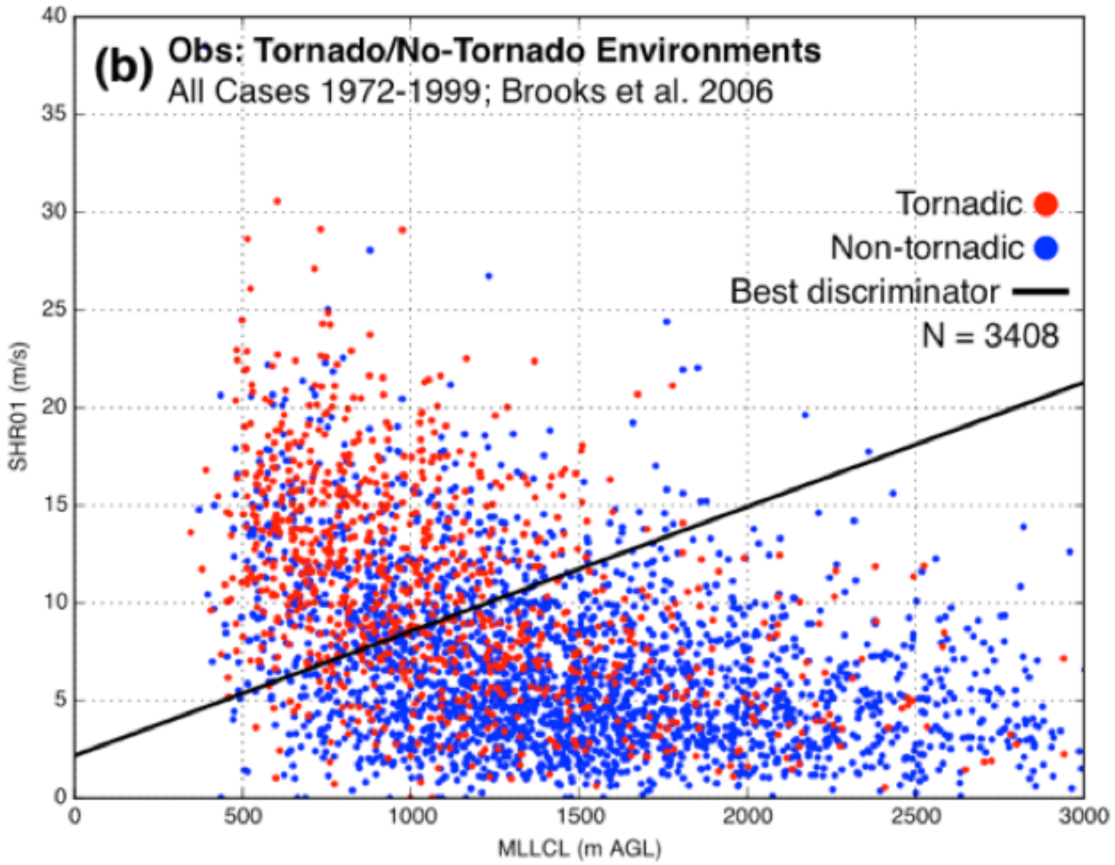
From high-resolution simulations



Adapted from Sobash et al. (2016)

