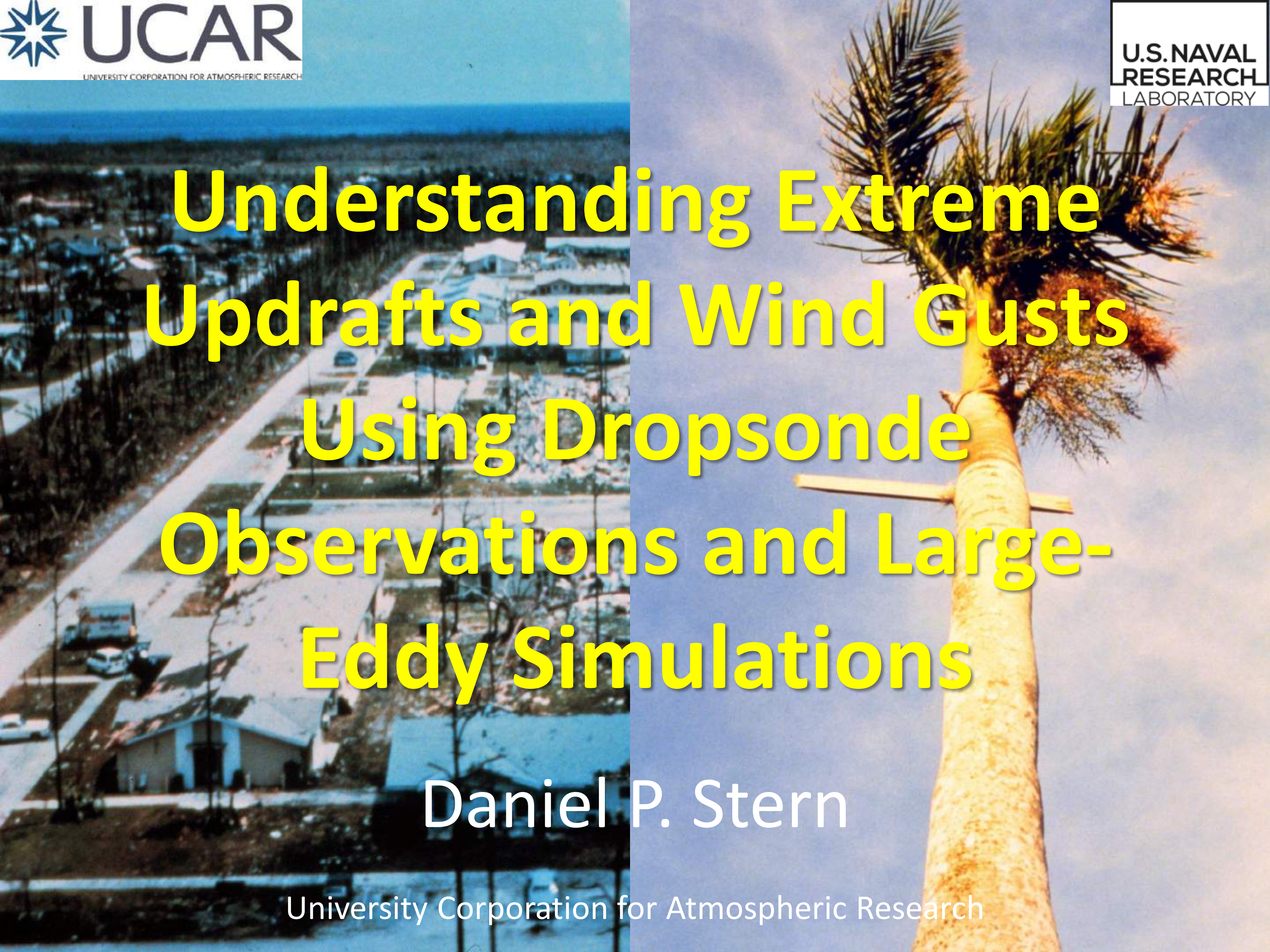


Understanding Extreme Updrafts and Wind Gusts Using Dropsonde Observations and Large-Eddy Simulations

Daniel P. Stern

University Corporation for Atmospheric Research

Outline of Topics

1. Overview of how we observe TCs
2. Dropsonde observations of extreme updrafts and wind gusts
3. Using Large-Eddy Simulations (LES) to understand the structure and dynamics of updrafts, wind gusts, and associated vortices.

Strong hurricanes can cause tremendous wind damage, and this damage can be extremely localized.

Hurricane Andrew (1992): Category 5

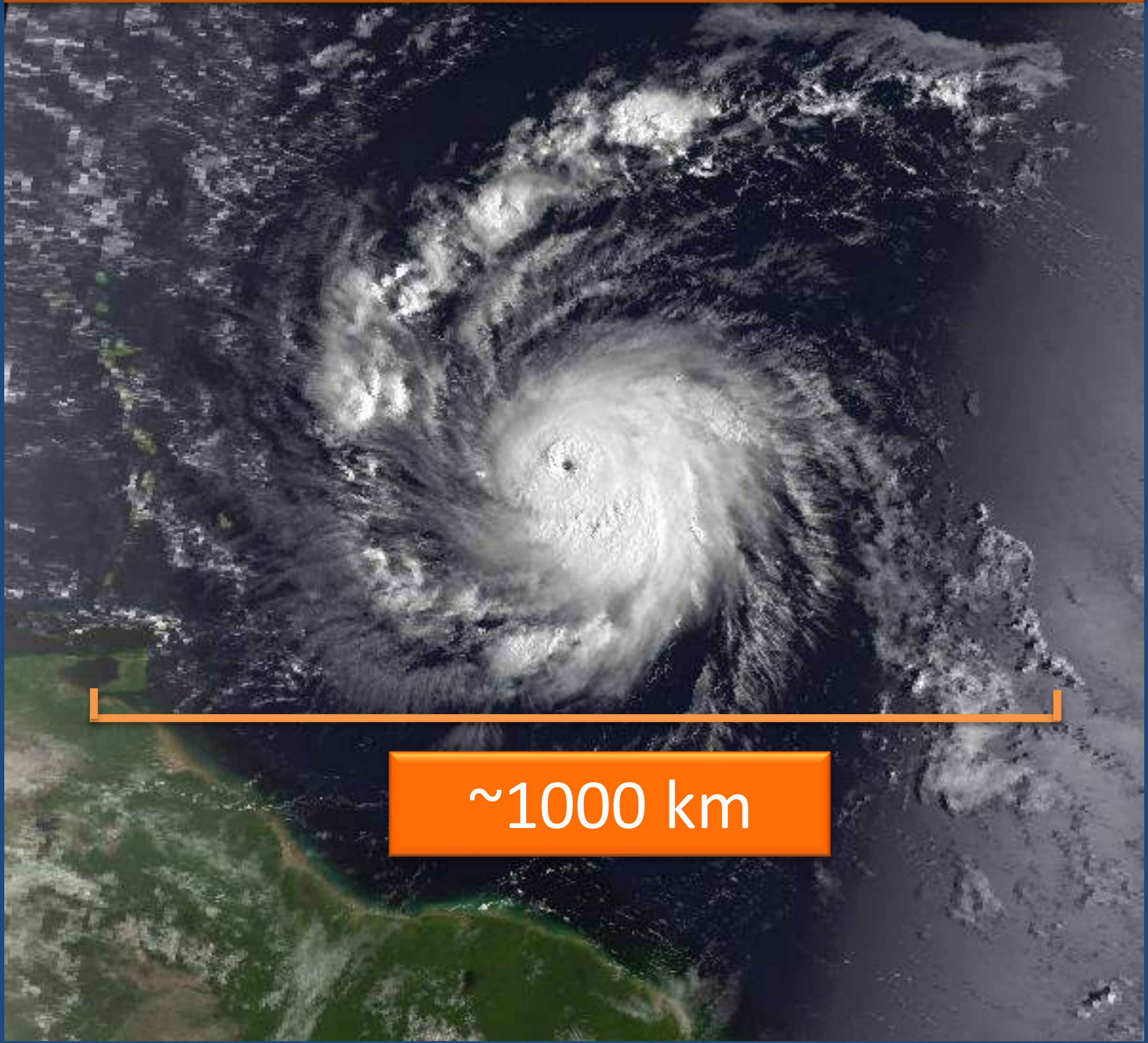
Hurricane Andrew (1992): Category 5

Hurricane Wilma (2005): Category 1

Hurricane Wilma (2005): Category 1

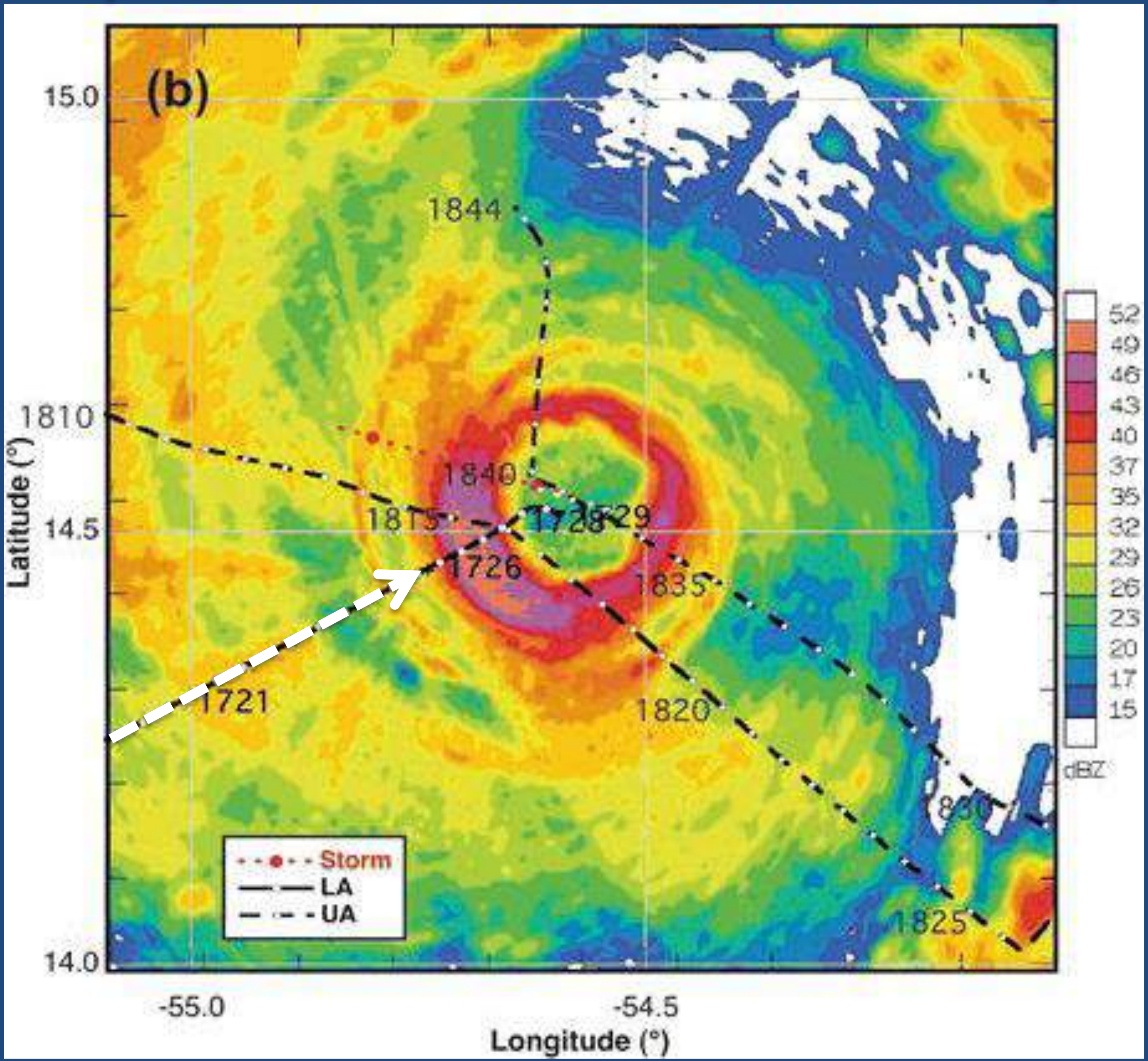
How Do We Observe Tropical Cyclones?

Hurricane Hugo (1989)



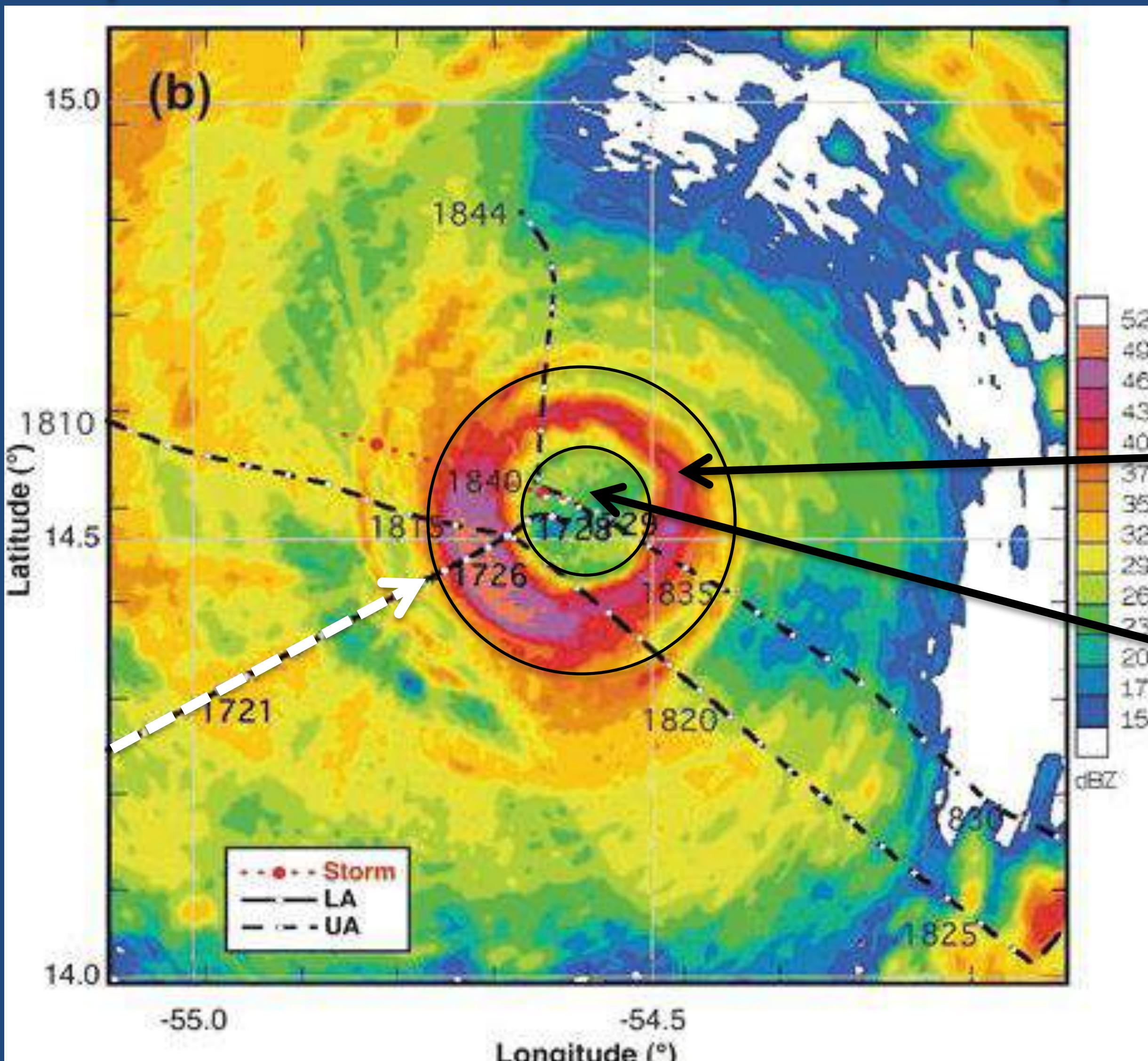
NOAA P3 Hurricane Hunters

120 km



Marks et al. (2008)

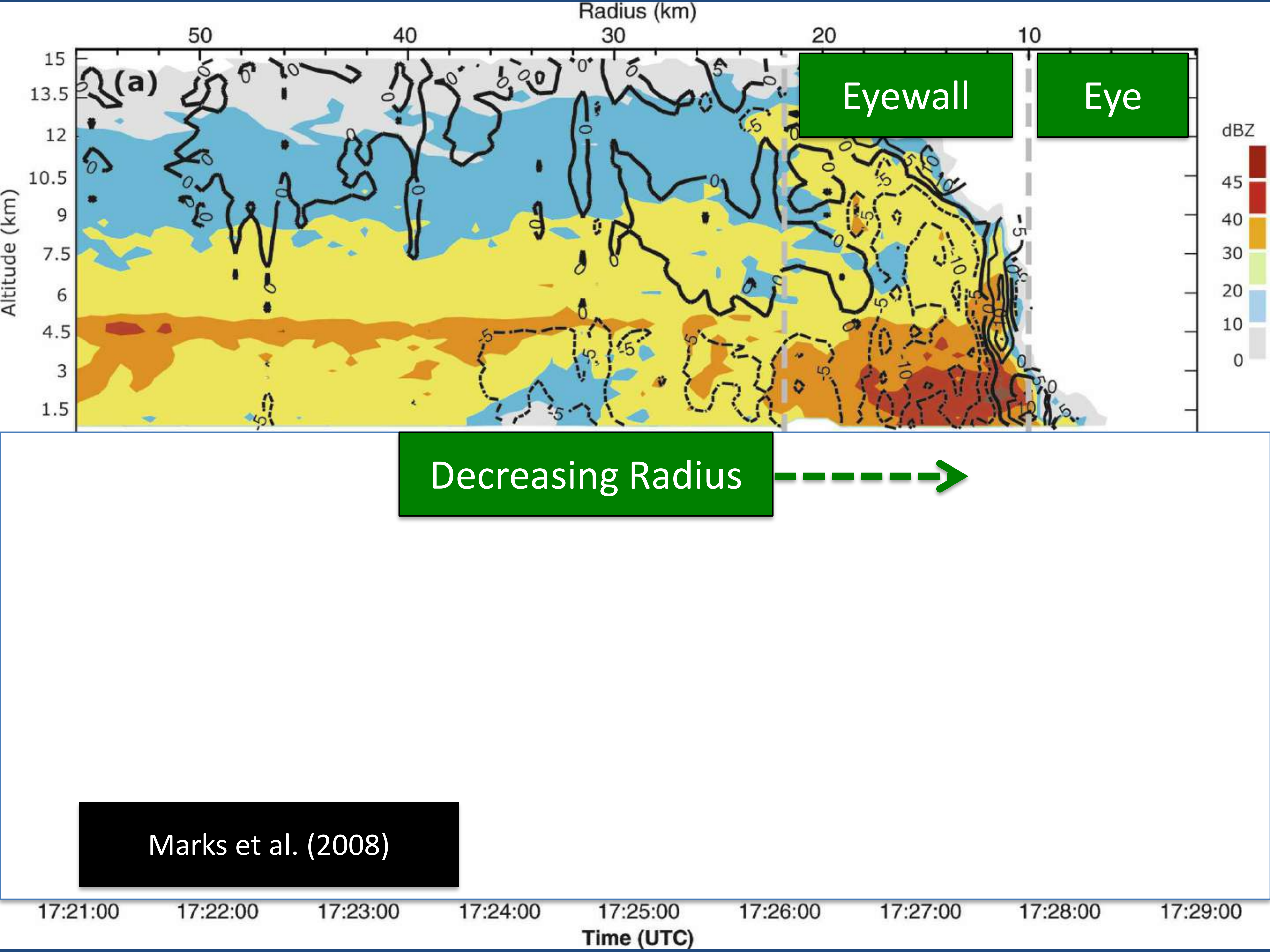
120 km



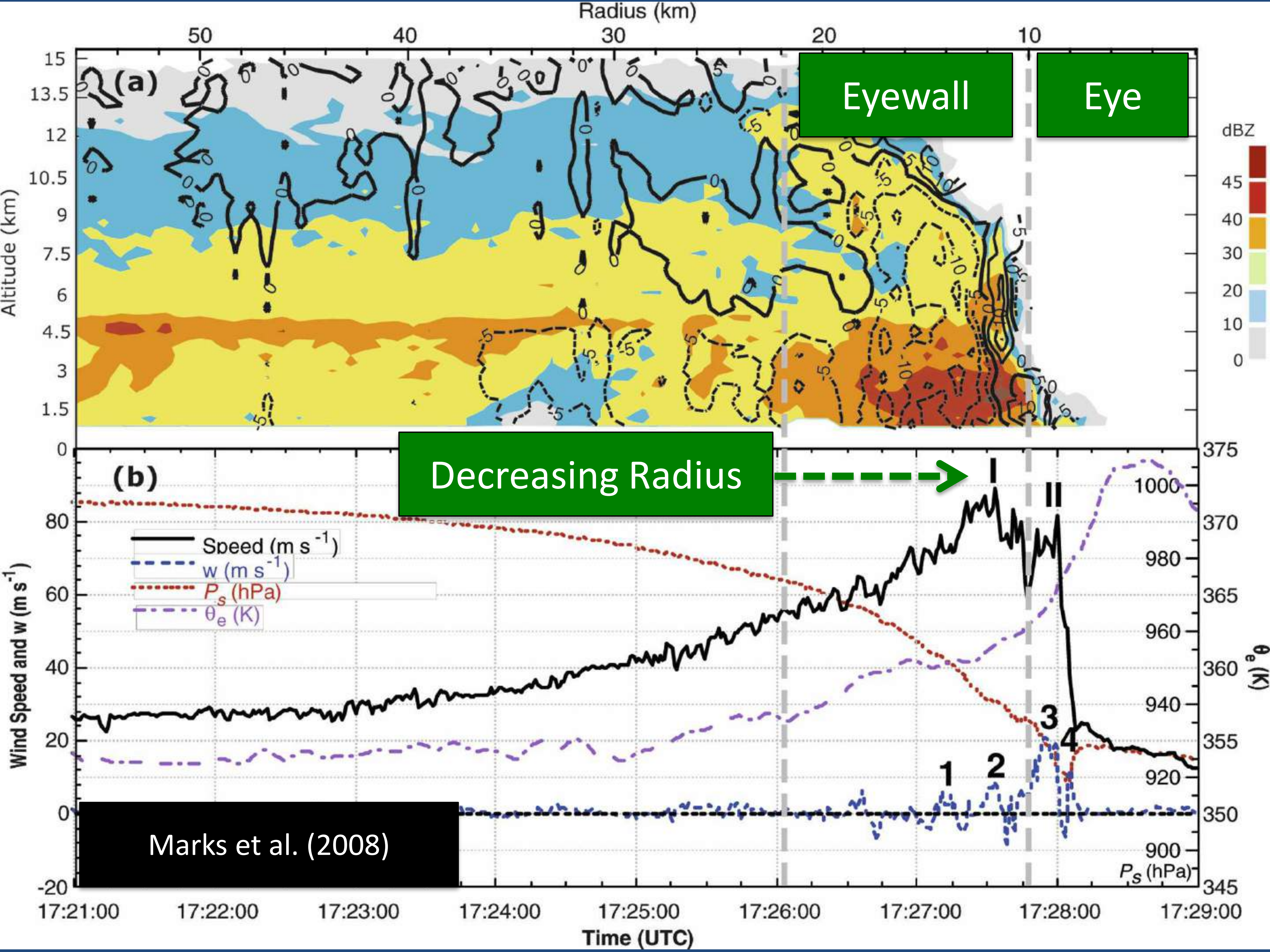
Eyewall

Eye

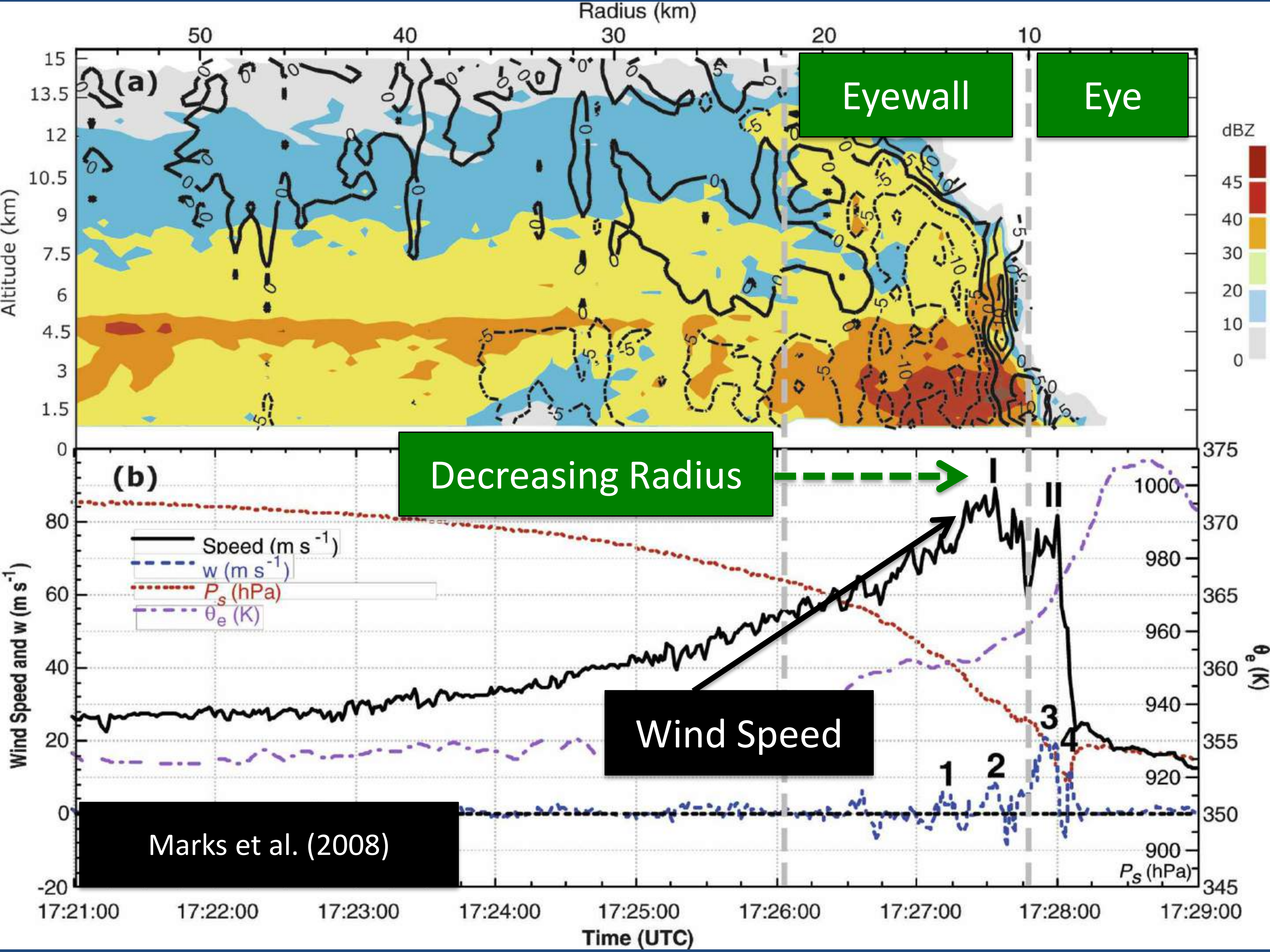
Marks et al. (2008)



Radius (km)
50
40
30
20
10
(a)
Eyewall
Eye
dBZ
45
40
30
20
10
0
Altitude (km)
15
13.5
12
10.5
9
7.5
6
4.5
3
1.5
Decreasing Radius
Marks et al. (2008)
17:21:00
17:22:00
17:23:00
17:24:00
17:25:00
17:26:00
17:27:00
17:28:00
17:29:00
Time (UTC)



Radius (km)
50
40
30
20
10
(a)
Eyewall
Eye
Altitude (km)
dBZ
Decreasing Radius
(b)
I
II
1
2
3
4
Speed (m s⁻¹)
w (m s⁻¹)
P_s (hPa)
θ_e (K)
Wind Speed and w (m s⁻¹)
θ_e (K)
P_s (hPa)
Time (UTC)
17:21:00
17:22:00
17:23:00
17:24:00
17:25:00
17:26:00
17:27:00
17:28:00
17:29:00
Marks et al. (2008)



Radius (km)
50
40
30
20
10
(a)
Eyewall
Eye
dBZ
45
40
30
20
10
0
Altitude (km)
15
13.5
12
10.5
9
7.5
6
4.5
3
1.5
0
Decreasing Radius
(b)
I
II
Speed (m s^{-1})
w (m s^{-1})
P_s (hPa)
θ_e (K)
Wind Speed
1
2
3
4
Marks et al. (2008)
Wind Speed and w (m s^{-1})
80
60
40
20
0
-20
1000
980
960
940
920
900
P_s (hPa)
375
370
365
360
355
350
345
θ_e (K)
17:21:00
17:22:00
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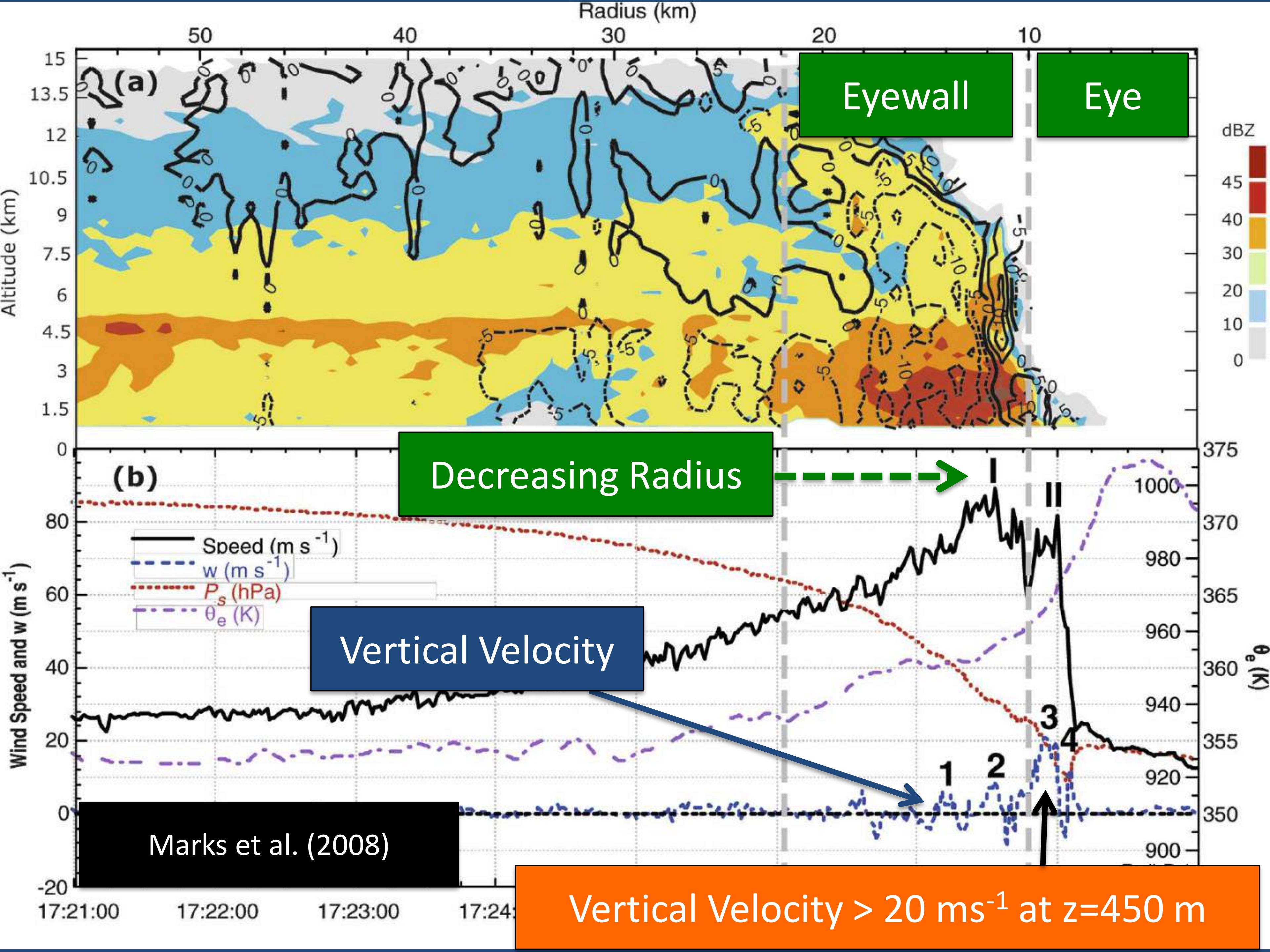
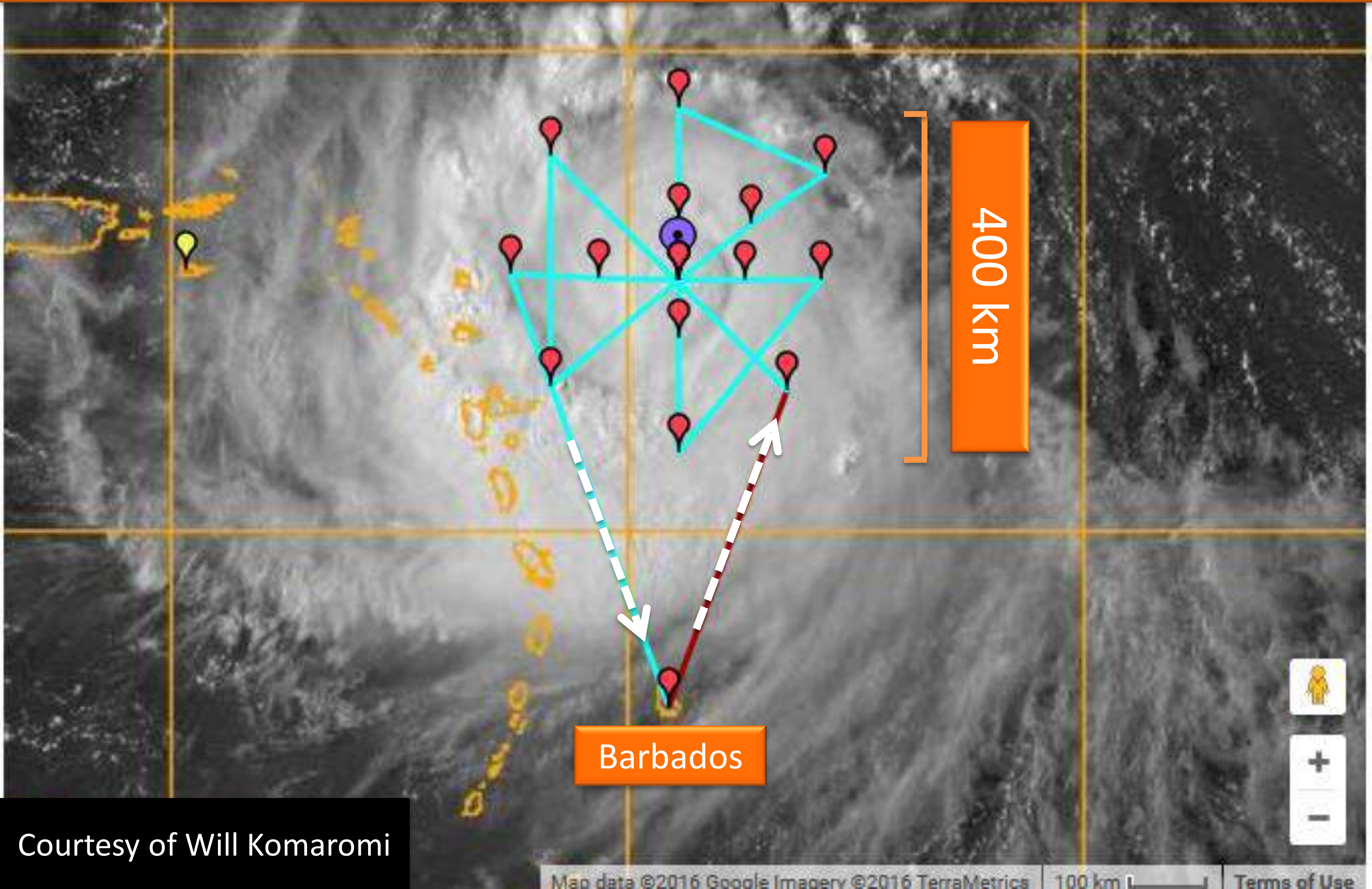
17:24:00
17:25:00
17:26:00
17:27:00
17:28:00
17:29:00
Time (UTC)