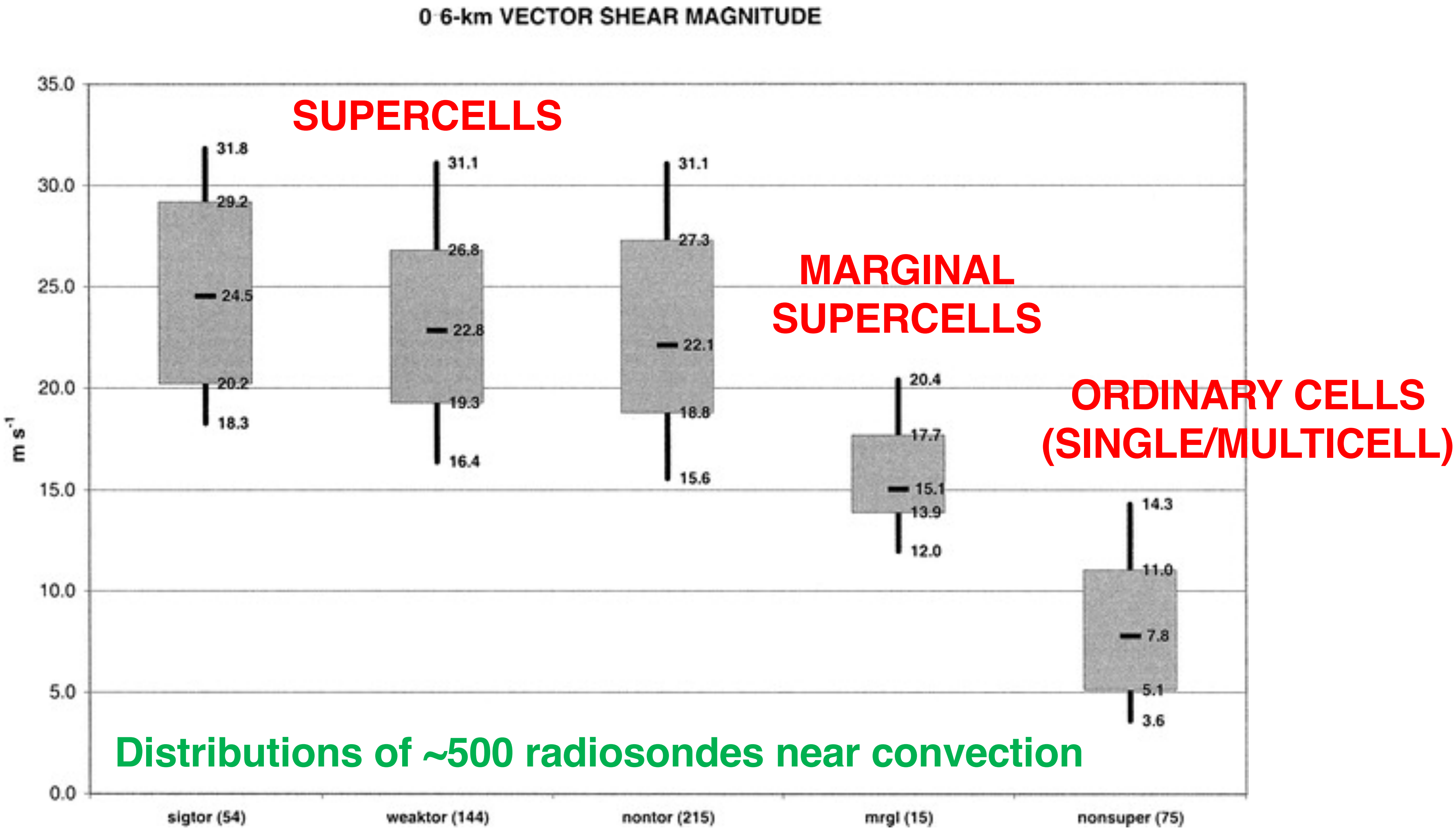
From observed soundings

Potential strength of VPPGF



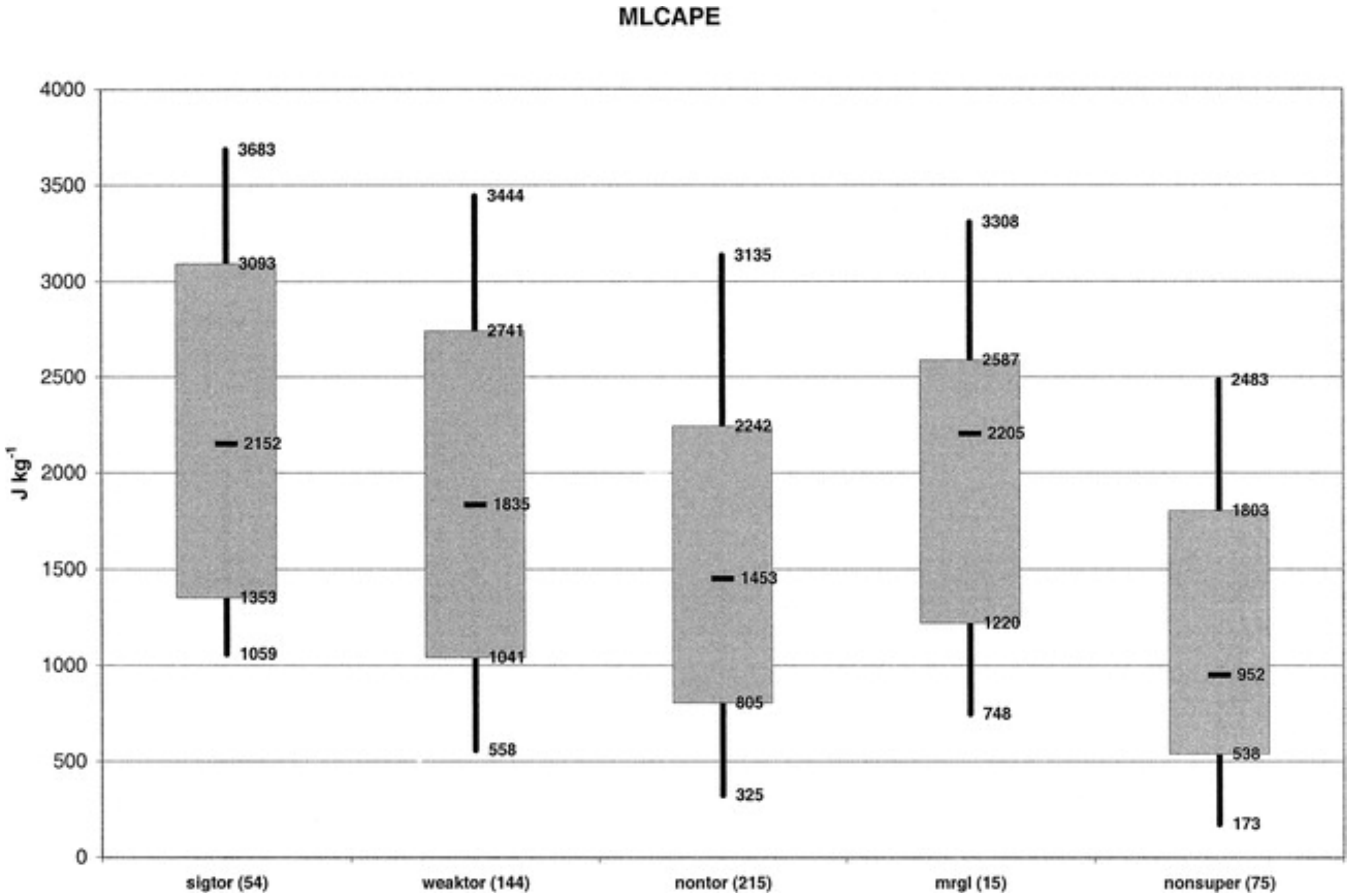
Potential cold pool strength

Discriminating Between Tornadic and Non-tornadic supercells



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

Discriminating Between Tornadic and Non-tornadic supercells



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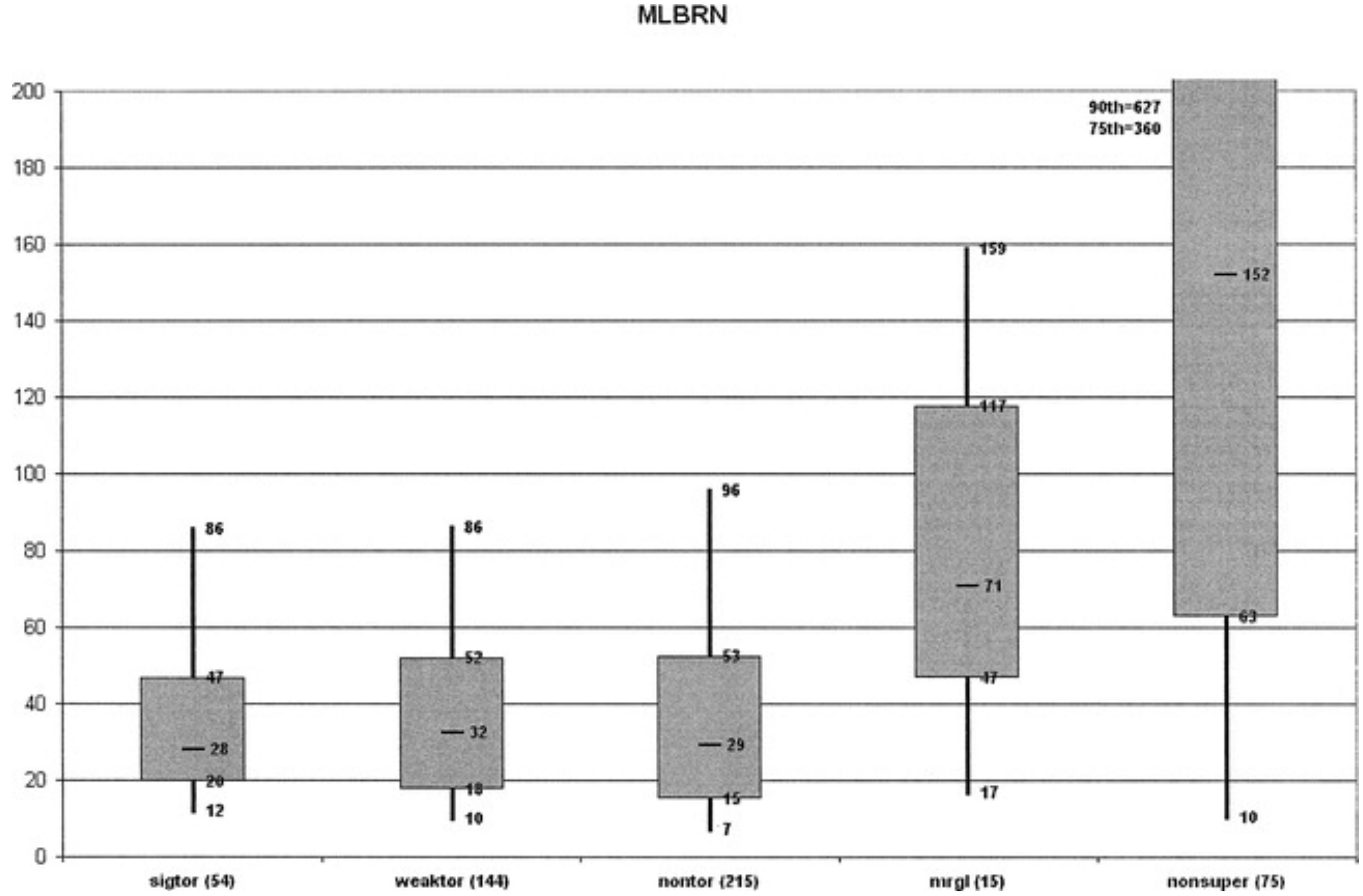

Thompson et al. (2003): "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle"

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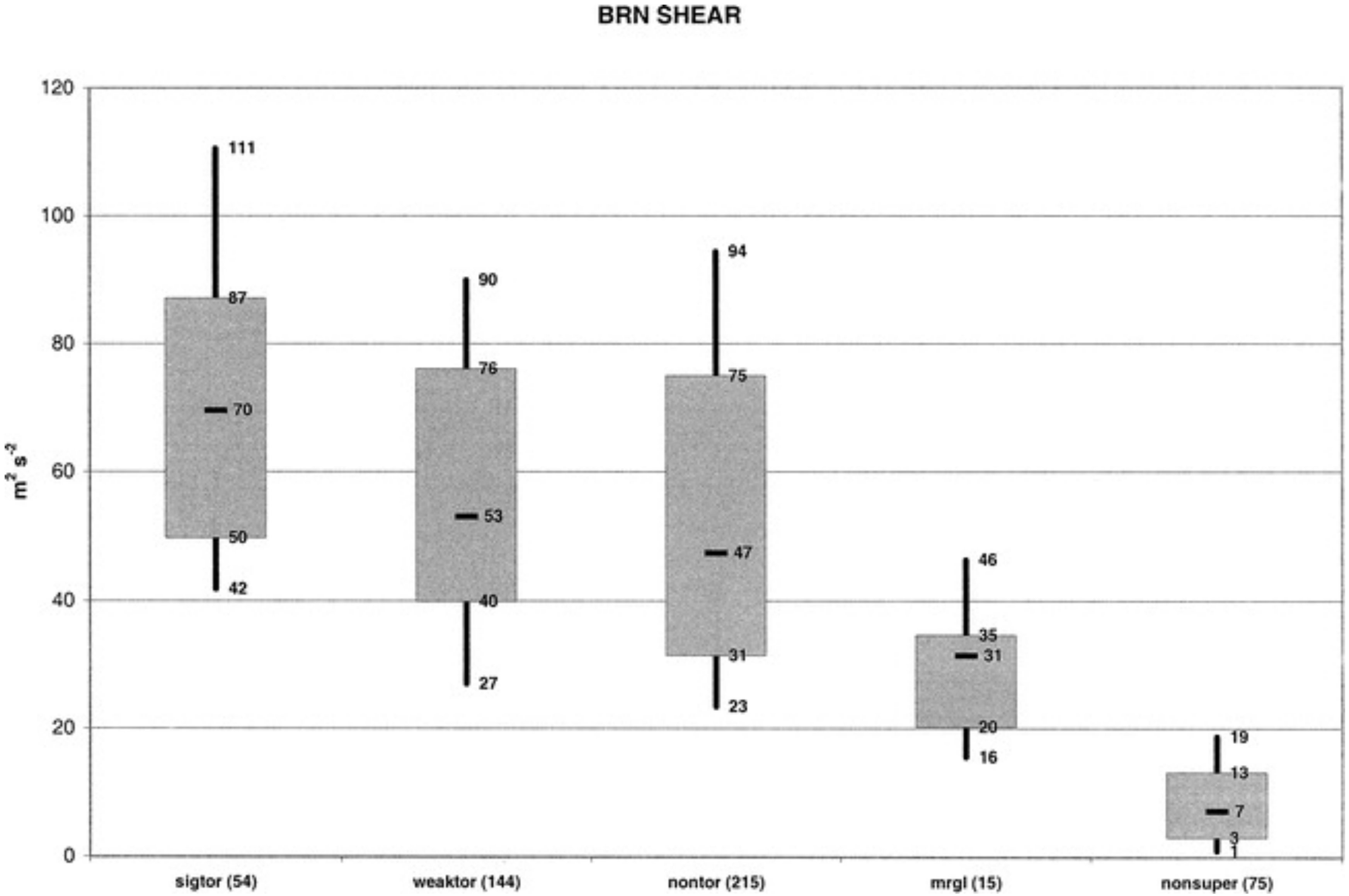

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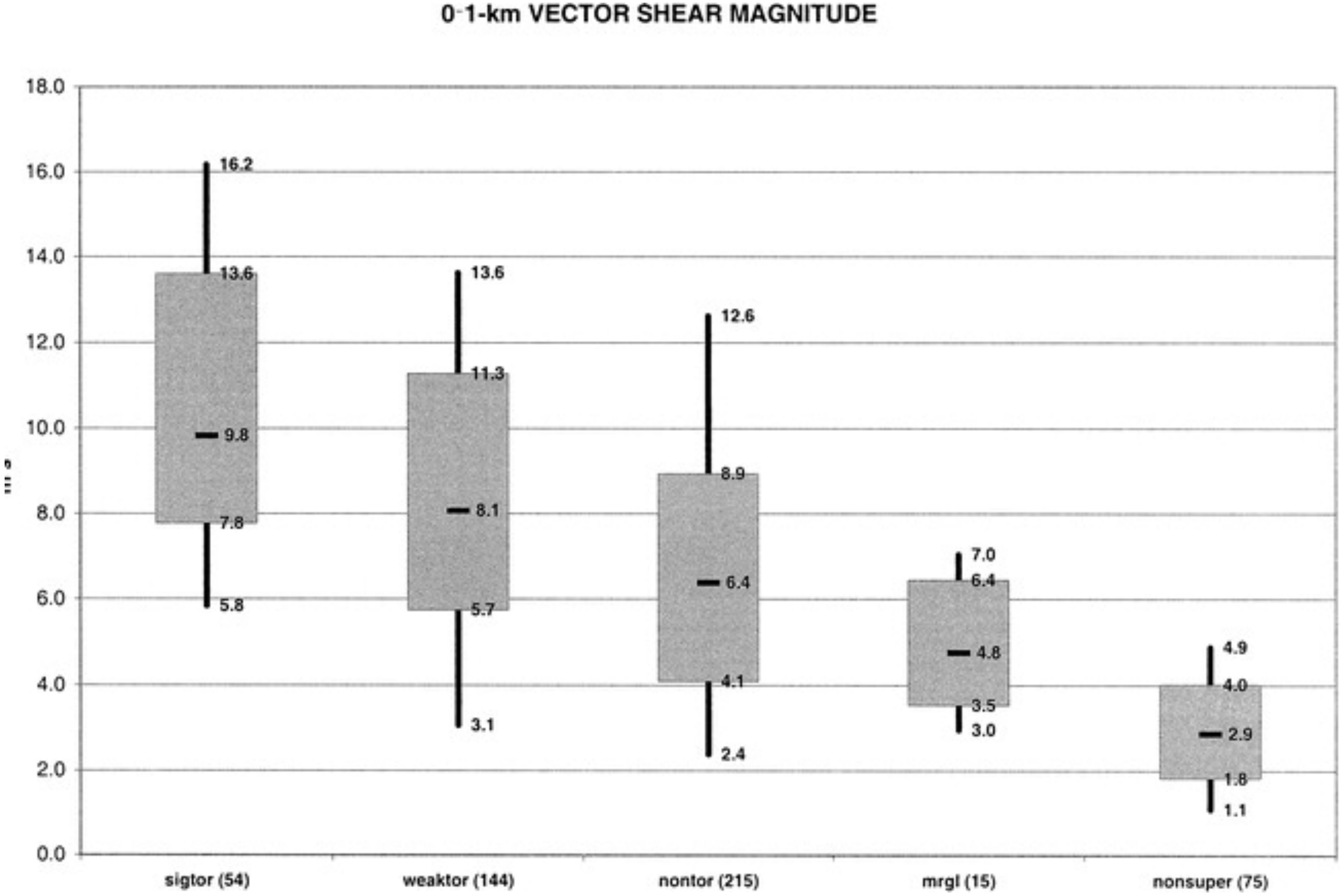

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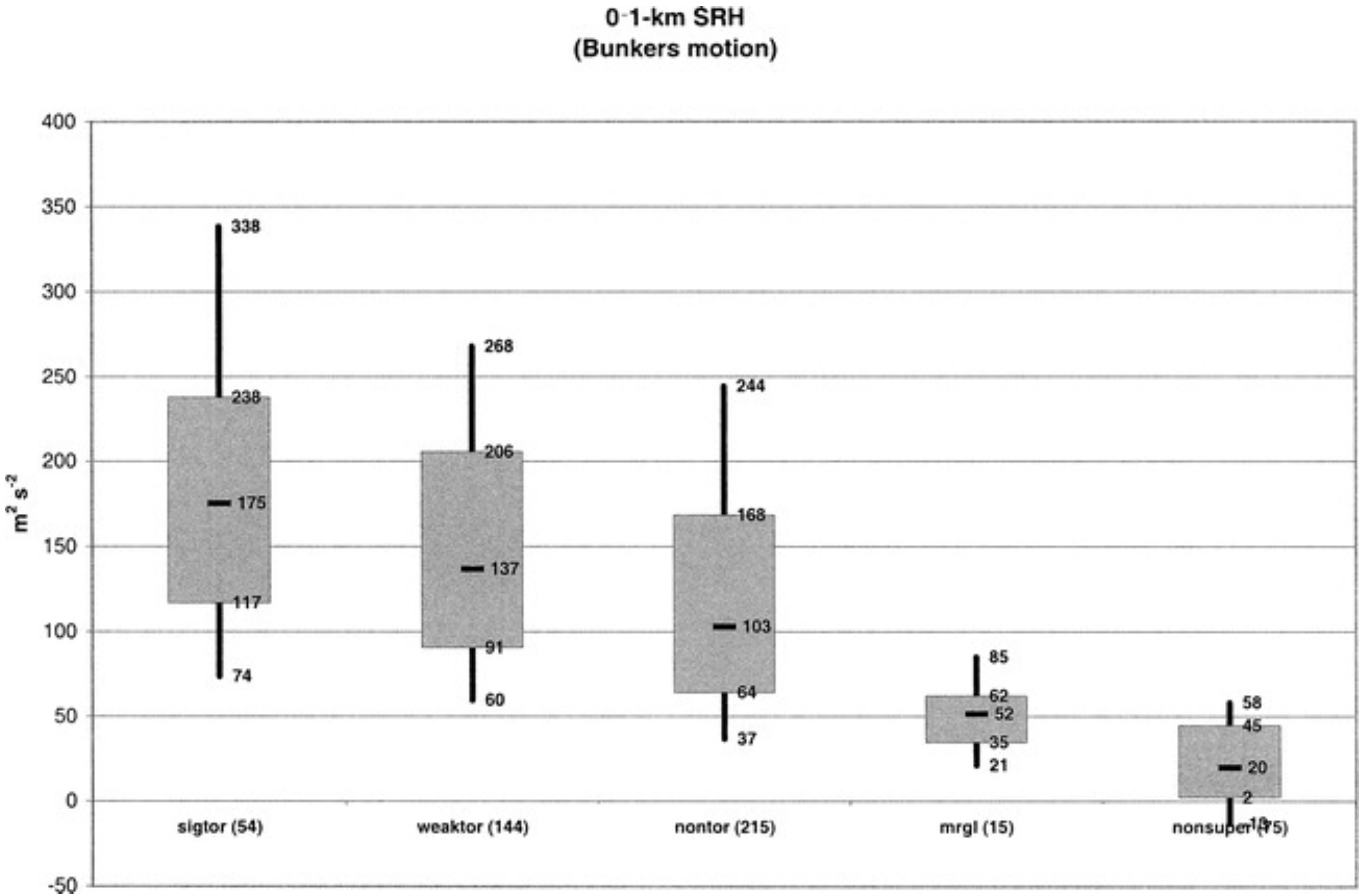