Radius (km)
50
40
30
20
10
(a)
Eyewall
Eye
dBZ
45
40
30
20
10
0
Altitude (km)
15
13.5
12
10.5
9
7.5
6
4.5
3
1.5
0
(b)
Decreasing Radius
I
II
Speed (m s⁻¹)
w (m s⁻¹)
Ps (hPa)
θe (K)
Vertical Velocity
1
2
3
4
Wind Speed and w (m s⁻¹)
80
60
40
20
0
-20
1000
980
960
940
920
900
375
370
365
360
355
350
θe (K)
Marks et al. (2008)
17:21:00
17:22:00
17:23:00
17:24
Vertical Velocity > 20 ms⁻¹ at z=450 m

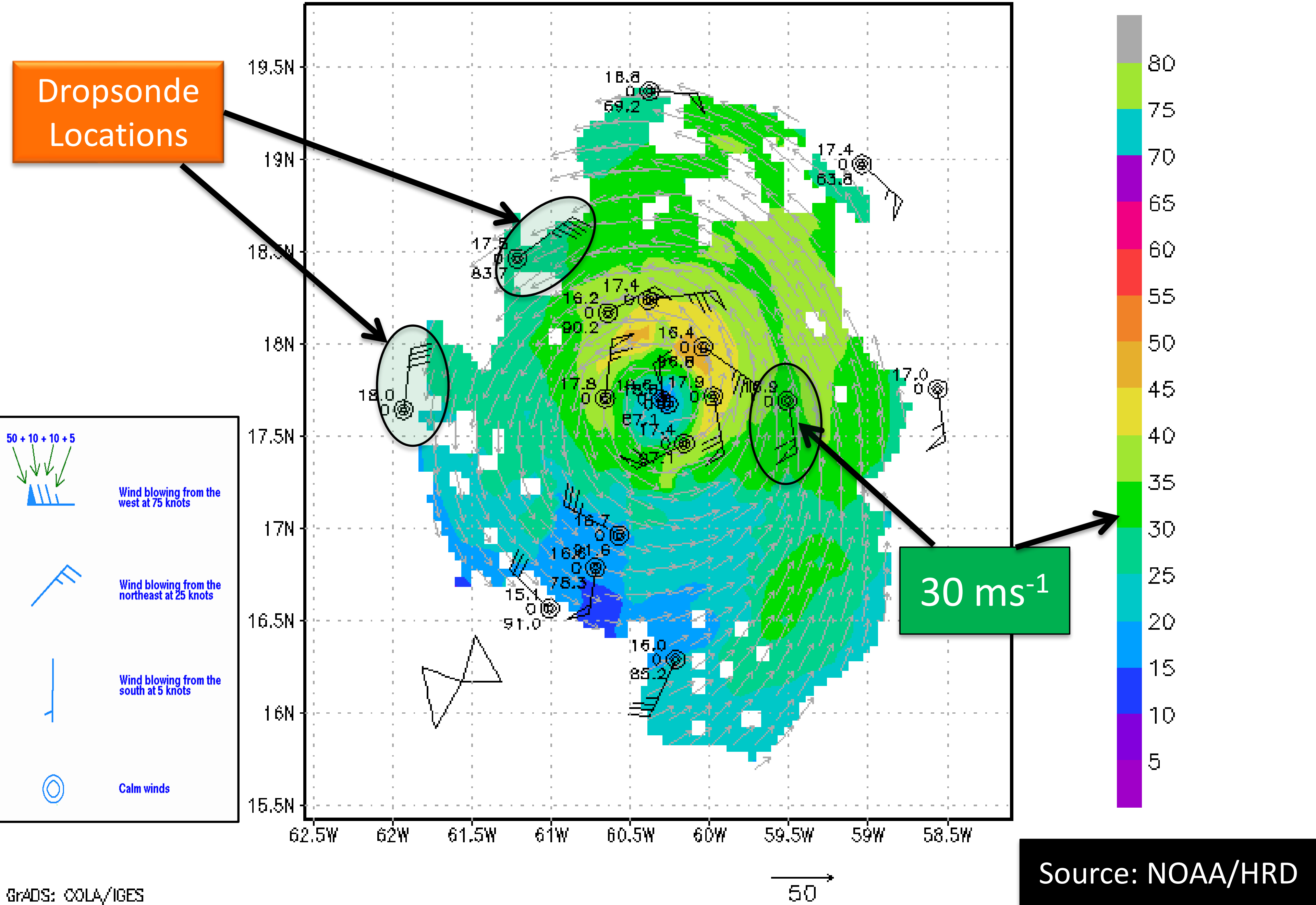
The GPS Dropsonde

Hurricane Earl (2010)
Hypothetical Flight Plan and Dropsonde Locations

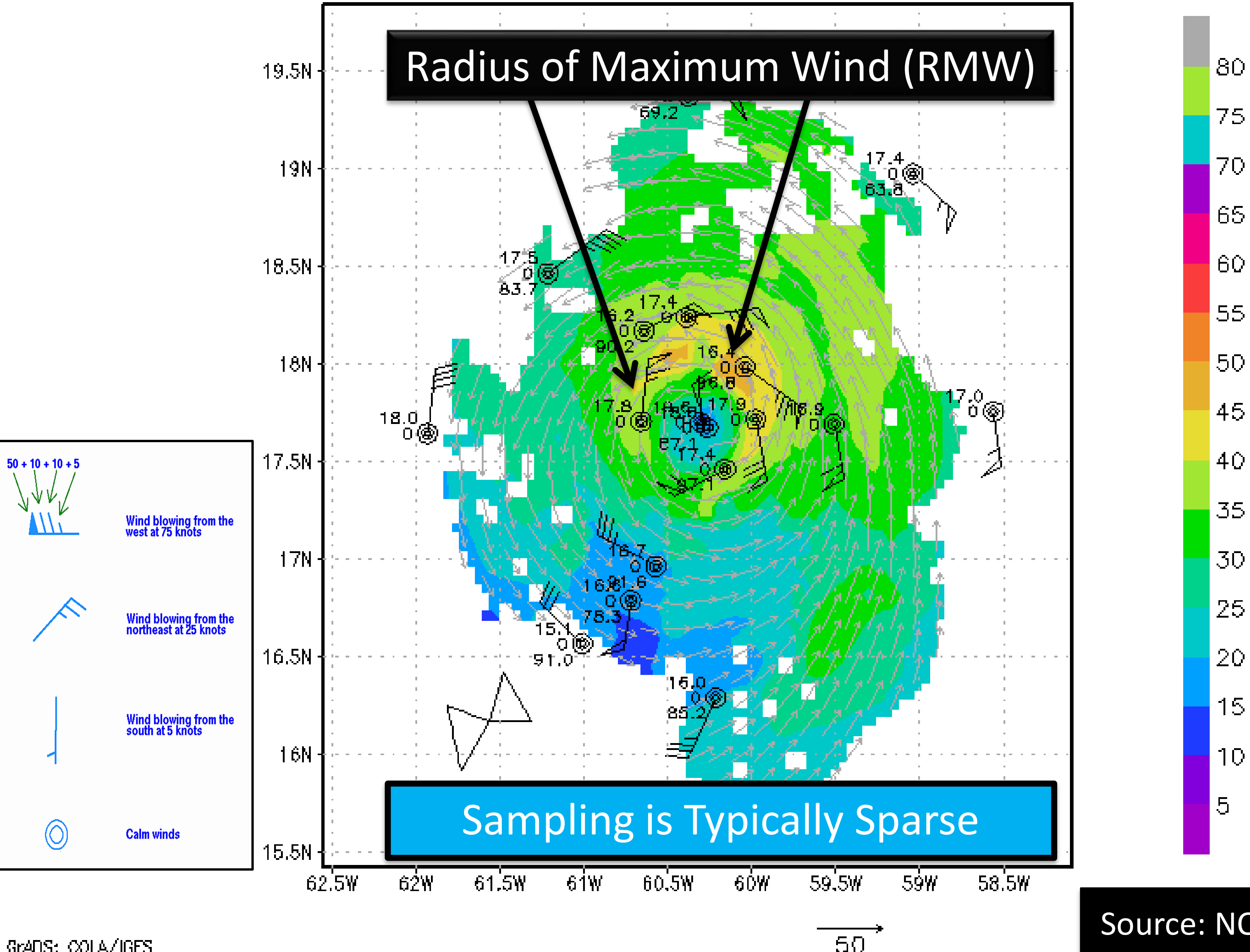


Courtesy of Will Komaromi

Hurricane Earl, Wind Speed (ms^{-1}) at z=2 km

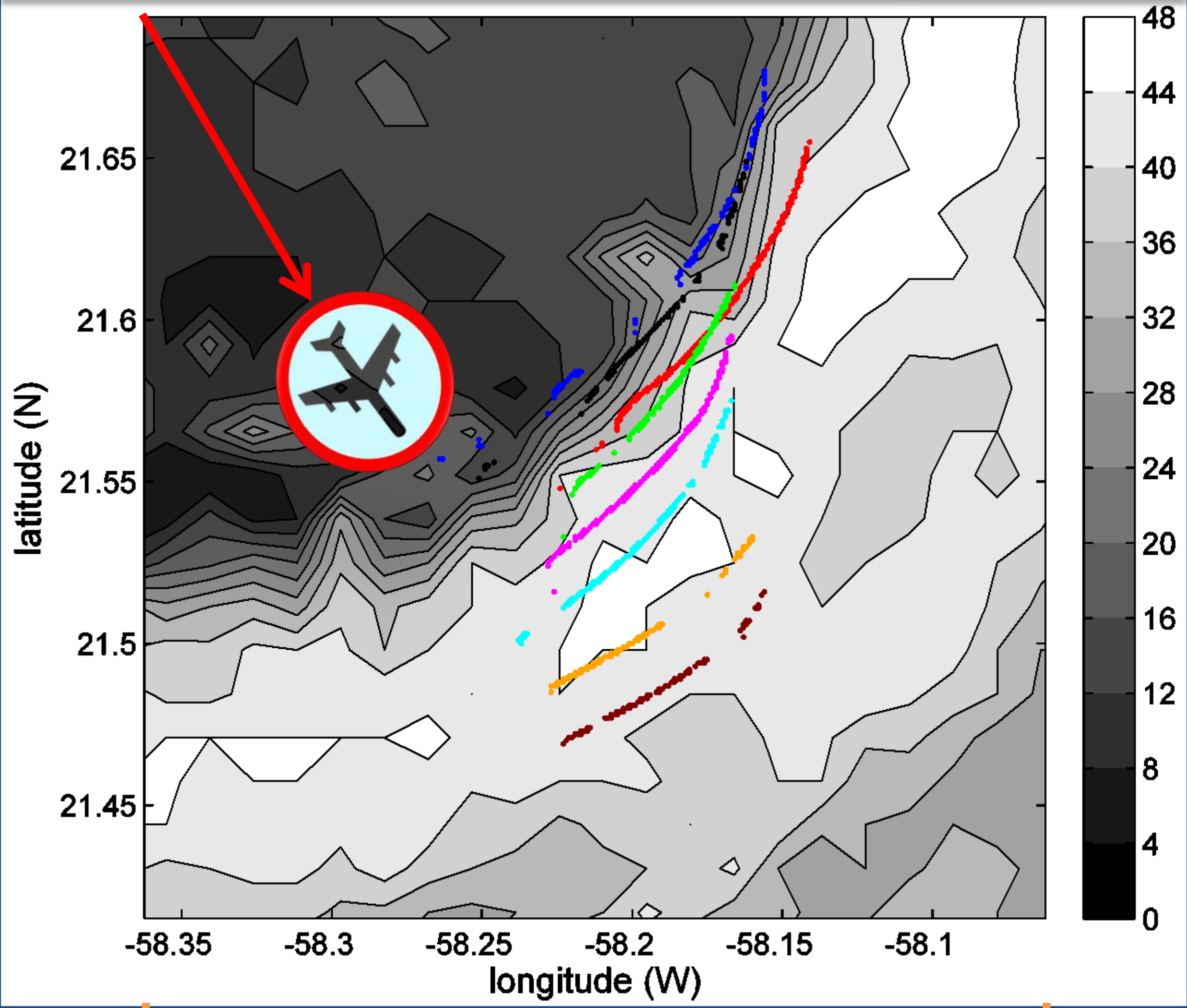


Hurricane Earl, Wind Speed (ms^{-1}) at z=2 km

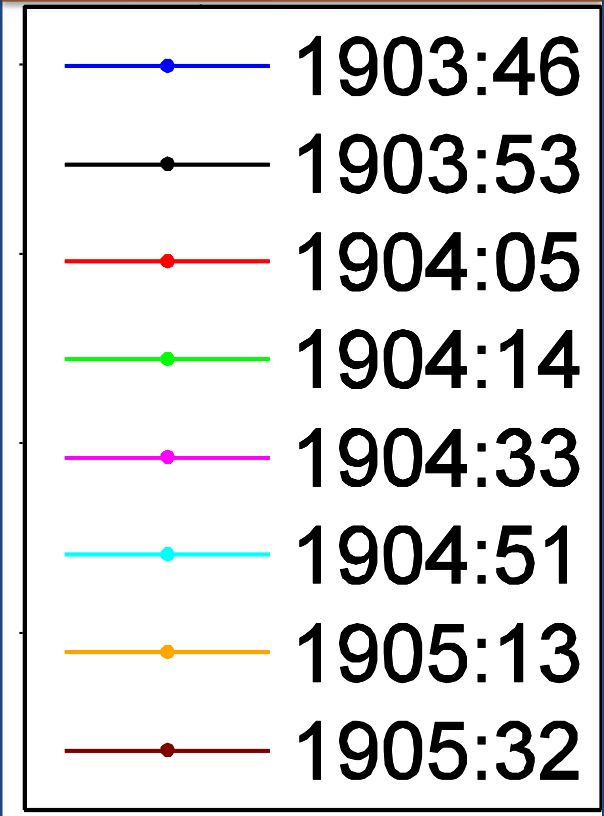


Source: NOAA/HRD

Hurricane Isabel, Radar Reflectivity



Time (UTC)



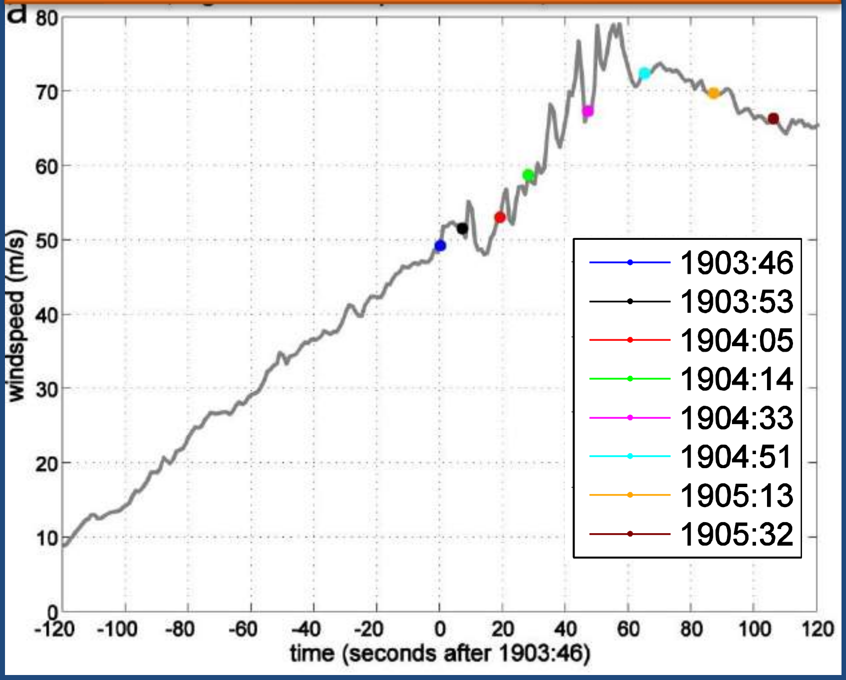
~30 km

Stern et al. (2016)