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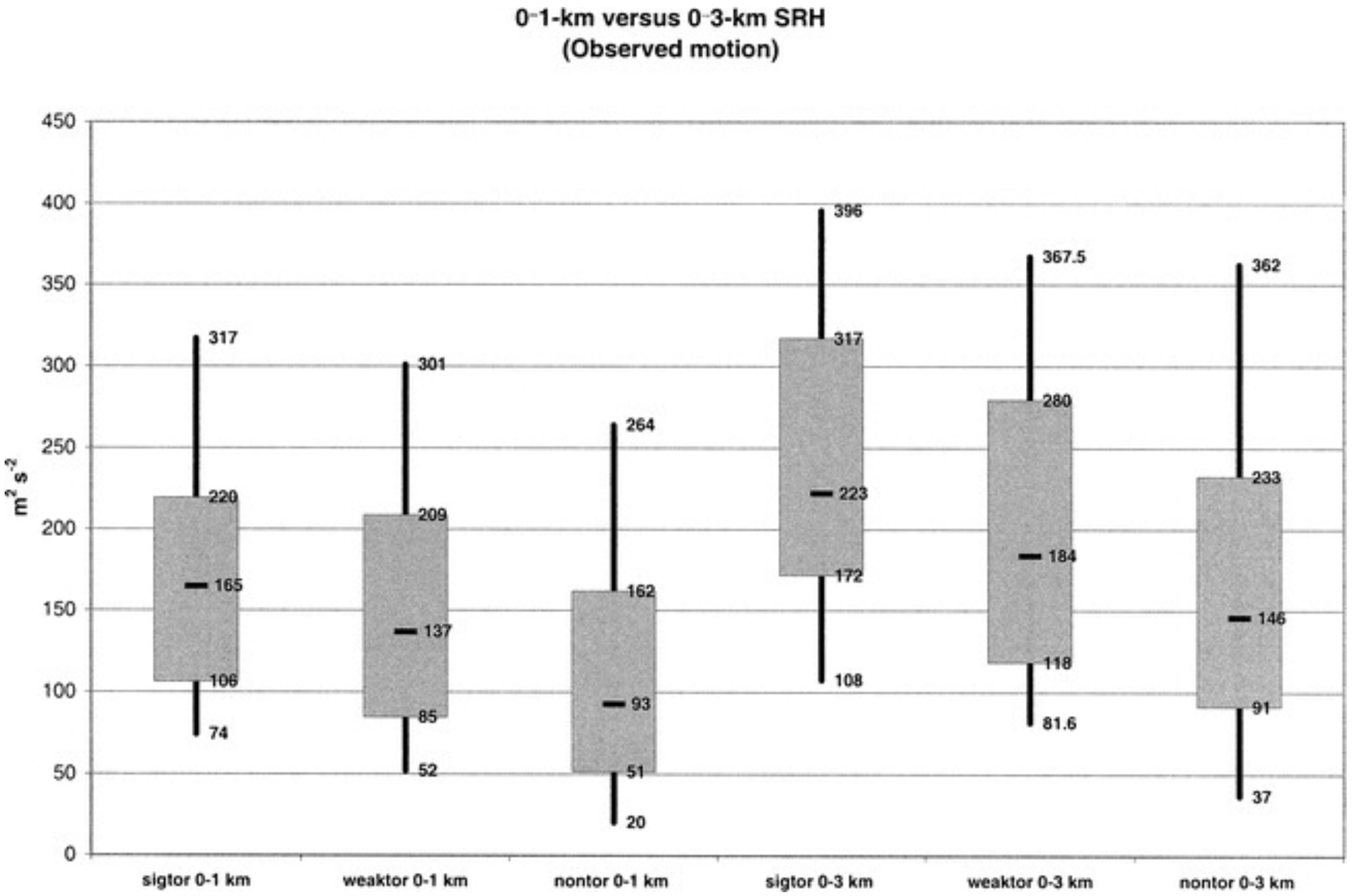

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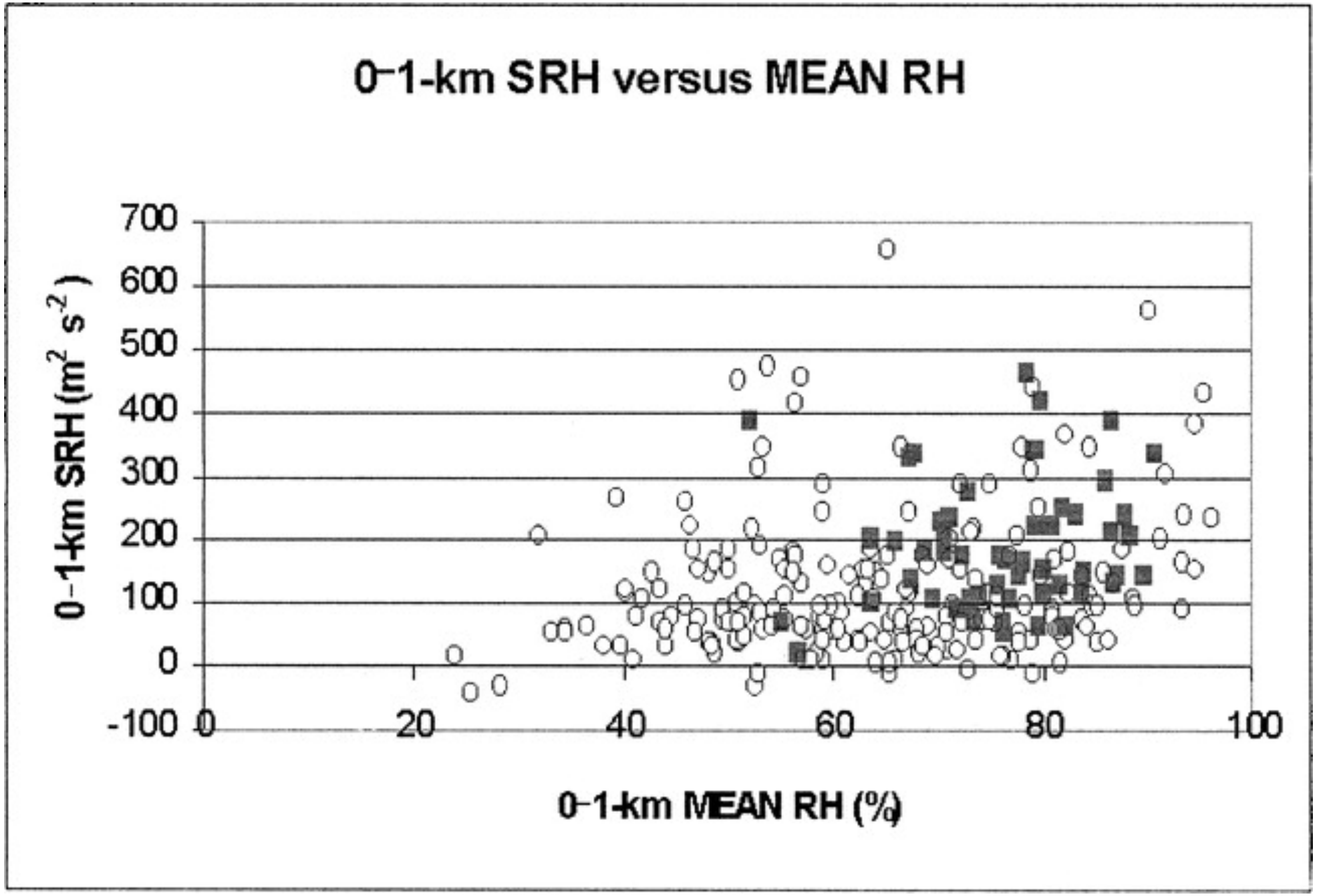

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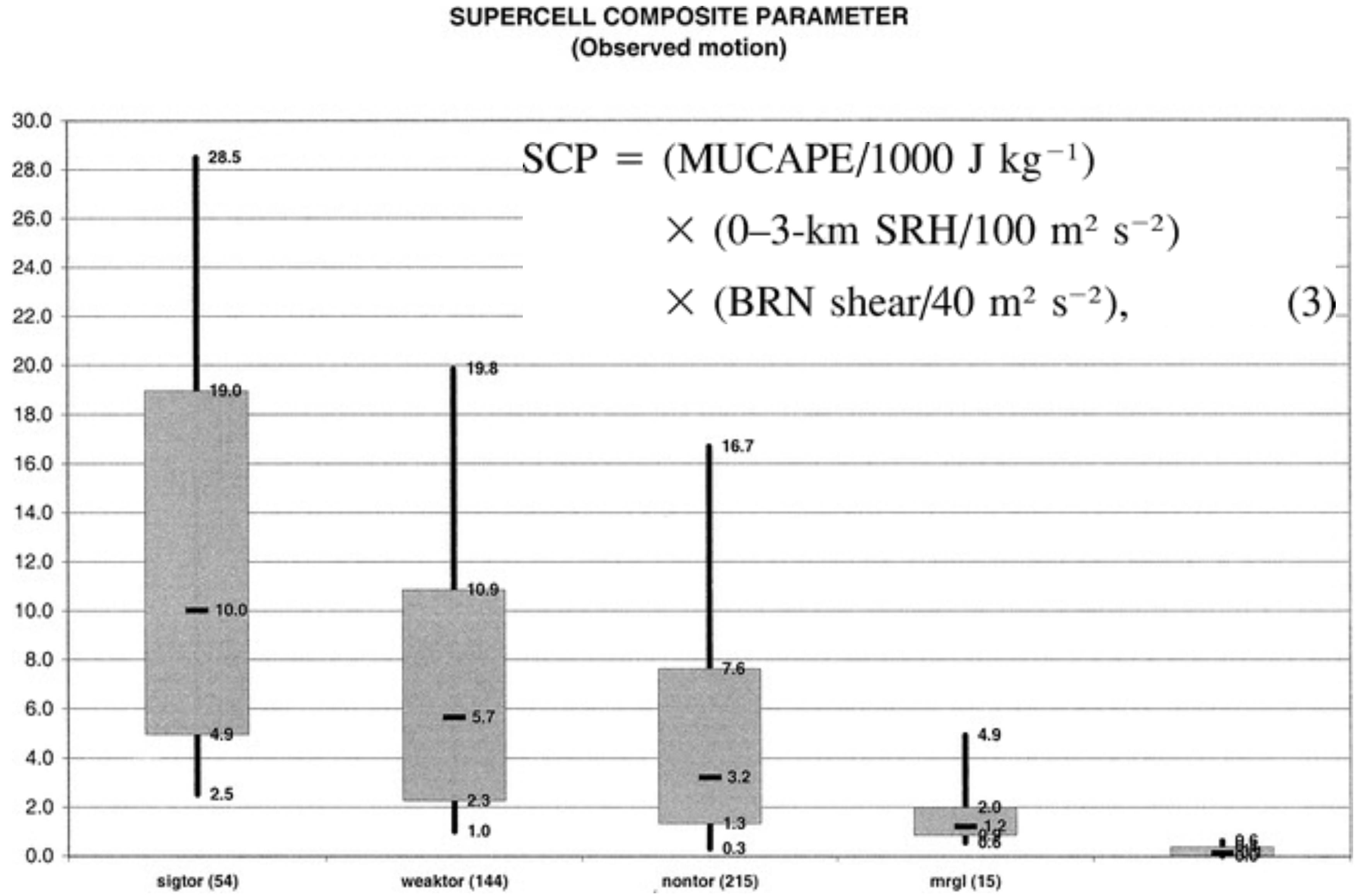

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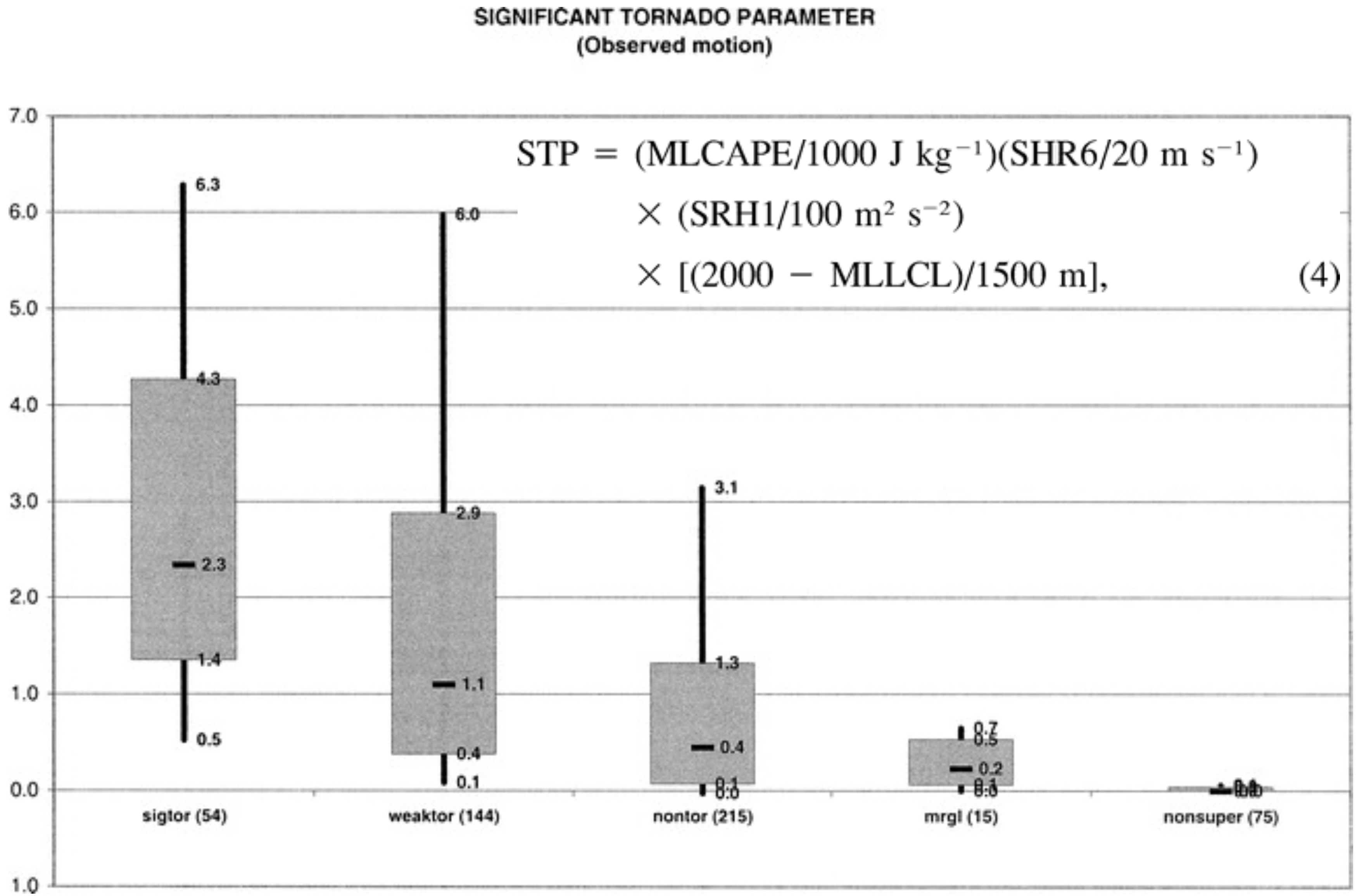
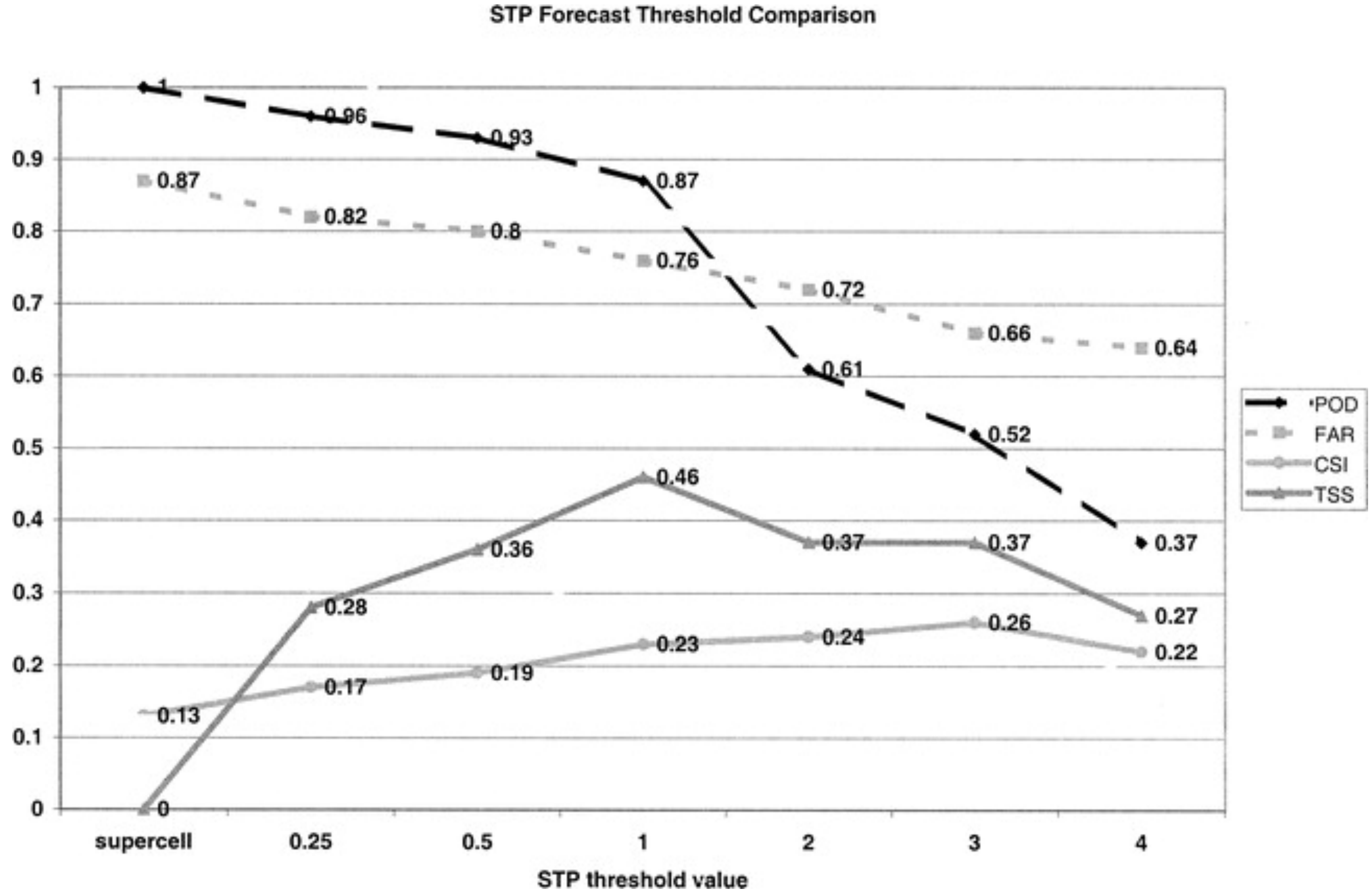
Discriminating Between Tornadic and Non-tornadic supercells