Eyewall Sampling of Hurricane Isabel

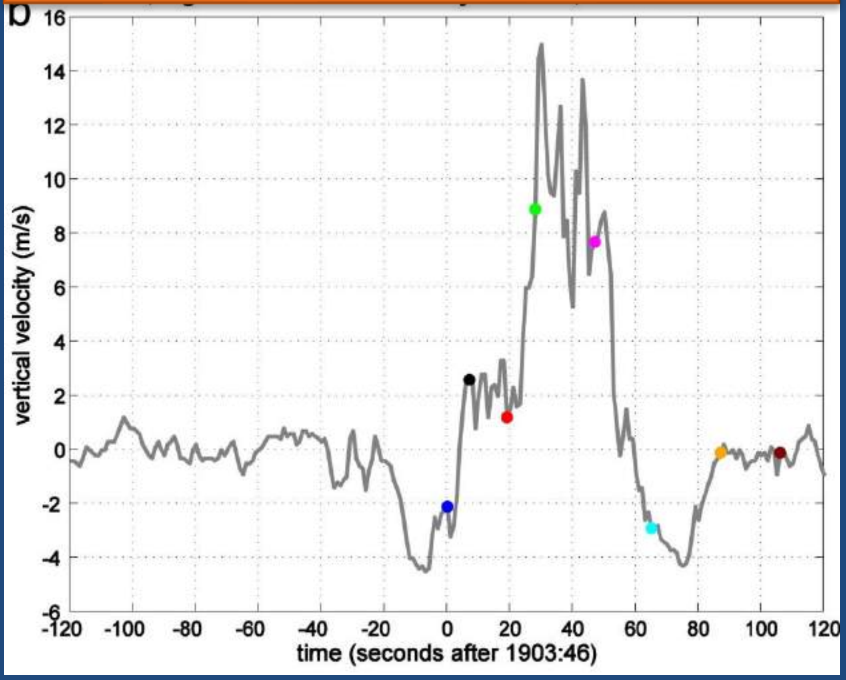
Time Series and Dropsonde Locations

Flight-Level Wind Speed



~30 km

Flight-Level Vertical Velocity

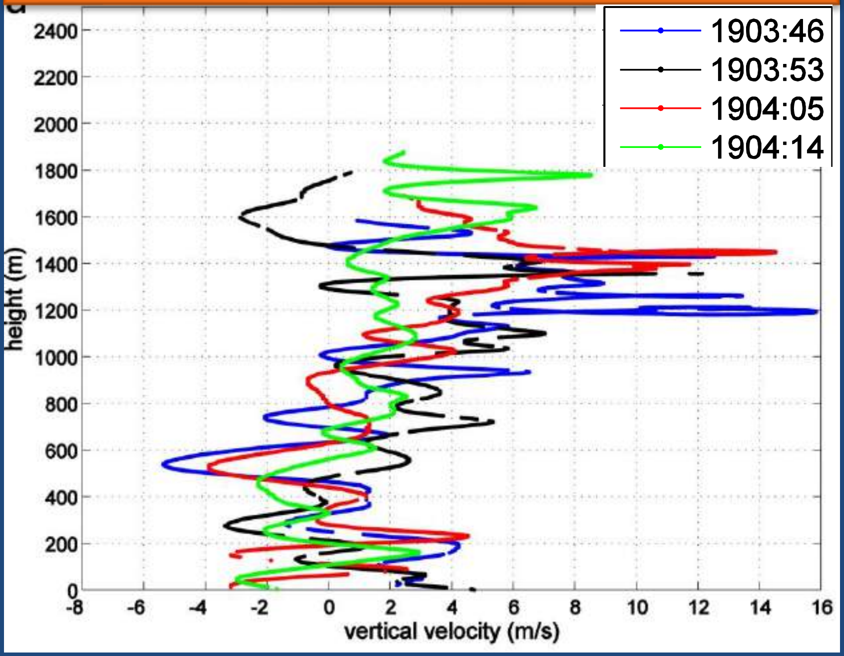


~30 km

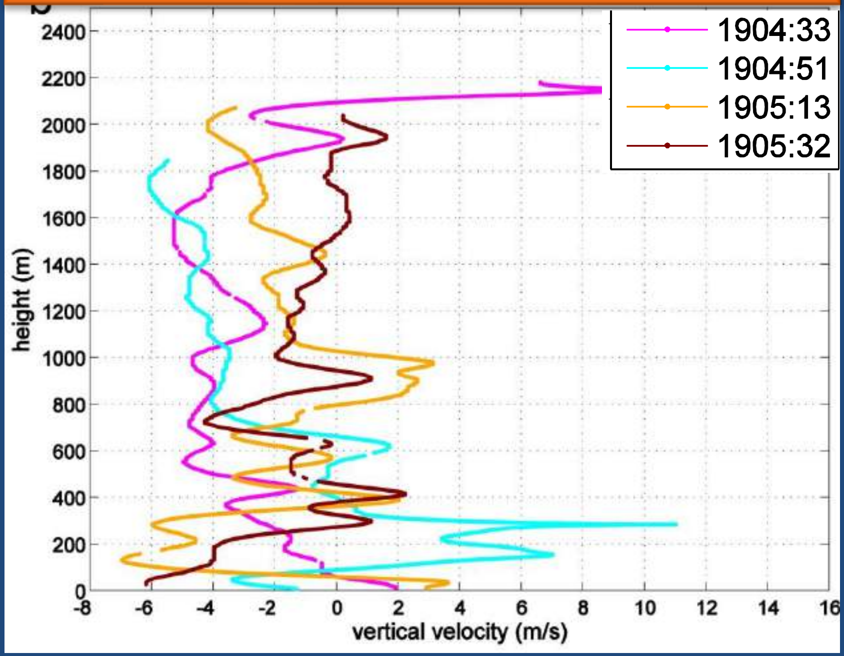
Stern et al. (2016)

Dropsonde Profiles in Hurricane Isabel

Vertical Velocity (ms^{-1})

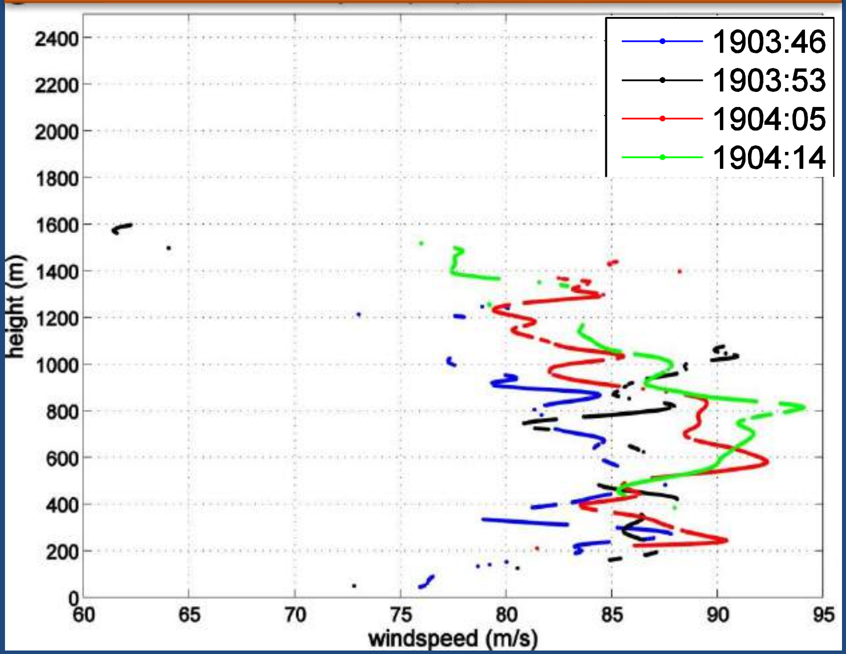


Vertical Velocity (ms^{-1})

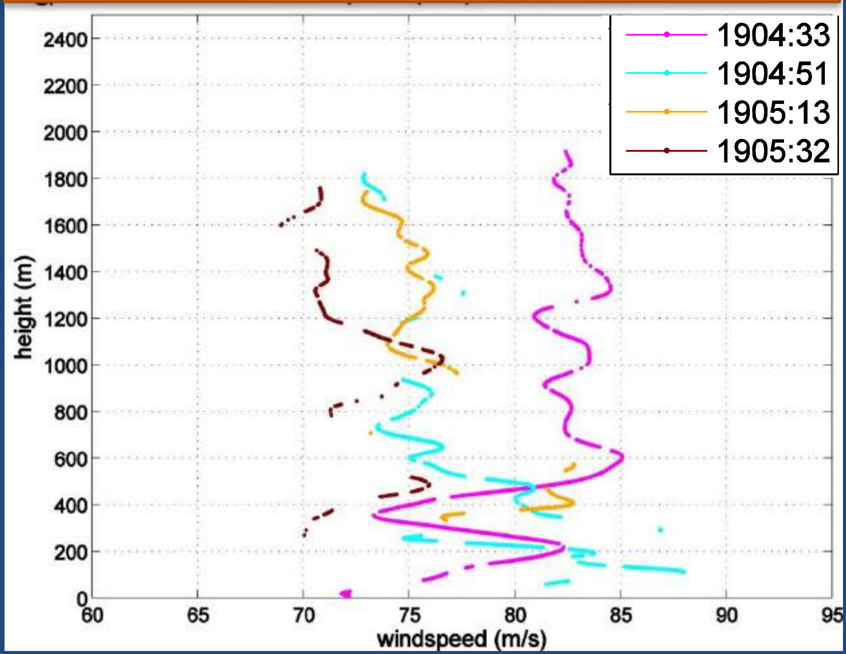


Dropsonde Profiles in Hurricane Isabel

Wind Speed (ms^{-1})



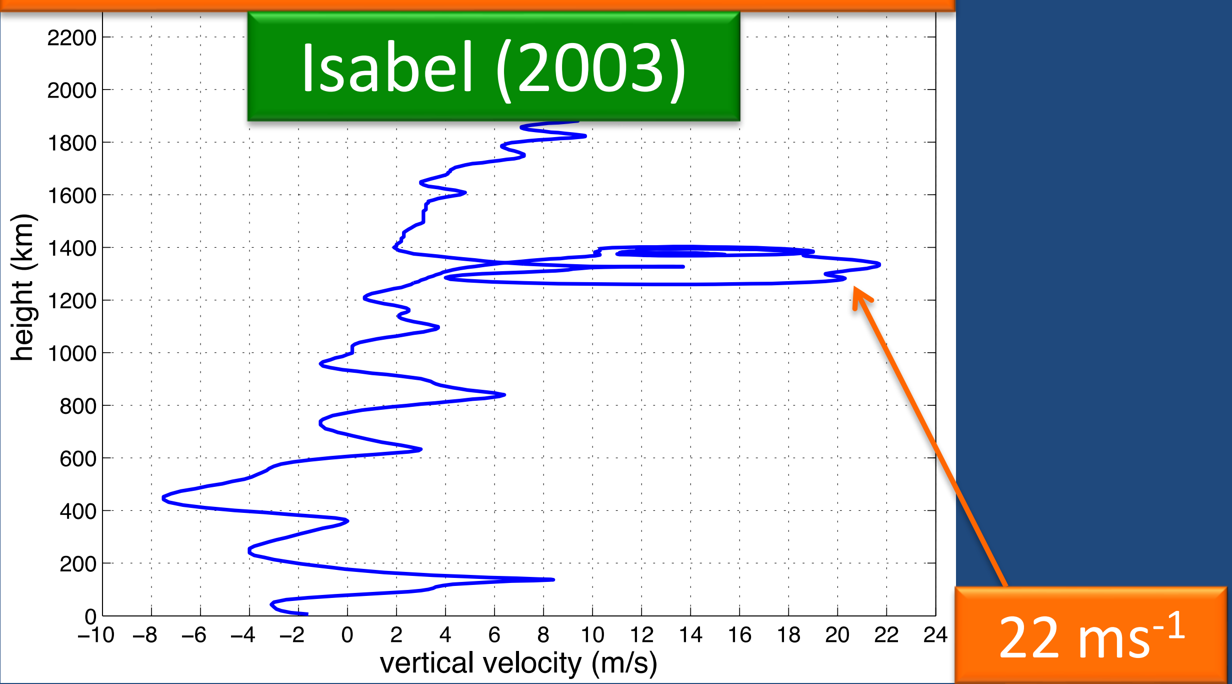
Wind Speed (ms^{-1})



Motivation

- Dropsondes occasionally sample 10-25 ms^{-1} updrafts within (and near) the TC boundary layer.

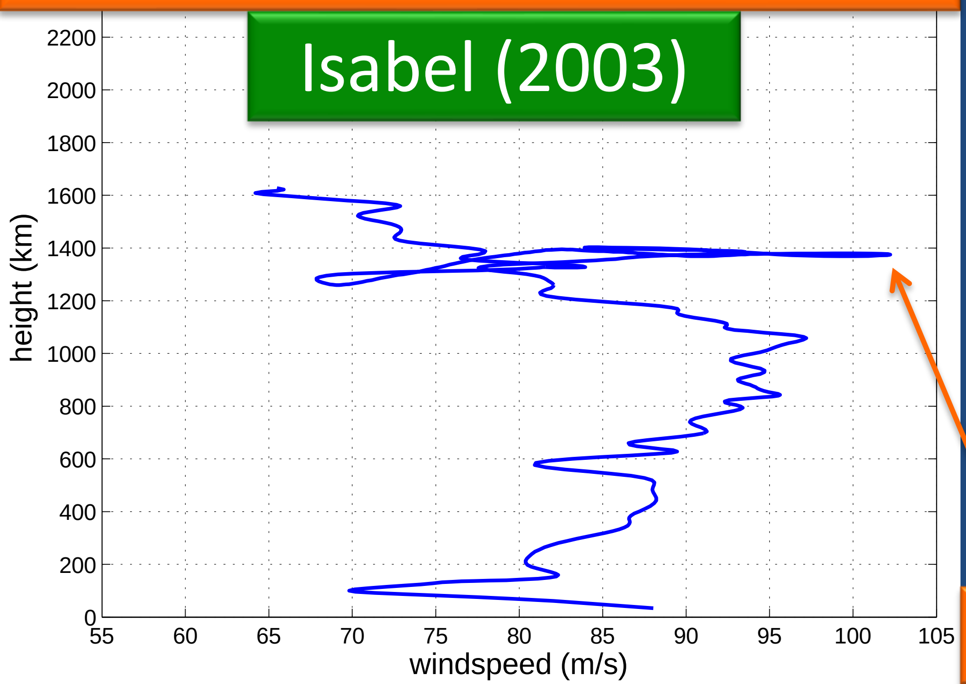
Vertical Velocity vs. Height



Motivation

- The extreme updrafts appear to be associated with extreme horizontal wind speeds (> 90 ms^{-1}).

Wind Speed vs. Height



Hypothesis:

Extreme updrafts and near-surface wind speeds are associated with small-scale (≤1 km) coherent vortices.

A New Dataset of Extreme Updrafts and Windspeeds

- ~12,000 sondes have been dropped into TCs
  - from NOAA and U.S. Air Force (1997-2013)

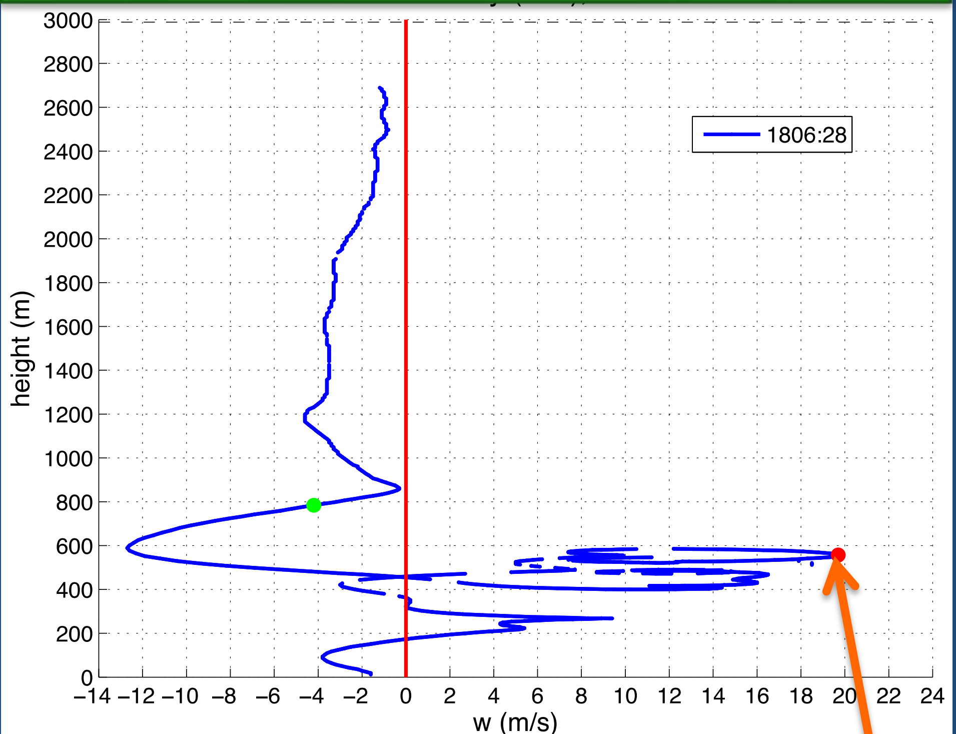
We found:

- 169 sondes (in 35 TCs) with $w > 10$ ms^{-1}
- 64 sondes (in 12 TCs) with wspd > 90 ms^{-1}

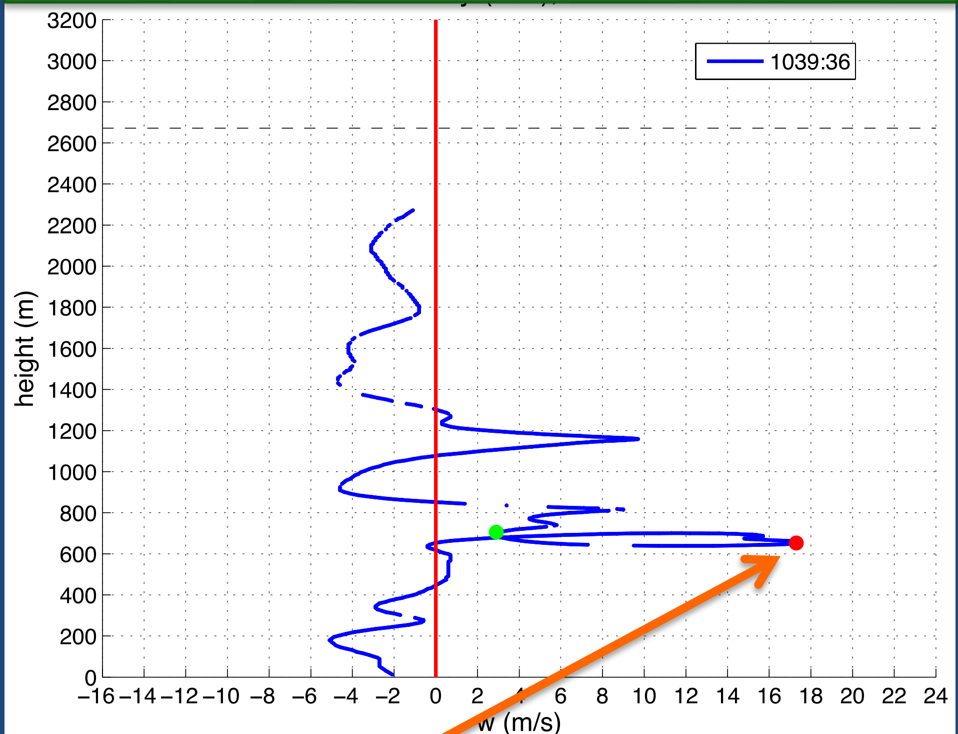
Stern et al. (2016)

Examples: Extreme Updrafts

Hurricane Iris (2001)



Hurricane Frances (2004)



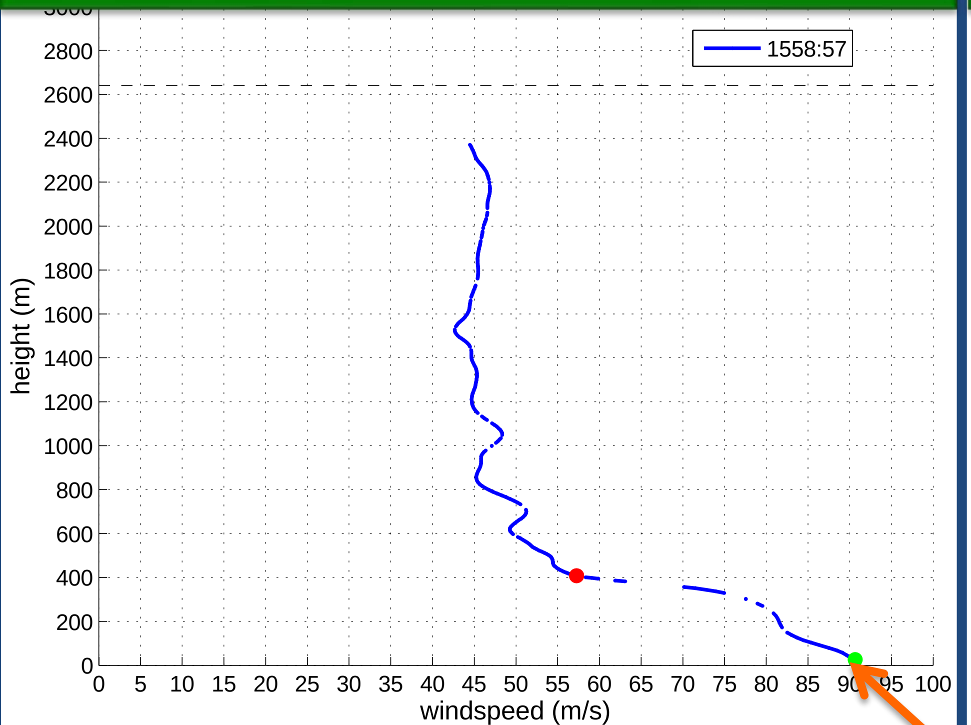
>17 ms^{-1} updrafts at z=600 m

Max Vertical Velocity

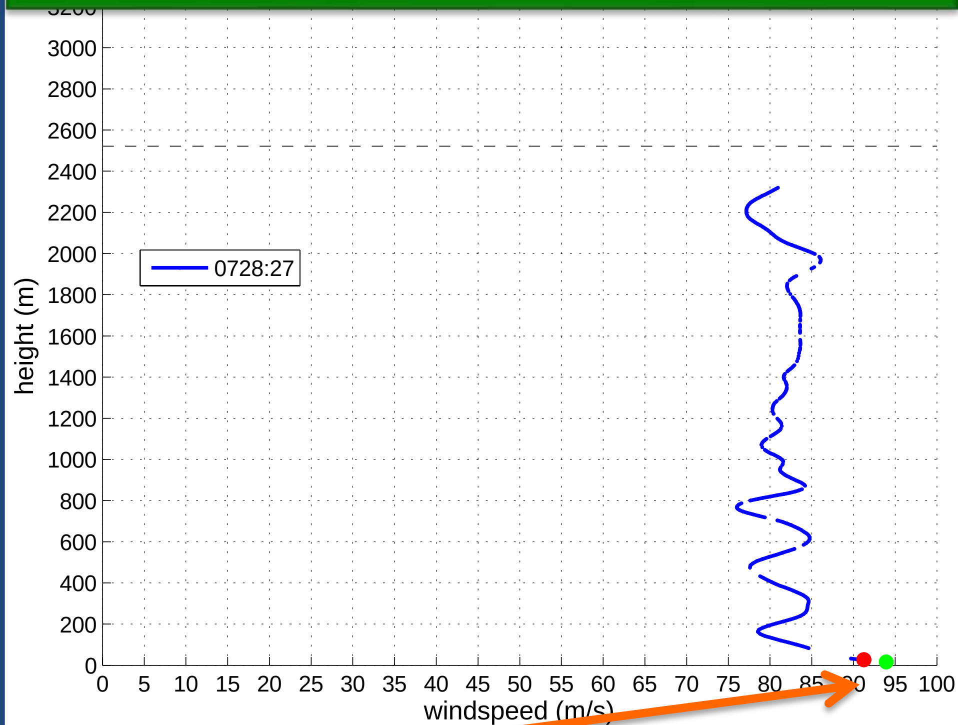
Max Wind Speed

Examples: Extreme Windspeeds

Hurricane Rita (2005)



Hurricane Dean (2007)

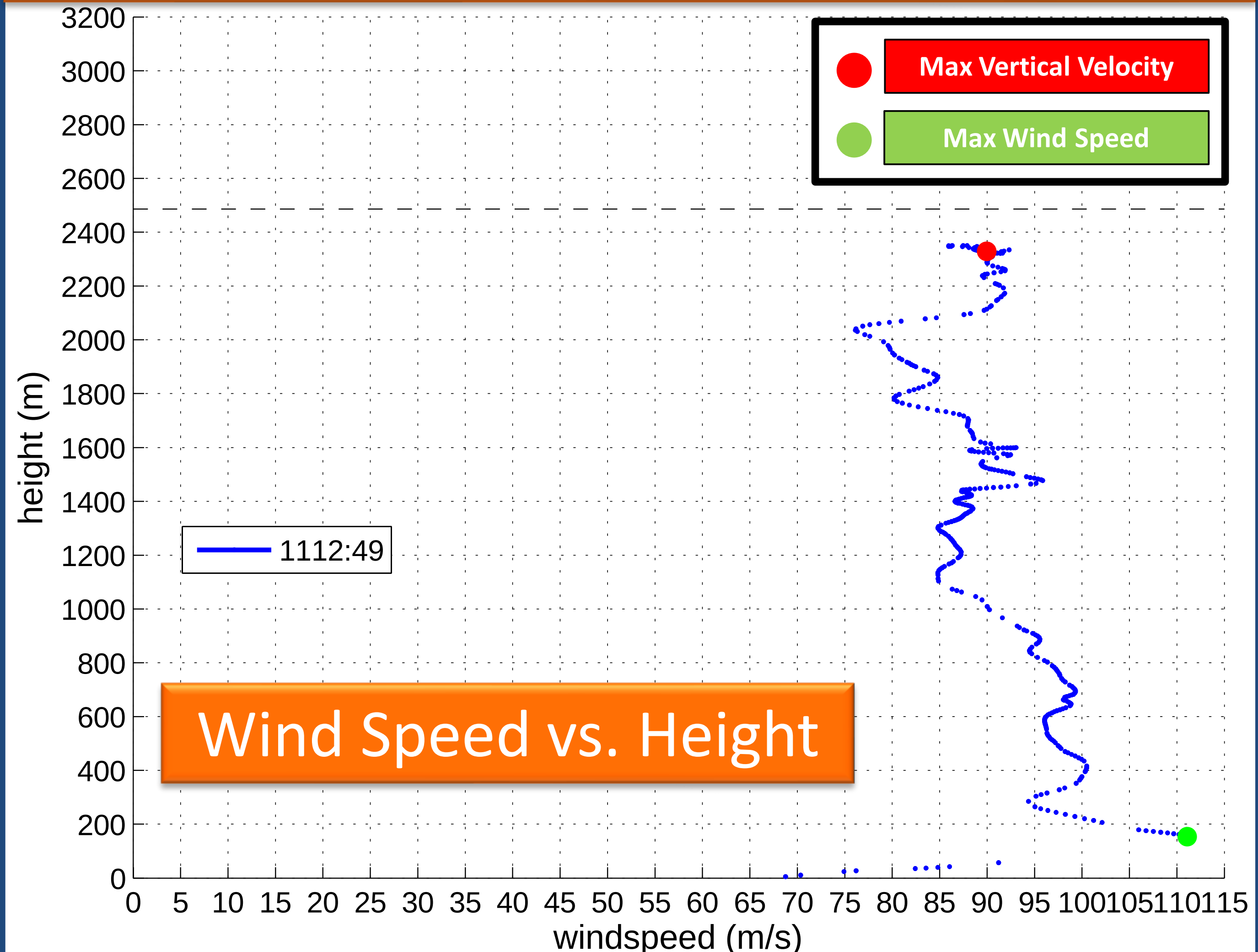


>90 ms^{-1} windspeed at z<100 m

Max Vertical Velocity

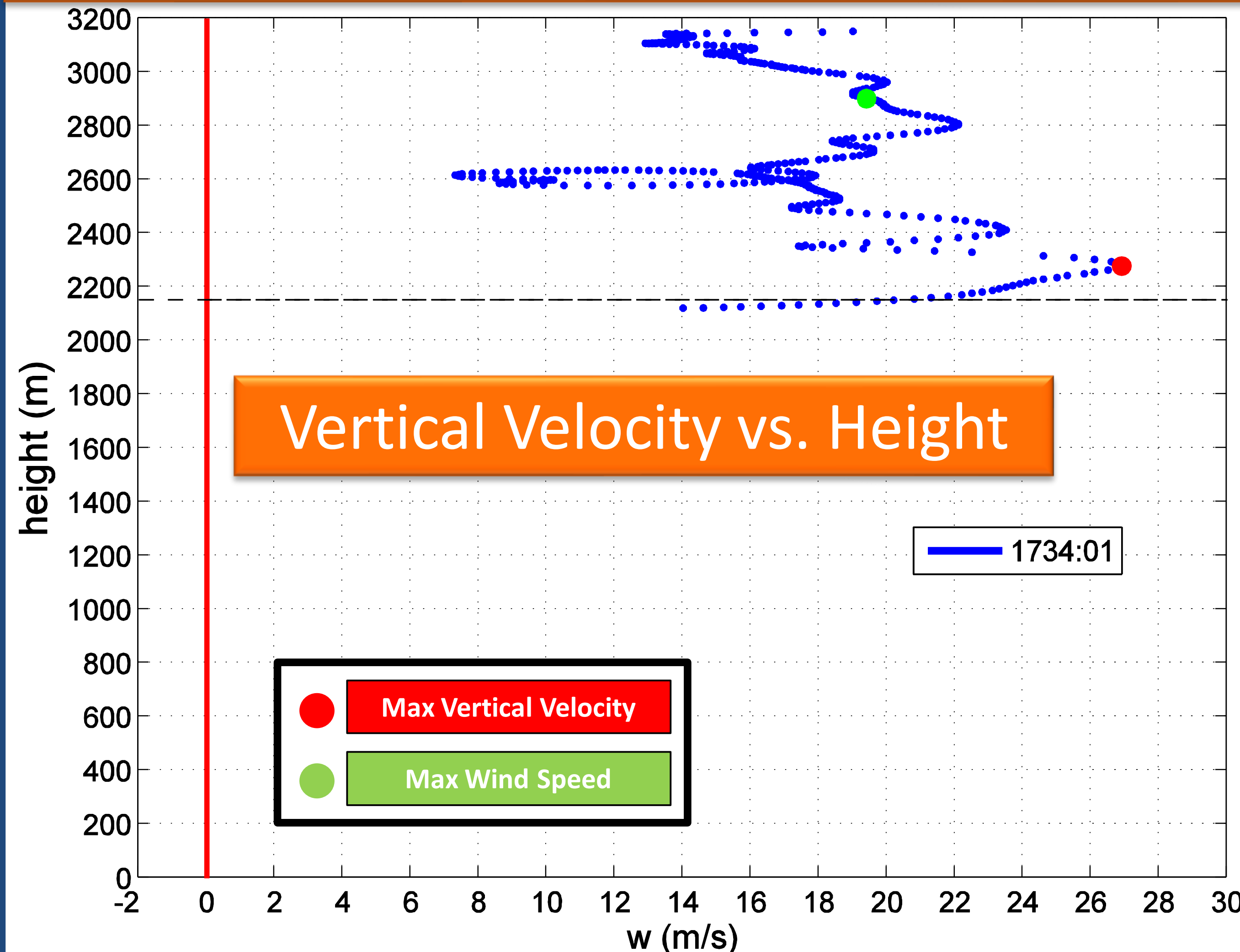
Max Wind Speed

Oct 17th 2010, Super Typhoon Megi



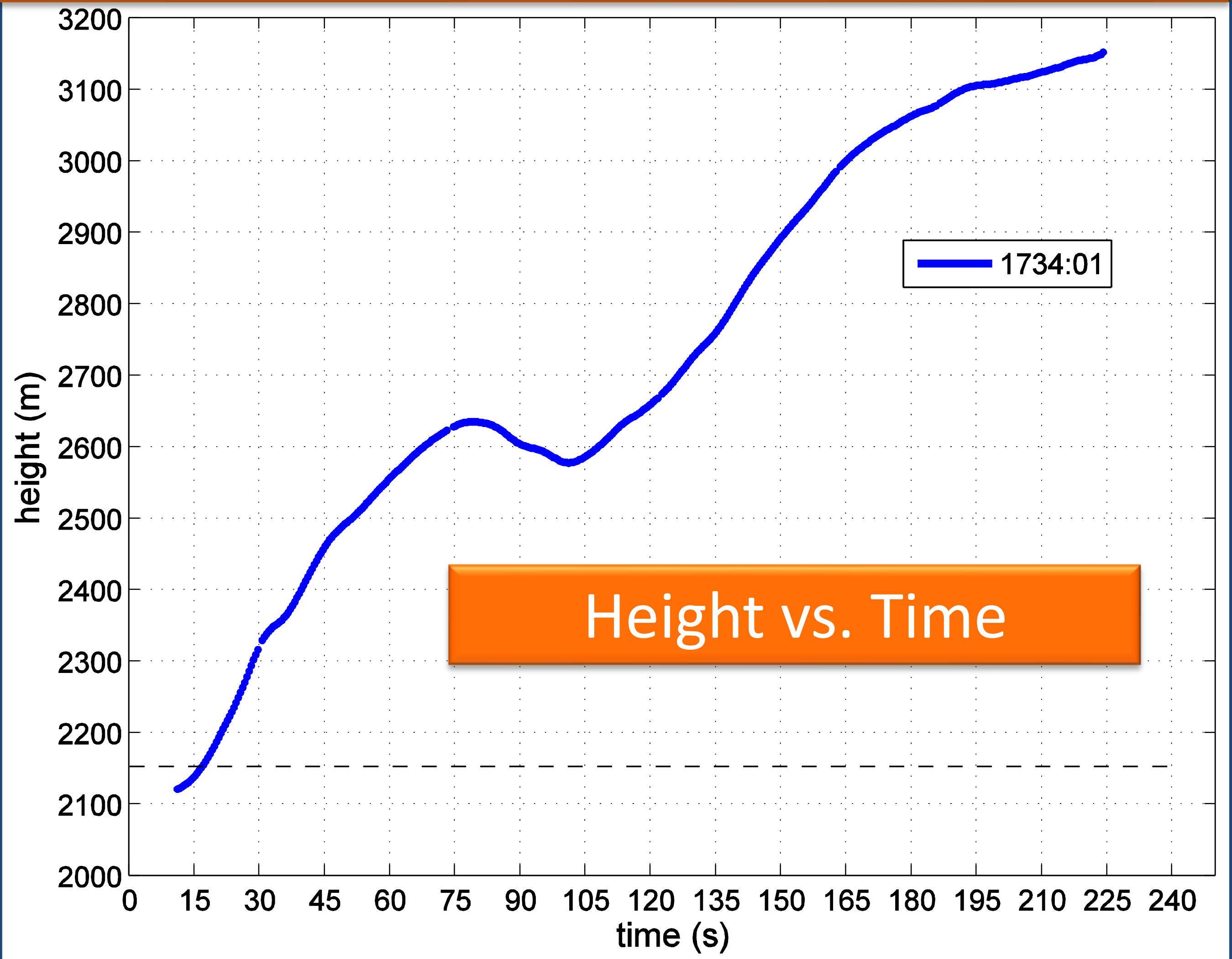
Maximum winds measured by any dropsonde: 111 ms^{-1} at ~150 m ASL