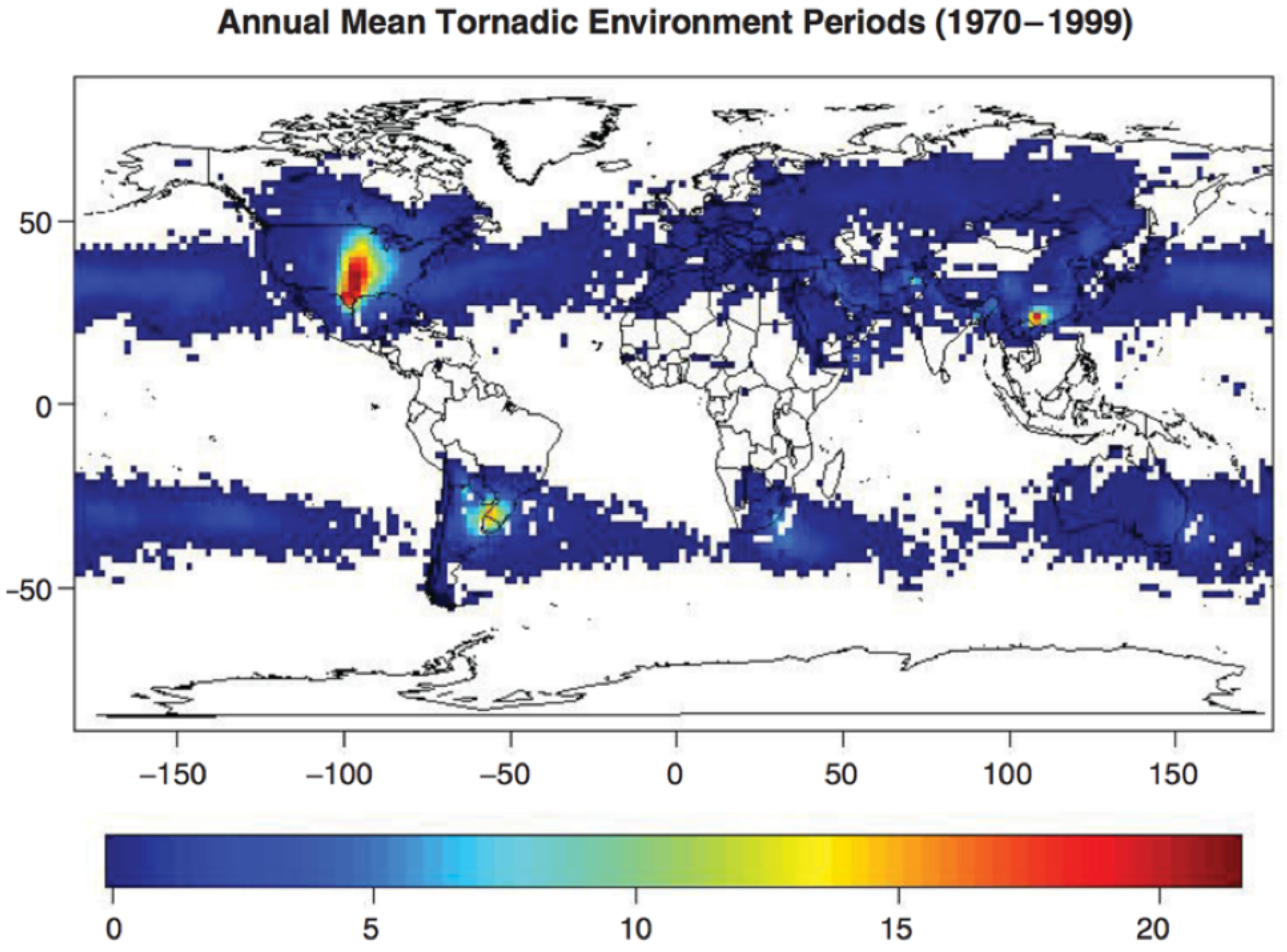
$$\mathrm{STP} = (\mathrm{MLCAPE}/1000\ \mathrm{J\ kg^{-1}})(\mathrm{SHR6}/20\ \mathrm{m\ s^{-1}}) \times (\mathrm{SRH1}/100\ \mathrm{m^2\ s^{-2}}) \times [(2000 - \mathrm{MLLCL})/1500\ \mathrm{m}], \qquad (4)$$

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

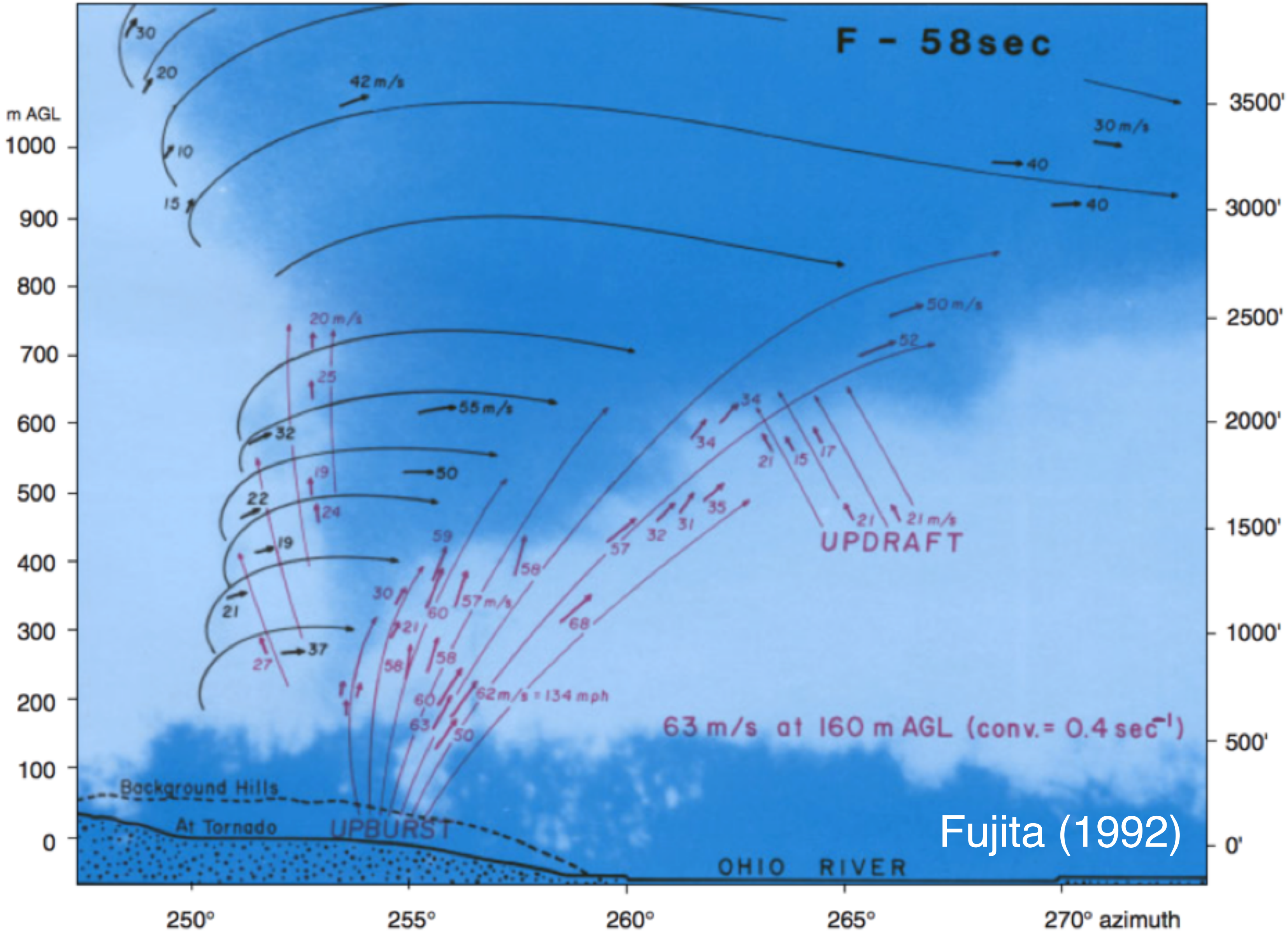
Discriminating Between Tornadic and Non-tornadic supercells



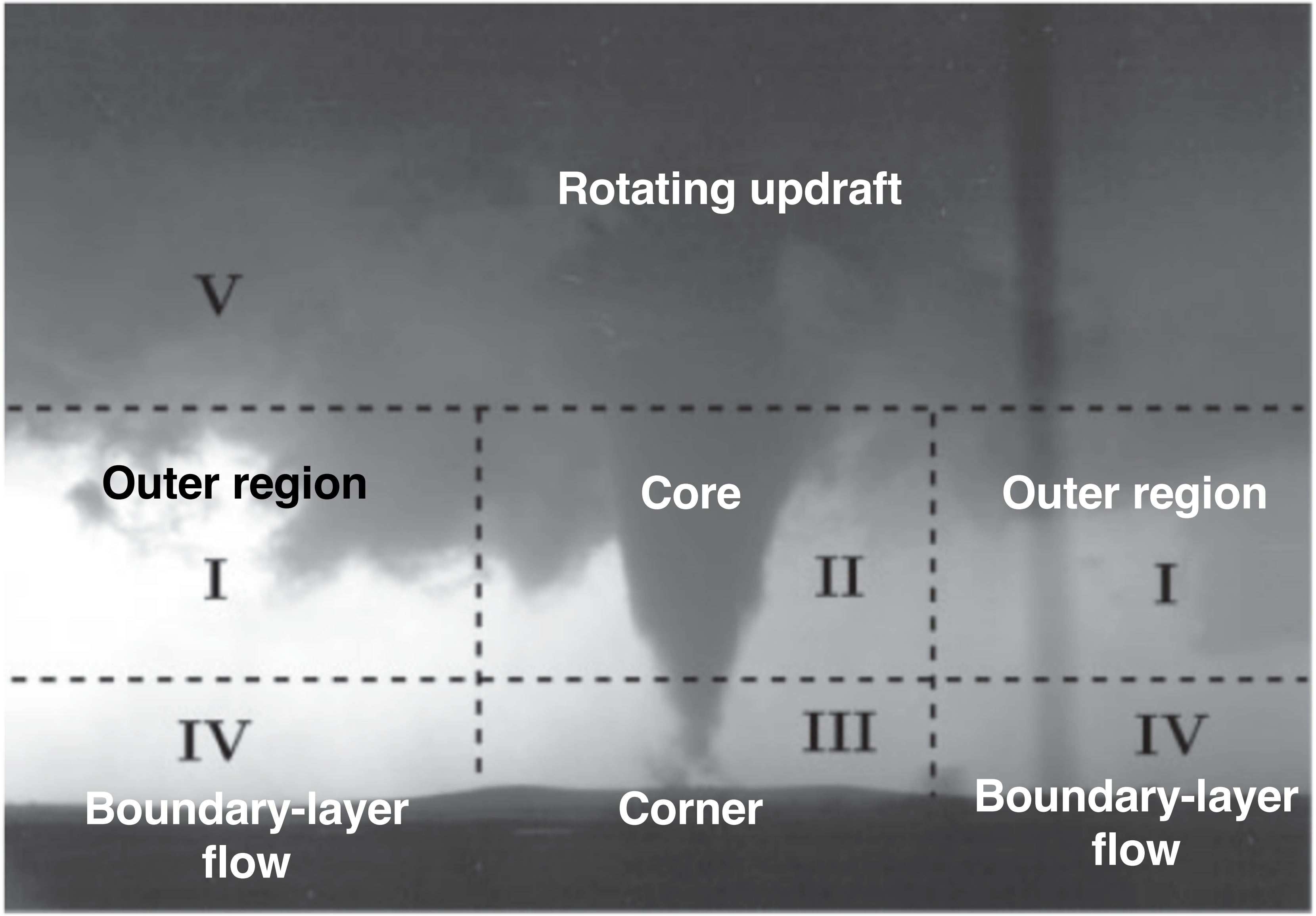
Thompson et al. (2003): “Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle”