Oct 23rd 2015, Hurricane Patricia



Maximum updraft measured by any dropsonde: 26.9 ms^{-1} at ~2300 m ASL

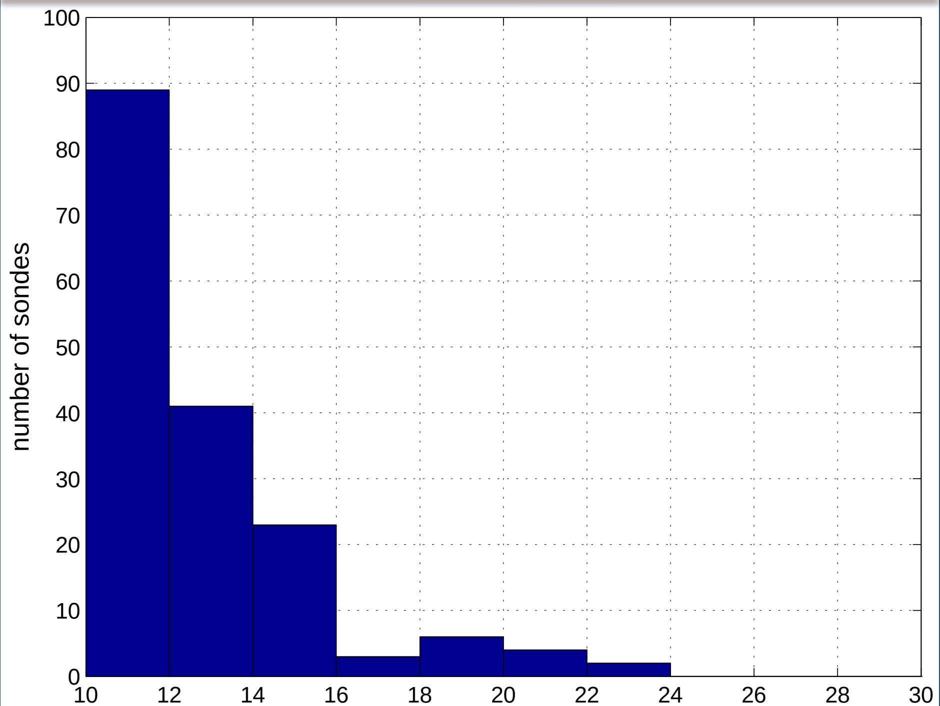
Oct 23rd 2015, Hurricane Patricia



Sonde was dropped at 2100 m, rose by 1000 m, then failed at 3100 m

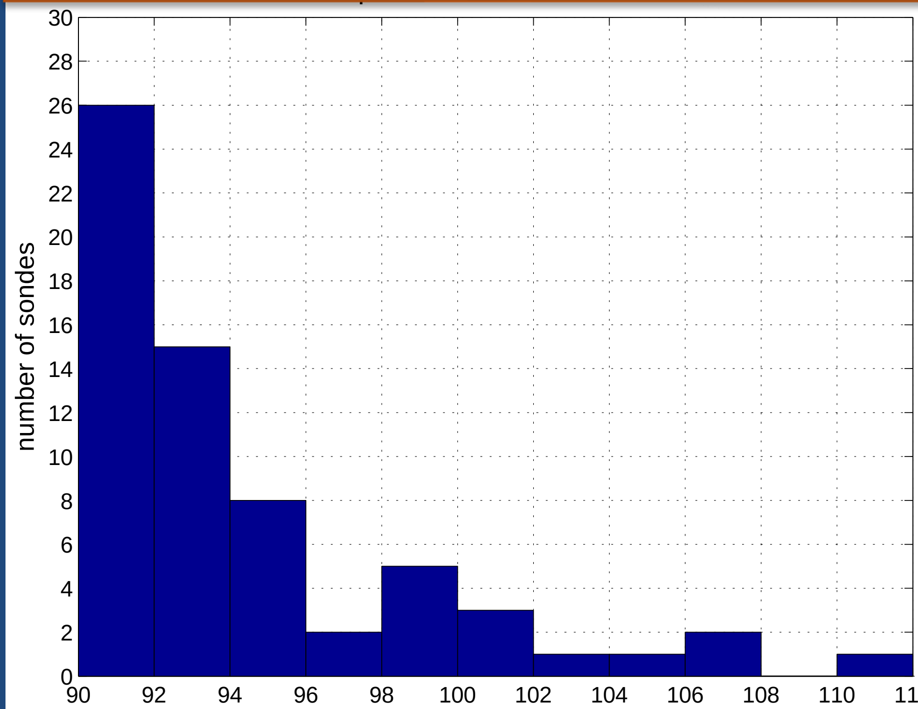
Distribution of Updraft/Windspeed Magnitudes

Sondes with w>10 ms^{-1}



Maximum Vertical Velocity (ms^{-1})

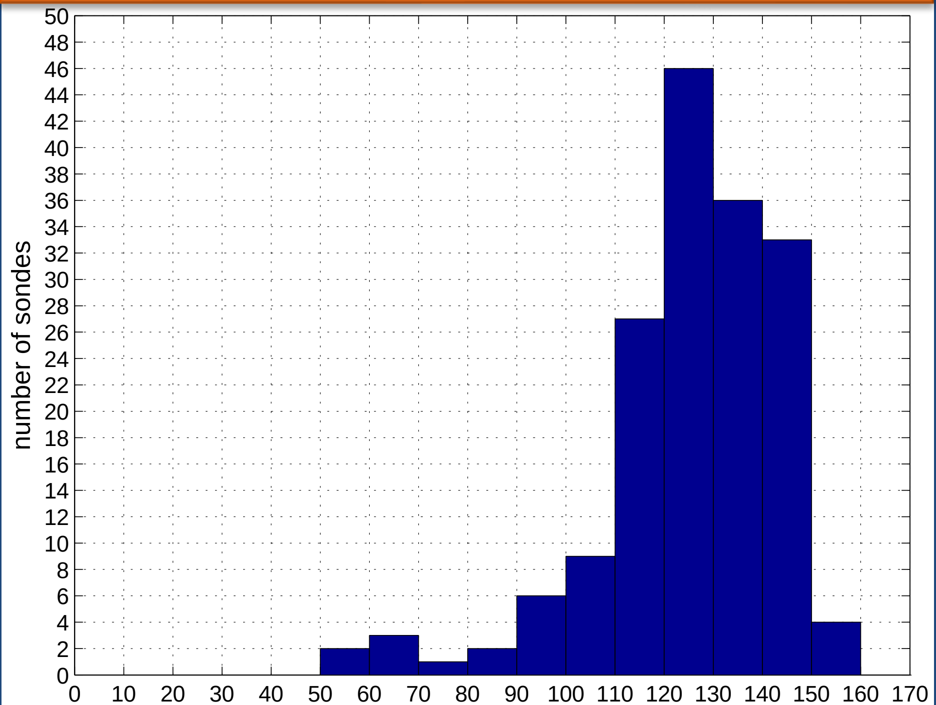
Sondes with wspd>90 ms^{-1}



Maximum Wind Speed (ms^{-1})

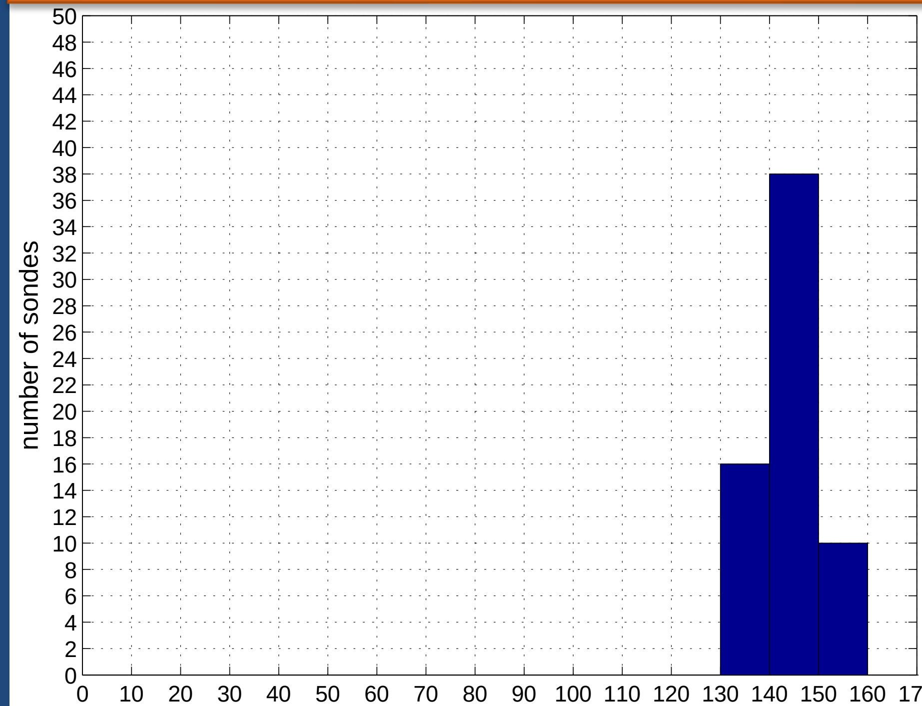
Relationship with Storm Intensity

Sondes with w>10 ms^{-1}



Best Track Intensity (kt)

Sondes with wspd>90 ms^{-1}



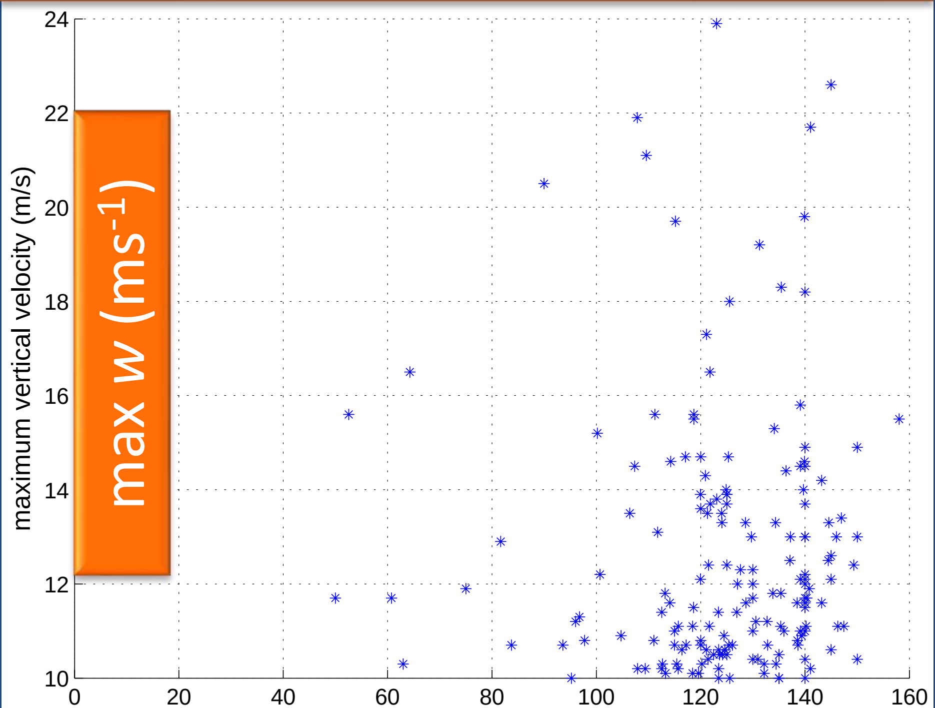
Best Track Intensity (kt)

92% of extreme updrafts from Cat 3-5

All extreme wind gusts from Cat 4-5

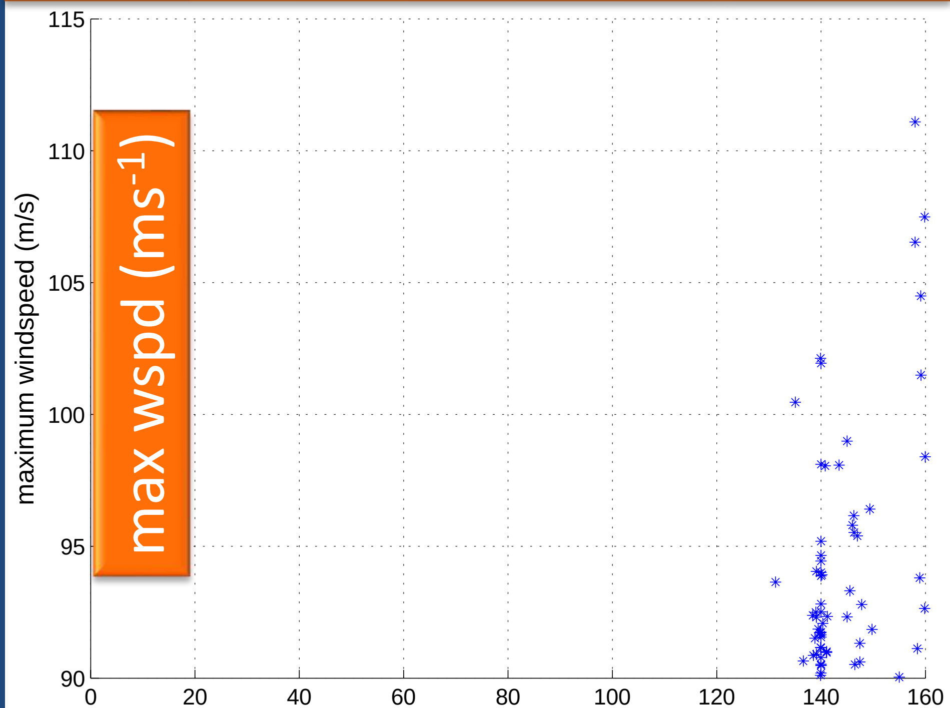
Relationship with Storm Intensity

Sondes with w>10 ms^{-1}



Best Track Intensity (kt)

Sondes with wspd>90 ms^{-1}

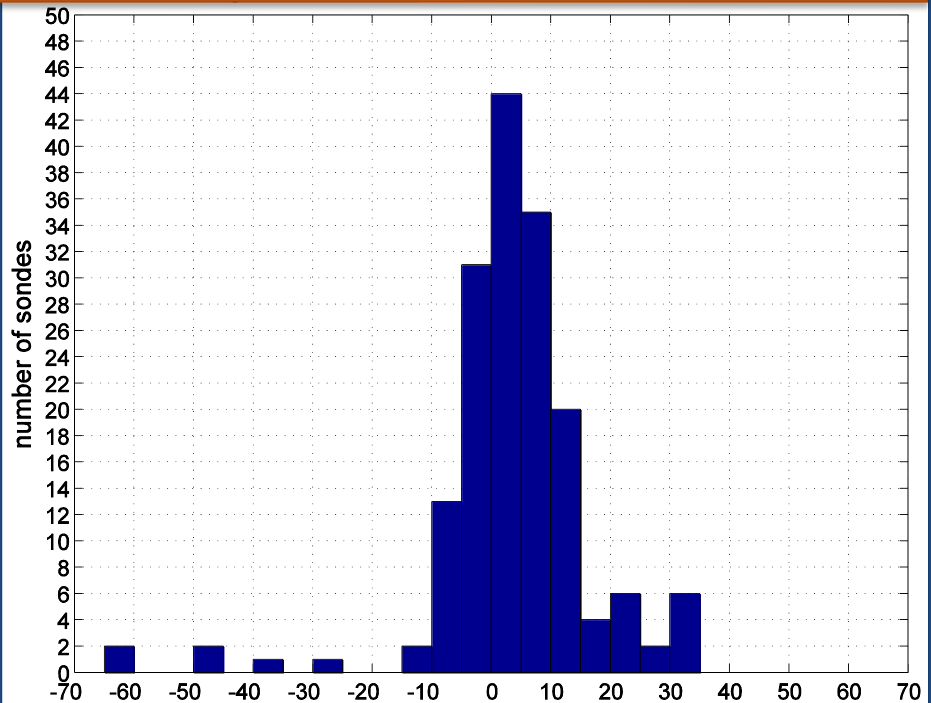


Best Track Intensity (kt)

- No correlation of updraft/windspeed magnitude with TC intensity.
- This is likely related to limited sampling.