Annual Mean Tornadic Environment Periods (1970−1999)
50
0
−50
−150
−100
−50
0
50
100
150
0
5
10
15
20

Photogrammetric analysis of wind velocities



Flow regions in tornadoes



Region I:
Angular momentum conservation

Region II:
Cyclostrophic balance

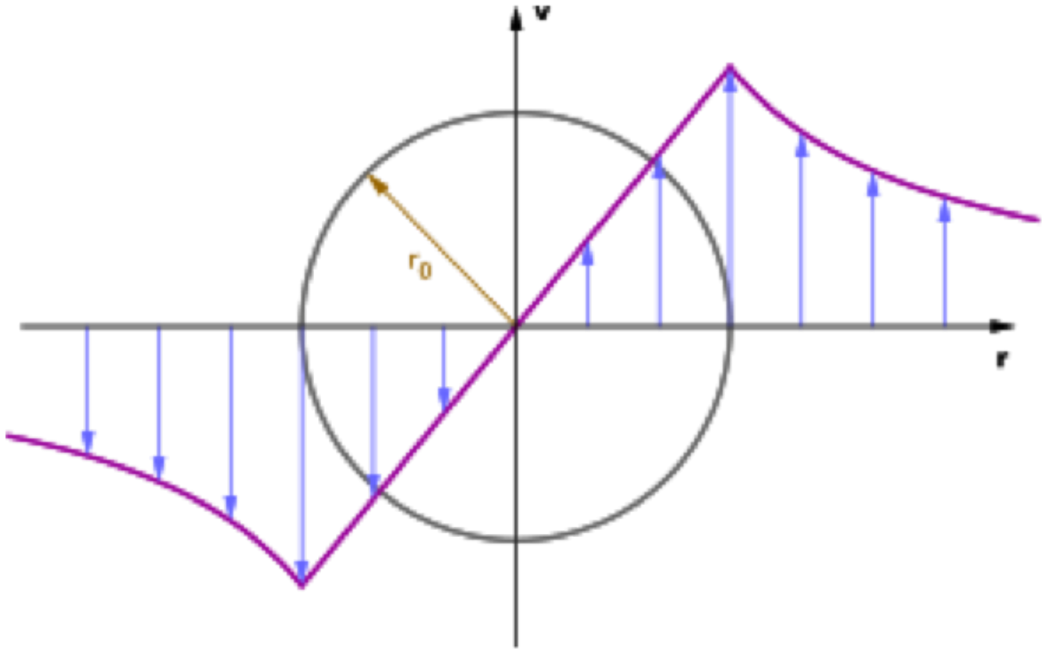
Region III:
Flow sharply “turns corner”

Region IV:
Radial inflow in boundary-layer flow due to friction disrupts cyclostrophic balance.

Region V:
Parent updraft above tornado.

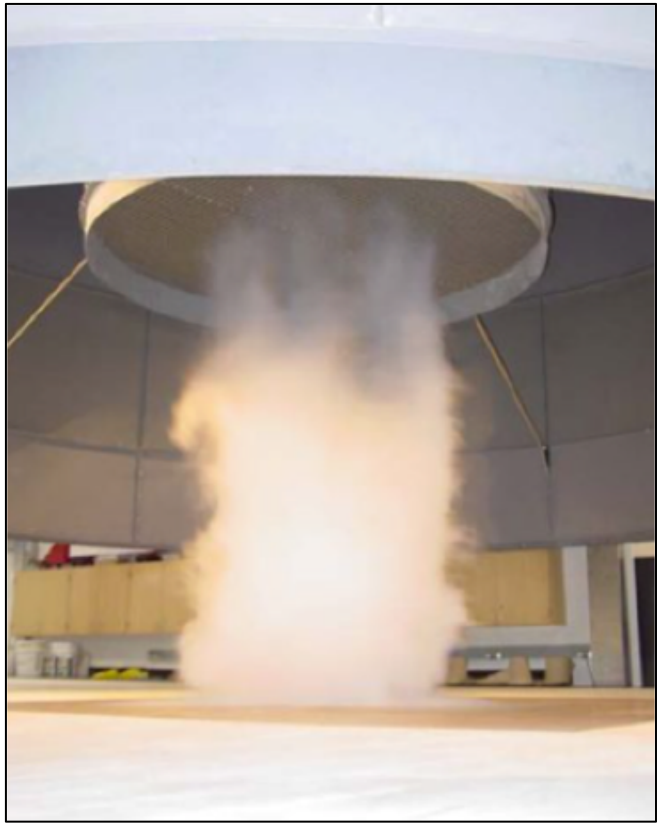
Tornadoes modeled as a Rankine vortex

Pressure / velocity relationship in tornadoes in modeled as a Rankine vortex:



Can derive formulas for pressure as a function of r…

Tornado structure and core observations



Tornado vortex chamber studies were primary source of quantitative information regarding tornado structure.

Two important parameters:

C = circulation of flow about the central axis
Q = rate of air flow through the chamber top

Define the **swirl ratio, S,** as,

$$S = \frac{r_0 C}{2Q} = \frac{v_0}{w_0}$$

$\mathbf{r_0}$ – radius of vortex
$\mathbf{v_0}$ – tangential velocity at r_0
$\mathbf{w_0}$ – mean w at top of chamber