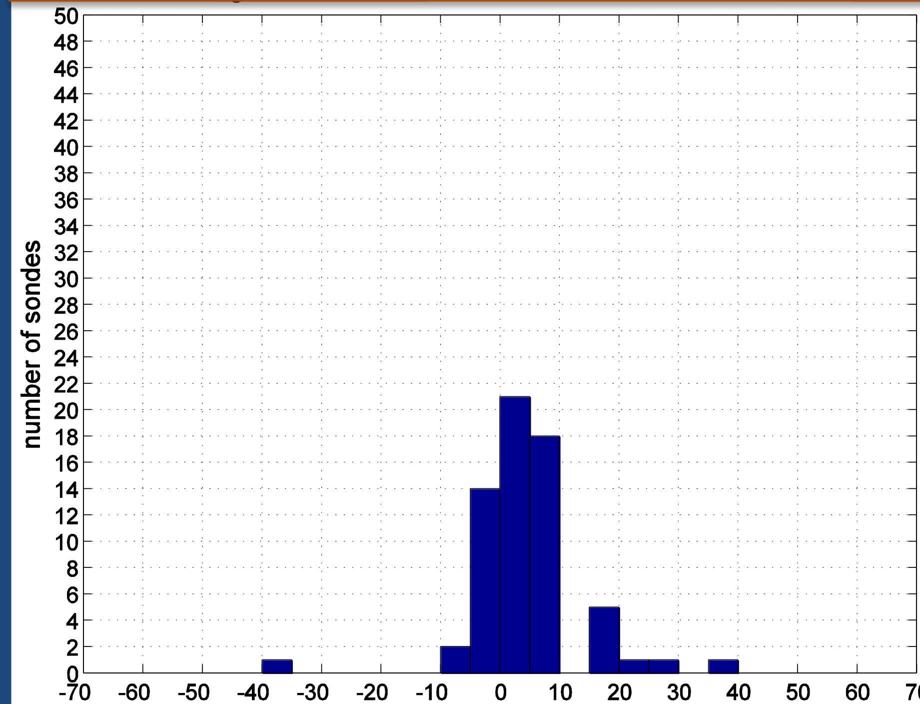
Relationship with Intensity Change

Sondes with w>10 ms^{-1}



6-h Intensity Change (kt)

Sondes with wspd>90 ms^{-1}

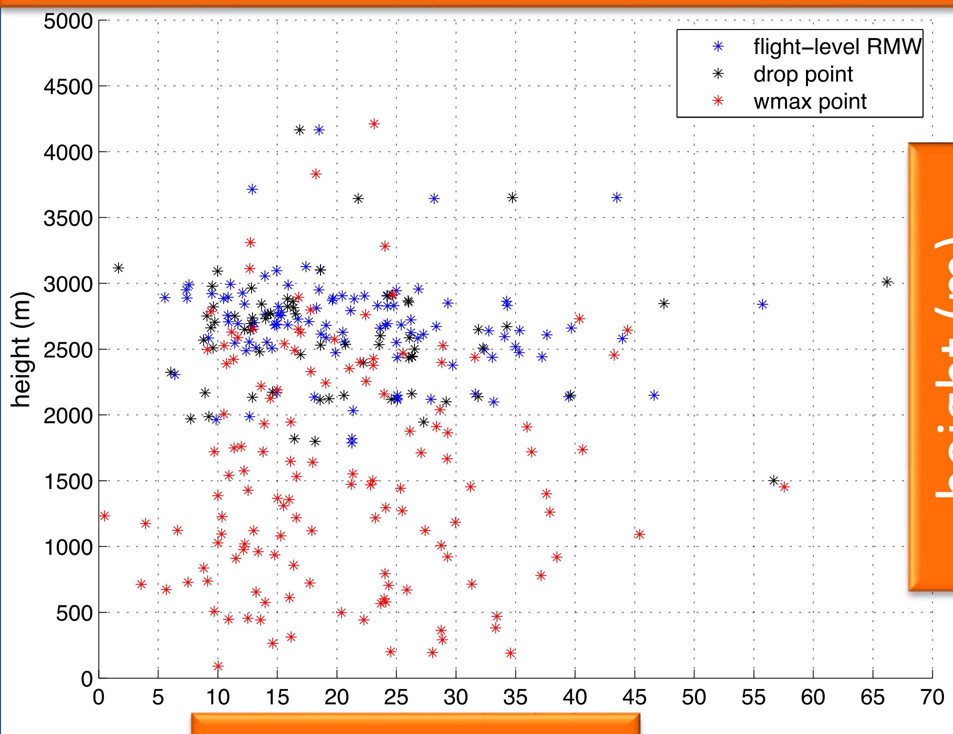


6-h Intensity Change (kt)

No clear relationship between TC intensity change and the frequency of extreme updrafts and wind gusts.

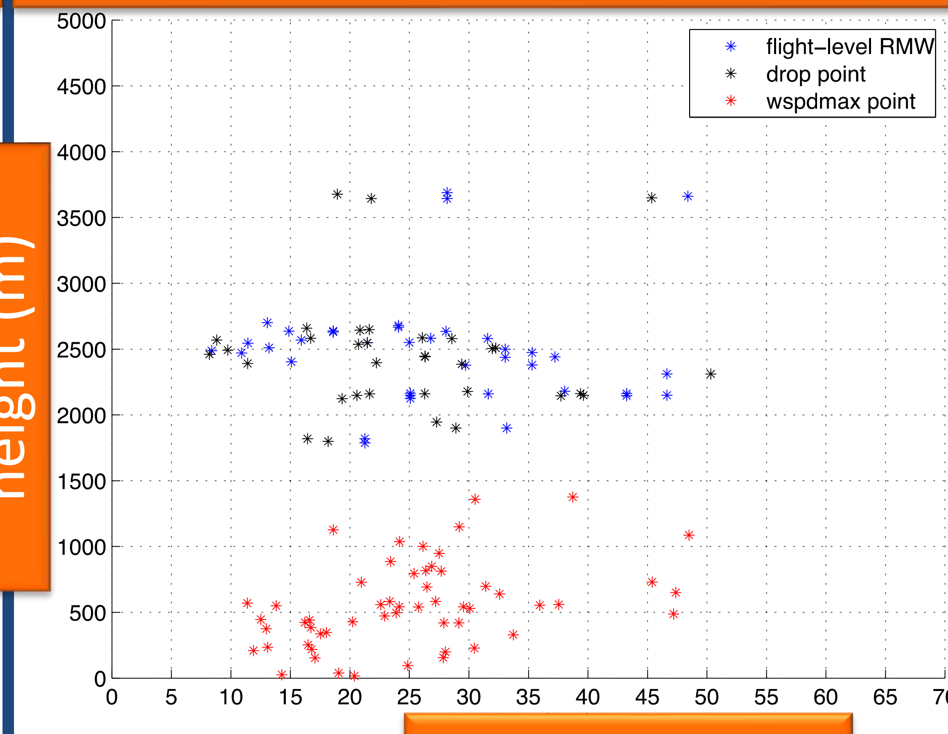
Radius-Height Location

Sondes with w>10 ms^{-1}



radius (km)

Sondes with wspd>90 ms^{-1}



height (m)

radius (km)

radius (km)

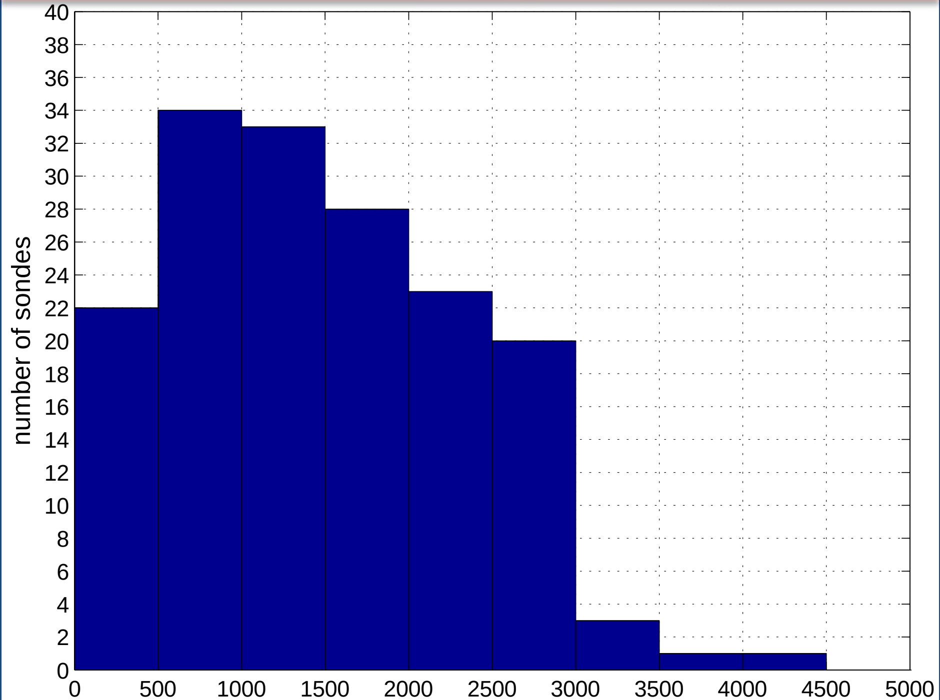
Red = Maximum

Black = Drop Point

Blue = Flight-Level RMW

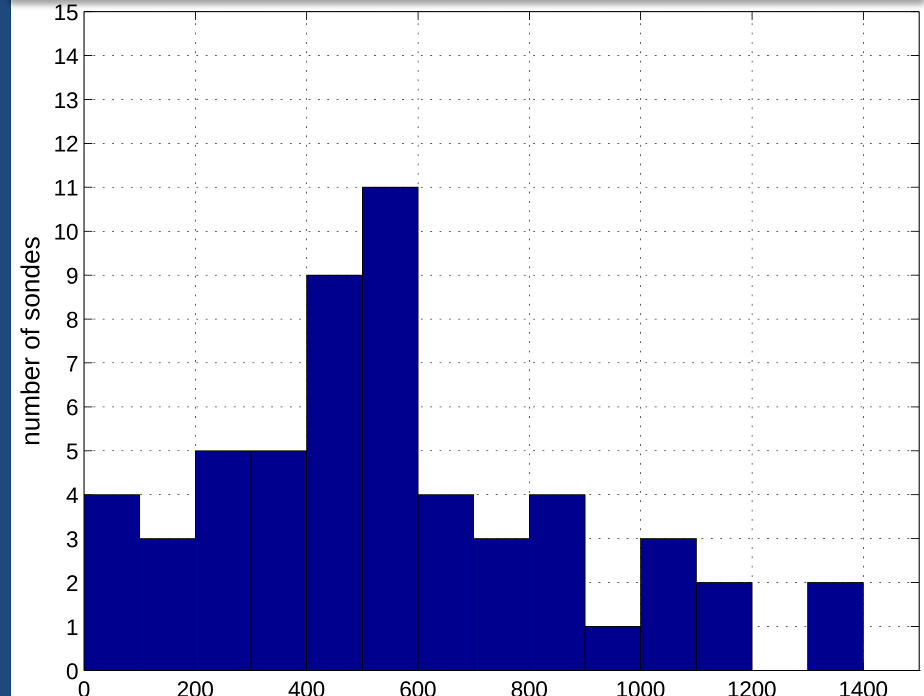
Heights of Maximum Updraft and Wind Speed

Sondes with w>10 ms^{-1}



Height of Max Vertical Velocity (m)

Sondes with wspd>90 ms^{-1}

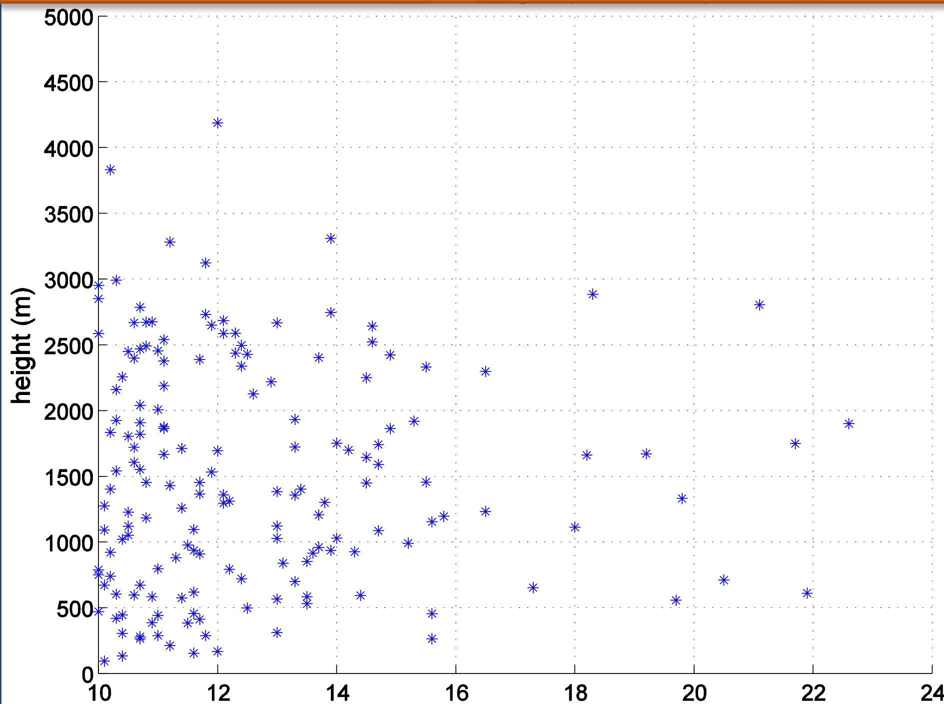


Height of Max Windspeed (m)

Extreme updrafts occur over a much deeper layer (note different axes)

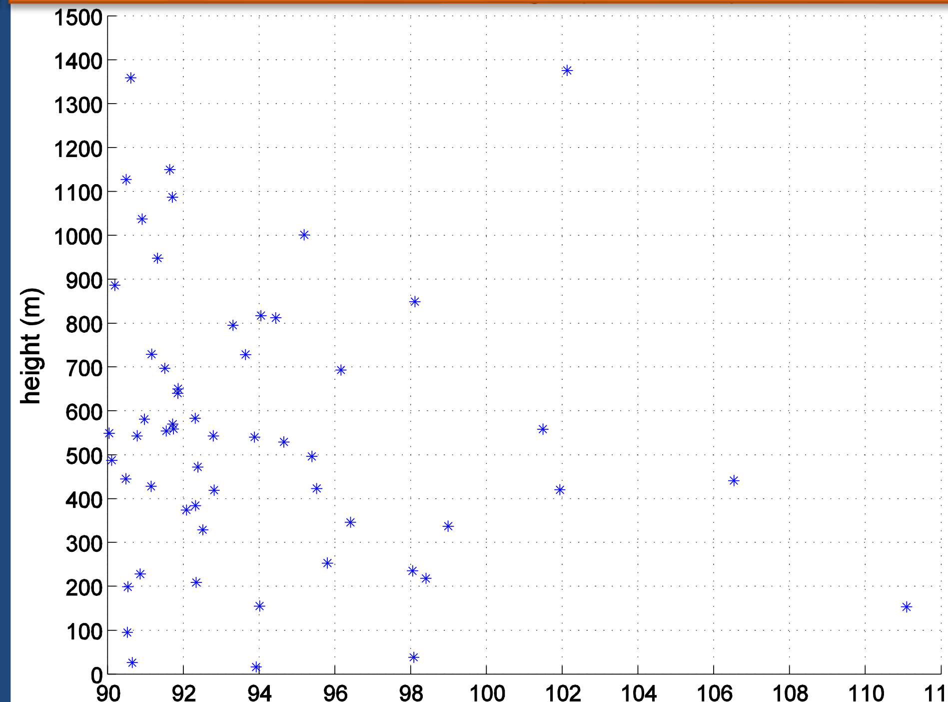
Maximum Updraft and Wind Speed vs. Height

Sondes with w>10 ms^{-1}



Maximum Vertical Velocity (ms^{-1})

Sondes with wspd>90 ms^{-1}



Maximum Wind Speed (ms^{-1})