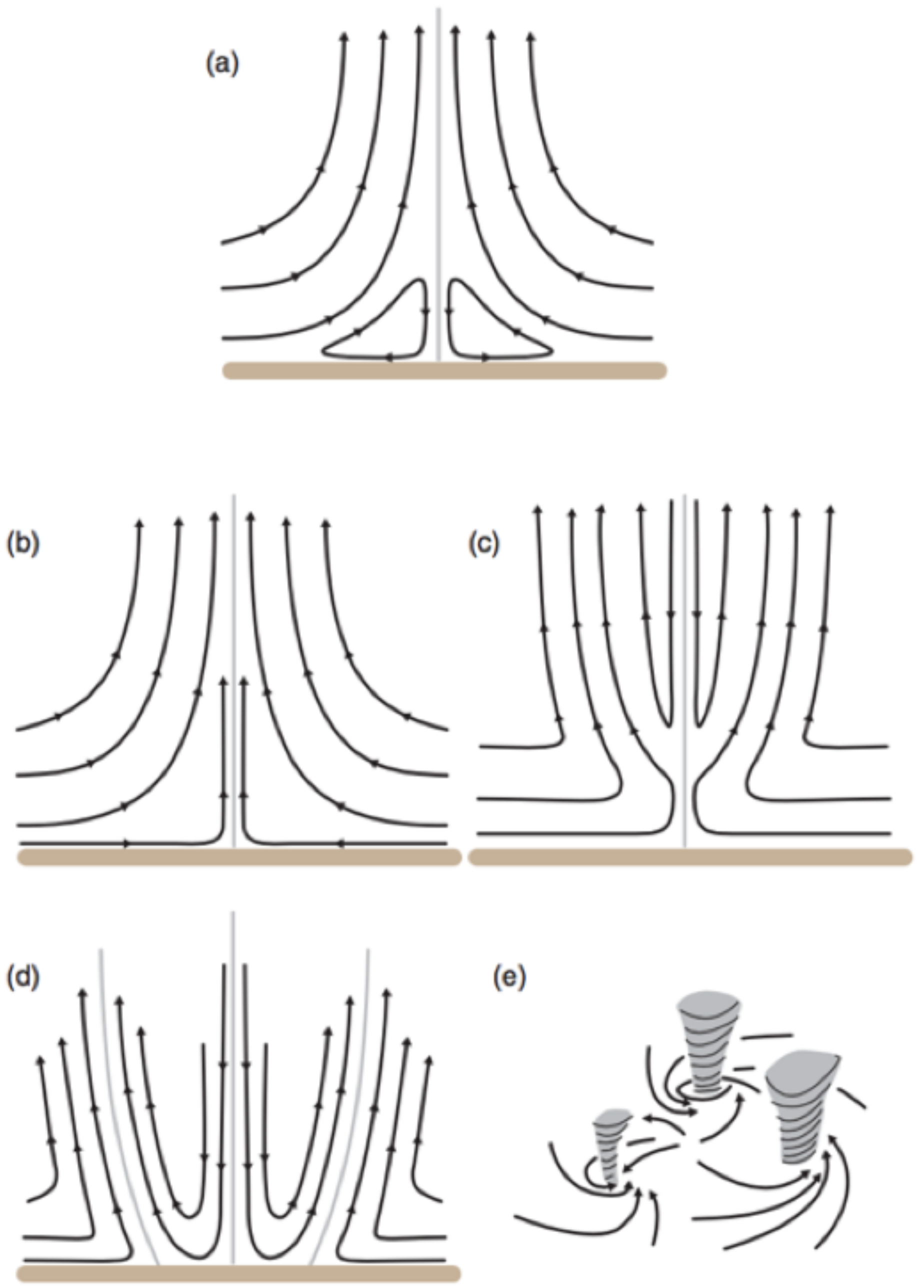
Tornado structure

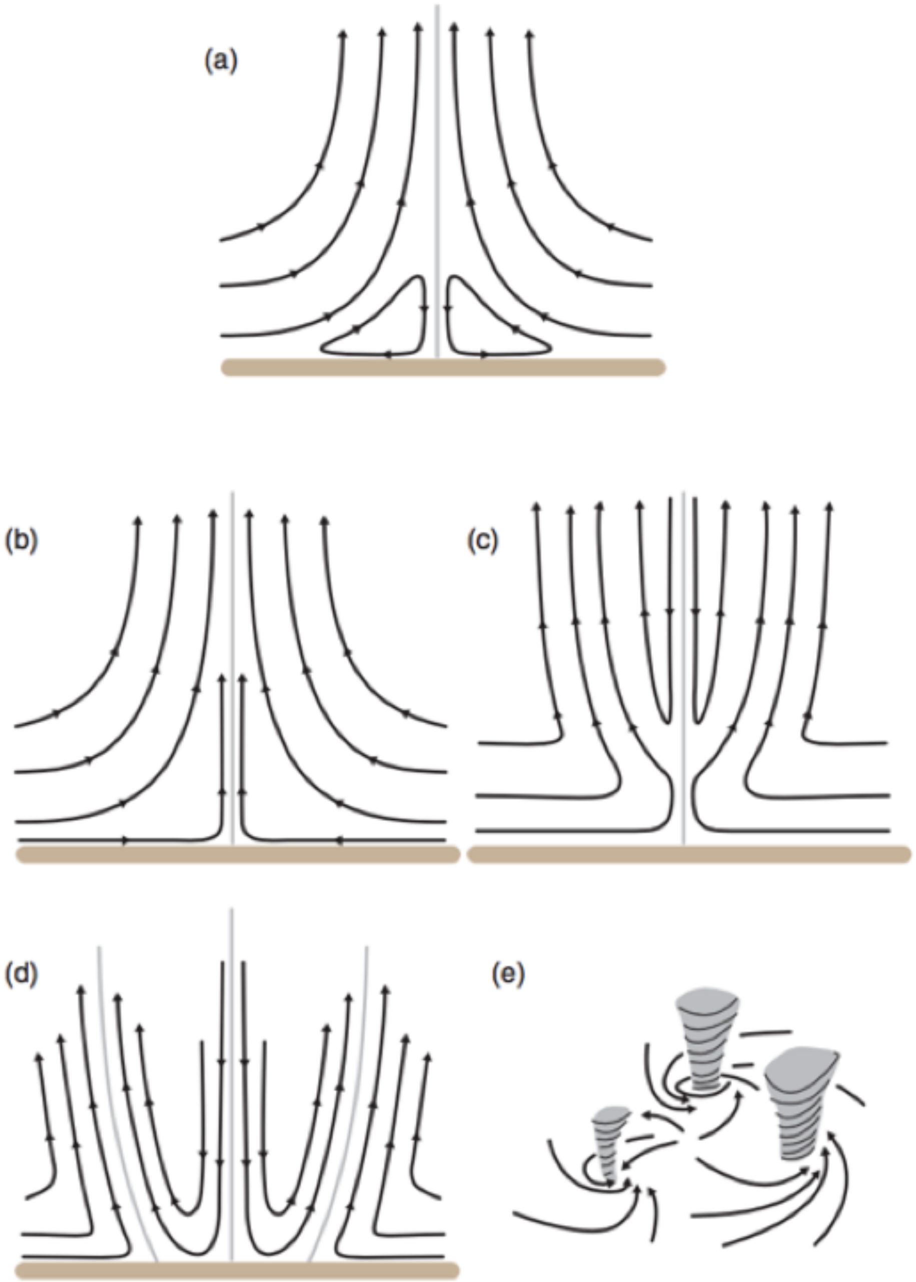
(a) **S** is small, updraft dominates over rotation, no rotation at surface (surface flow rises above surface).

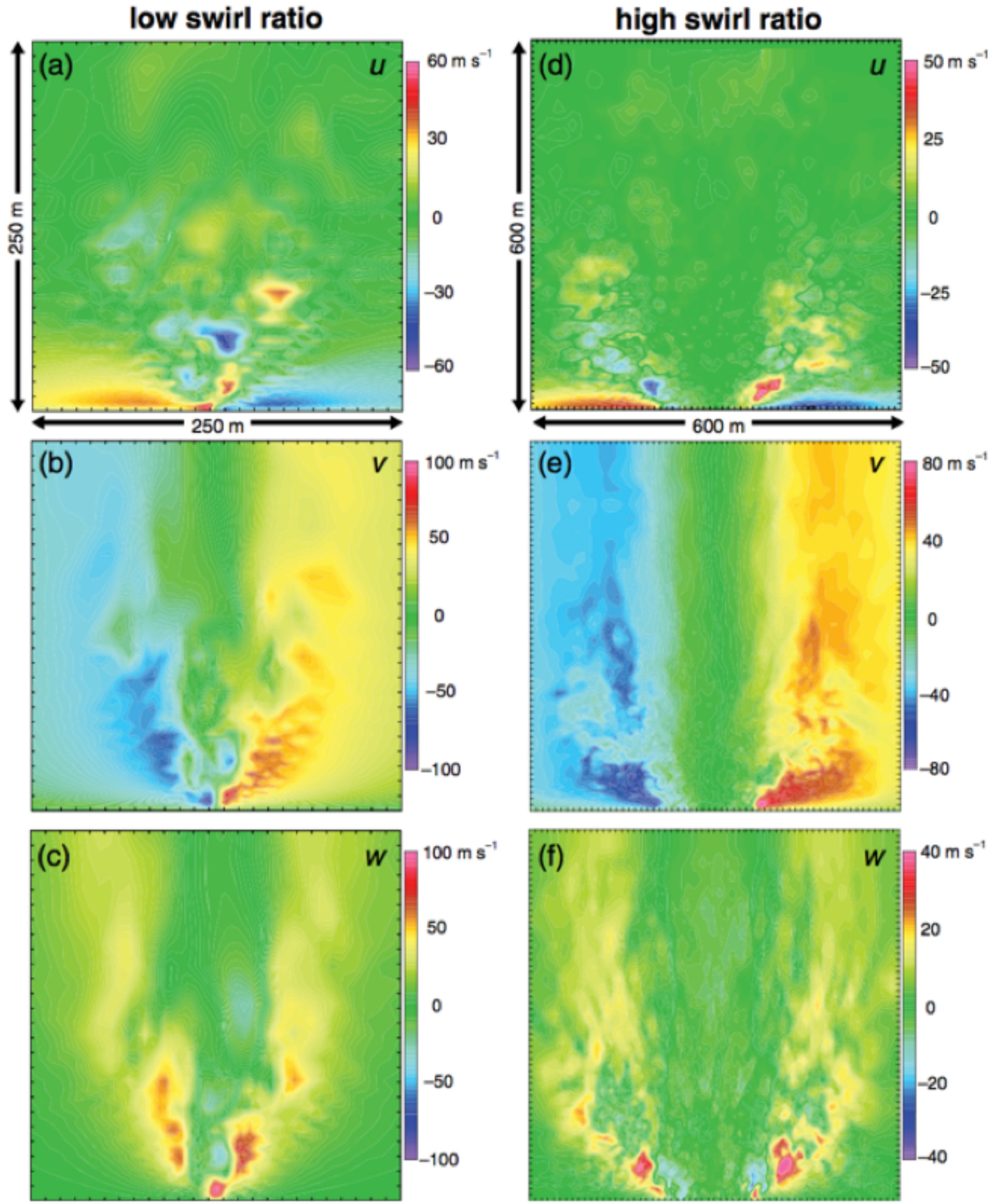
(b) **S** is increased, a vortex develops at the surface (one-cell vortex, one updraft). Surface flow penetrates to axis.

(c) **S** is increased further, downdraft develops within central axis, producing hollow center to the tornado

(d-e) **S** is very large, the downdraft penetrates the surface and creates a two-celled vortex. This results in multiple suction vortices. Process one-cell to two-cells is termed *vortex breakdown*.




(a)
(b)
(c)
(d)
(e)


low swirl ratio
high swirl ratio
(a)
u
60 m s⁻¹
30
0
–30
–60
250 m
250 m
(d)
u
50 m s⁻¹
25
0
–25
–50
600 m
600 m
(b)
v
100 m s⁻¹
50
0
–50
–100
(e)
v
80 m s⁻¹
40
0
–40
–80
(c)
w
100 m s⁻¹
50
0
–50
–100
(f)
w
40 m s⁻¹
20
0
–20
–40