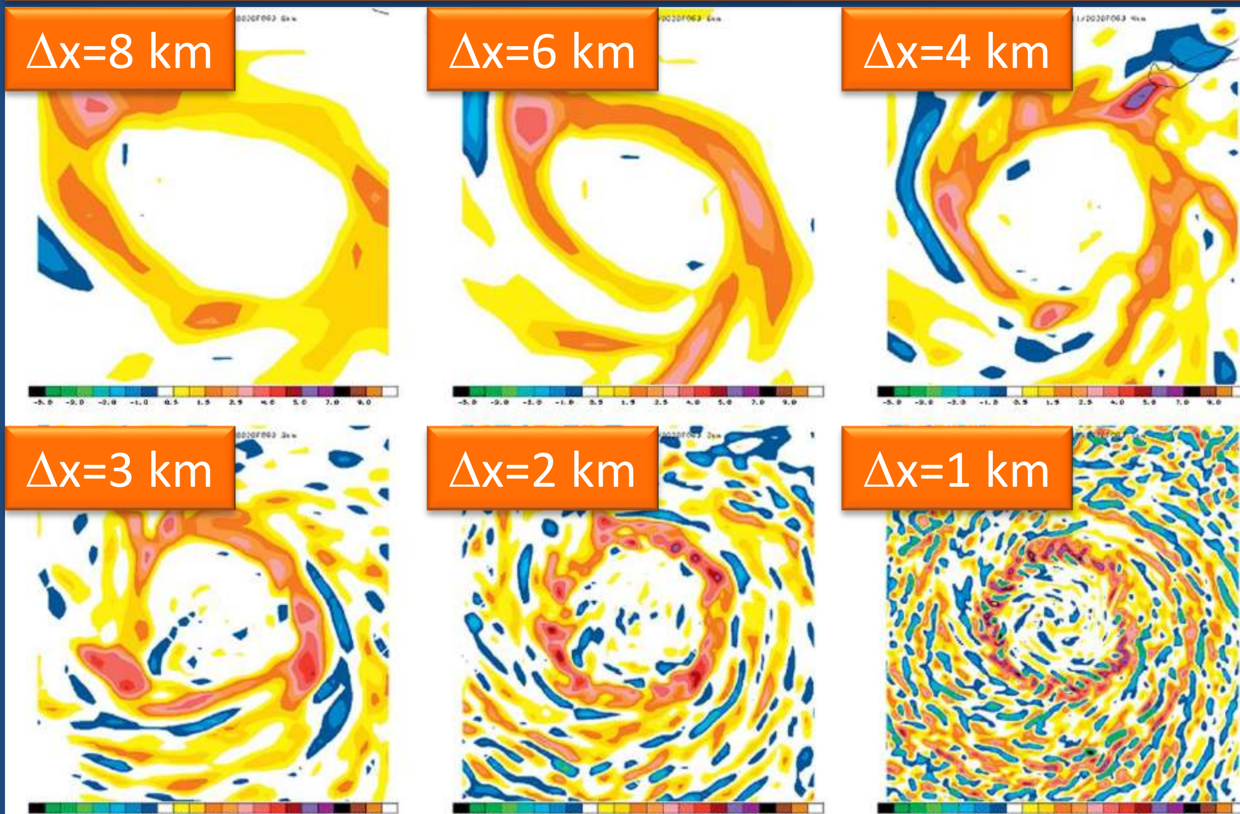
No clear relationship between magnitudes and heights of extremes.

The Limits of Observations

- Aircraft are unable to fly safely within the boundary layer in the eyewall.
- Dropsondes sample sparsely in space and time.
- We can gain further insight using Large-Eddy Simulations (LES).

Mesoscale Cloud-Permitting Modeling

Simulated Vertical Velocity, Hurricane Ivan (2004)



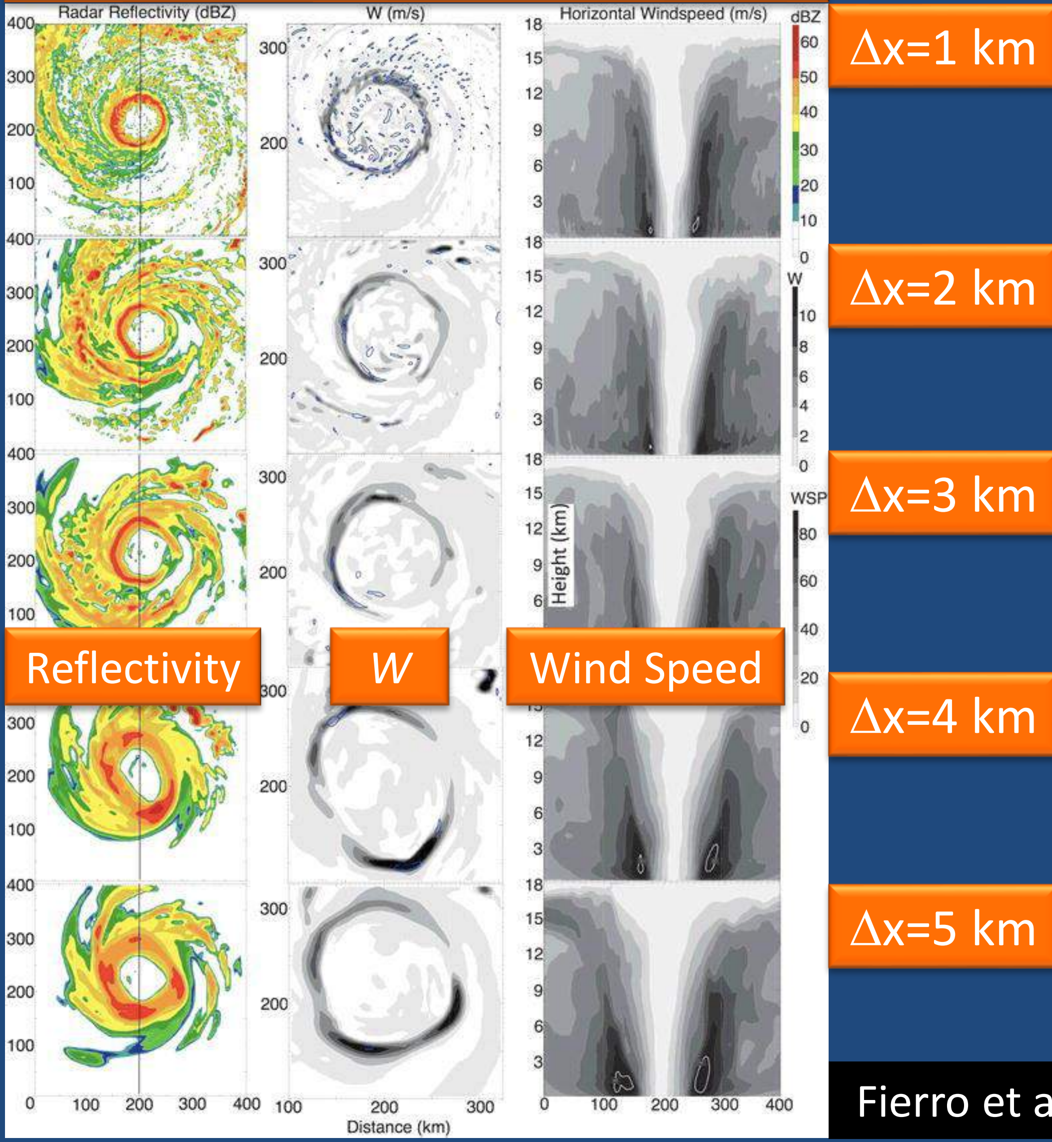
Gentry and Lackmann (2010)

As grid spacing decreases:

- More detailed and (hopefully) realistic structures are resolved.
- Updrafts tend to get stronger.
- The inner core tends to get smaller.

Mesoscale Cloud-Permitting Modeling

Simulated Hurricane Rita (2005)



Fierro et al. (2009)

As grid spacing decreases:

- More detailed and (hopefully) realistic structures are resolved.
- Updrafts tend to get stronger.
- The inner core tends to get smaller.
- The eyewall decreases in width and the area of strong winds decreases.

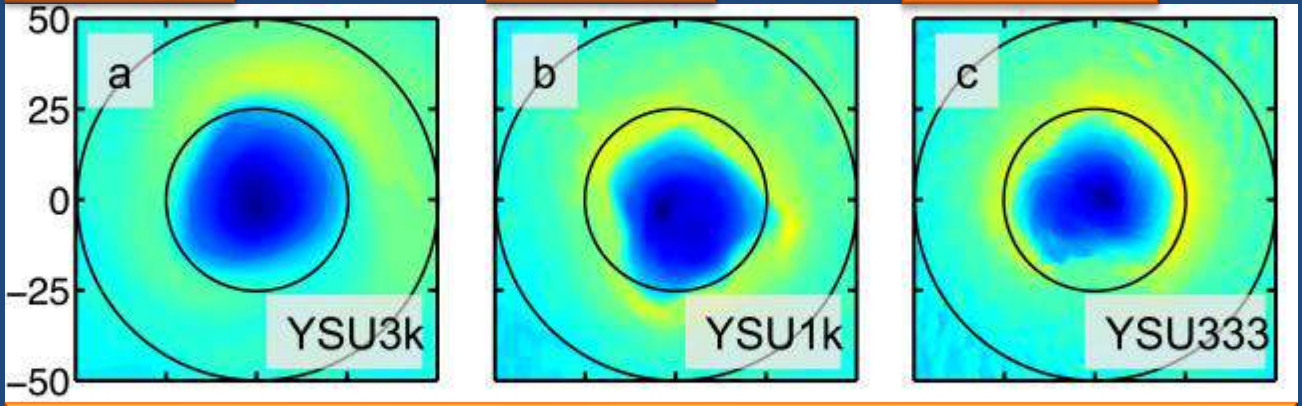
The Turbulent "Gray Zone"

- PBL schemes assume that ALL turbulence must be parameterized.
- But as we go to sub-kilometer grid spacing, we start to partially resolve large eddies, which can be problematic.

Δx=3 km

Δx=1 km

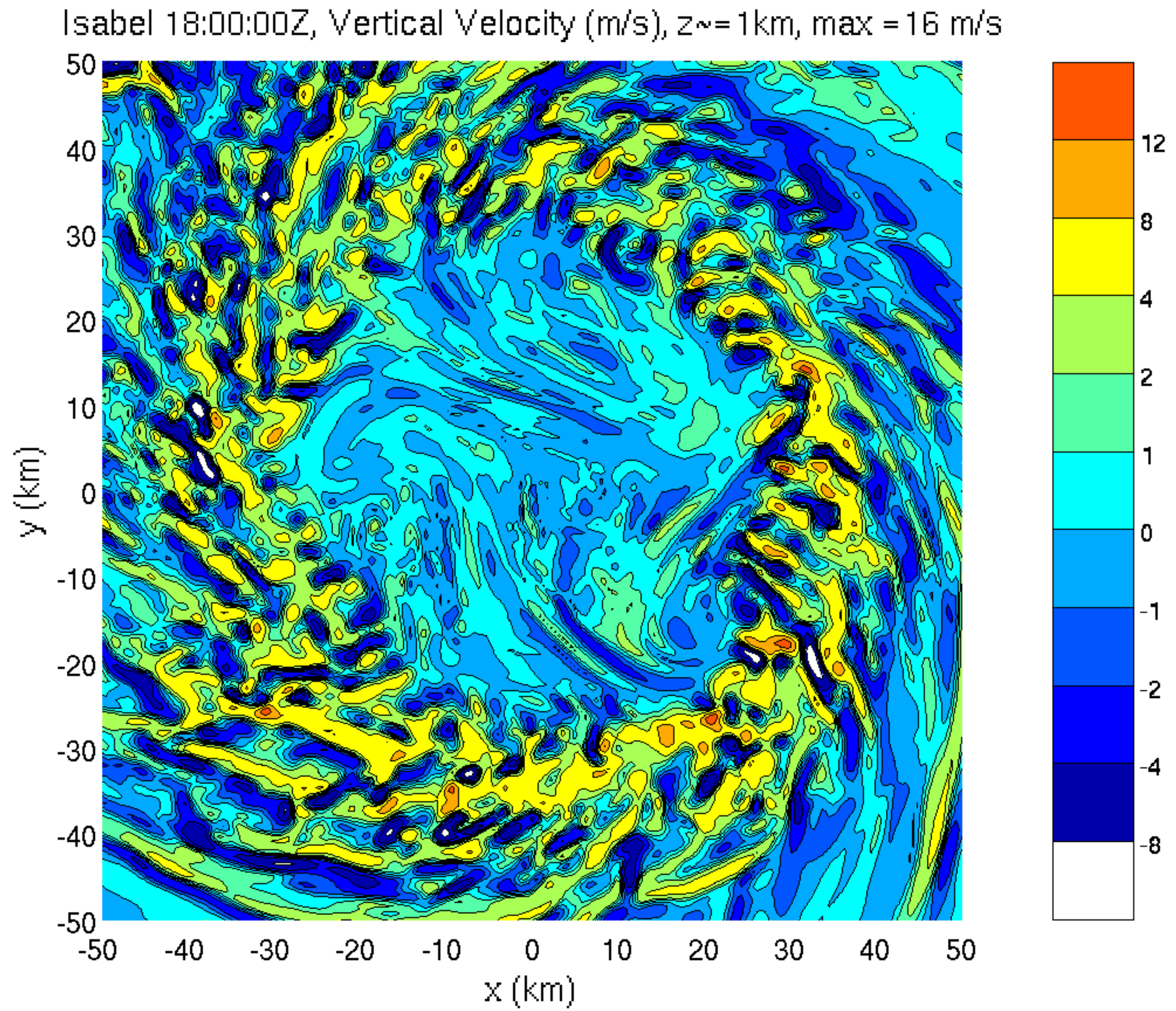
Δx=333 m



Simulated Hurricane Katrina (2005), 10-m Wind Speed

Green and Zhang (2015)

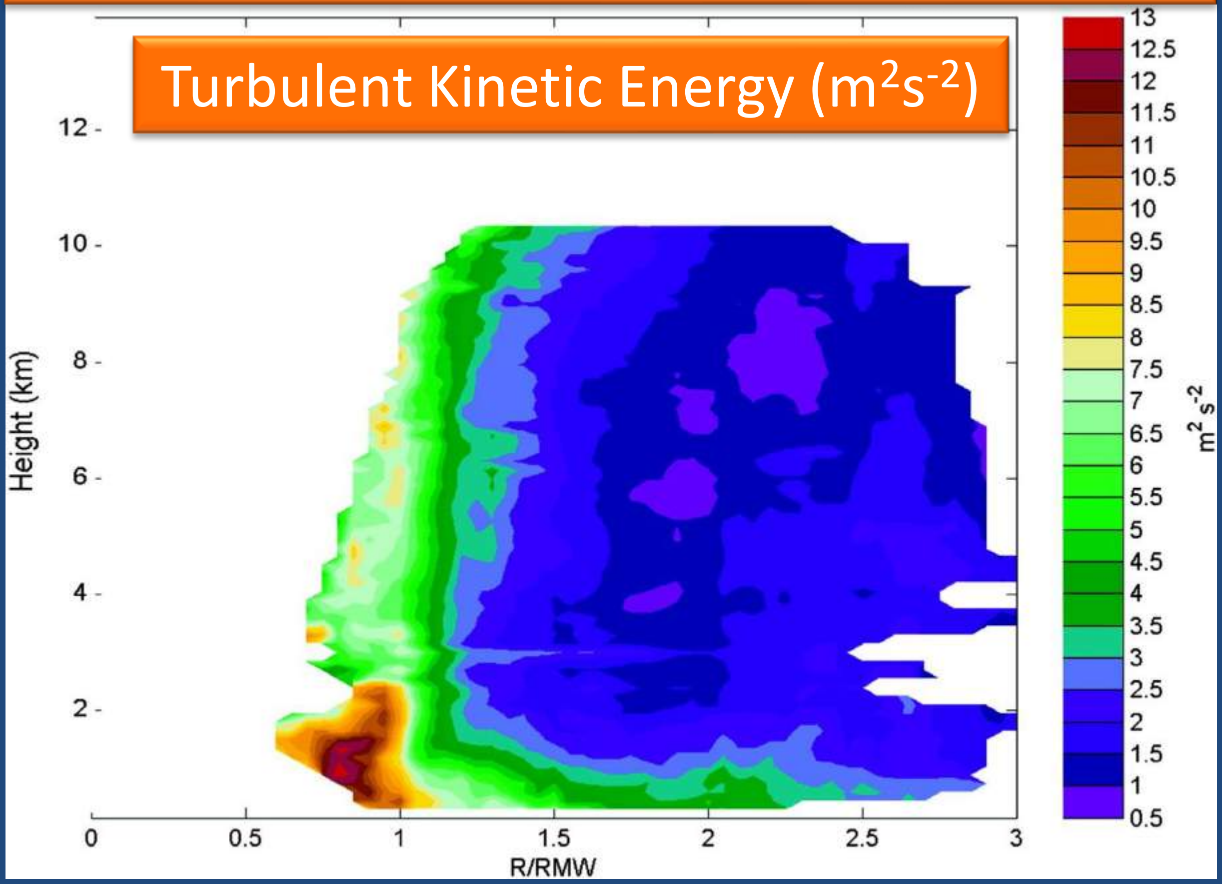
Vertical Velocity, Isabel, Δx=444 m



Simulation from Nolan et al. (2007 a,b)

The Hurricane Eyewall is Turbulent

Composite of Major Hurricanes



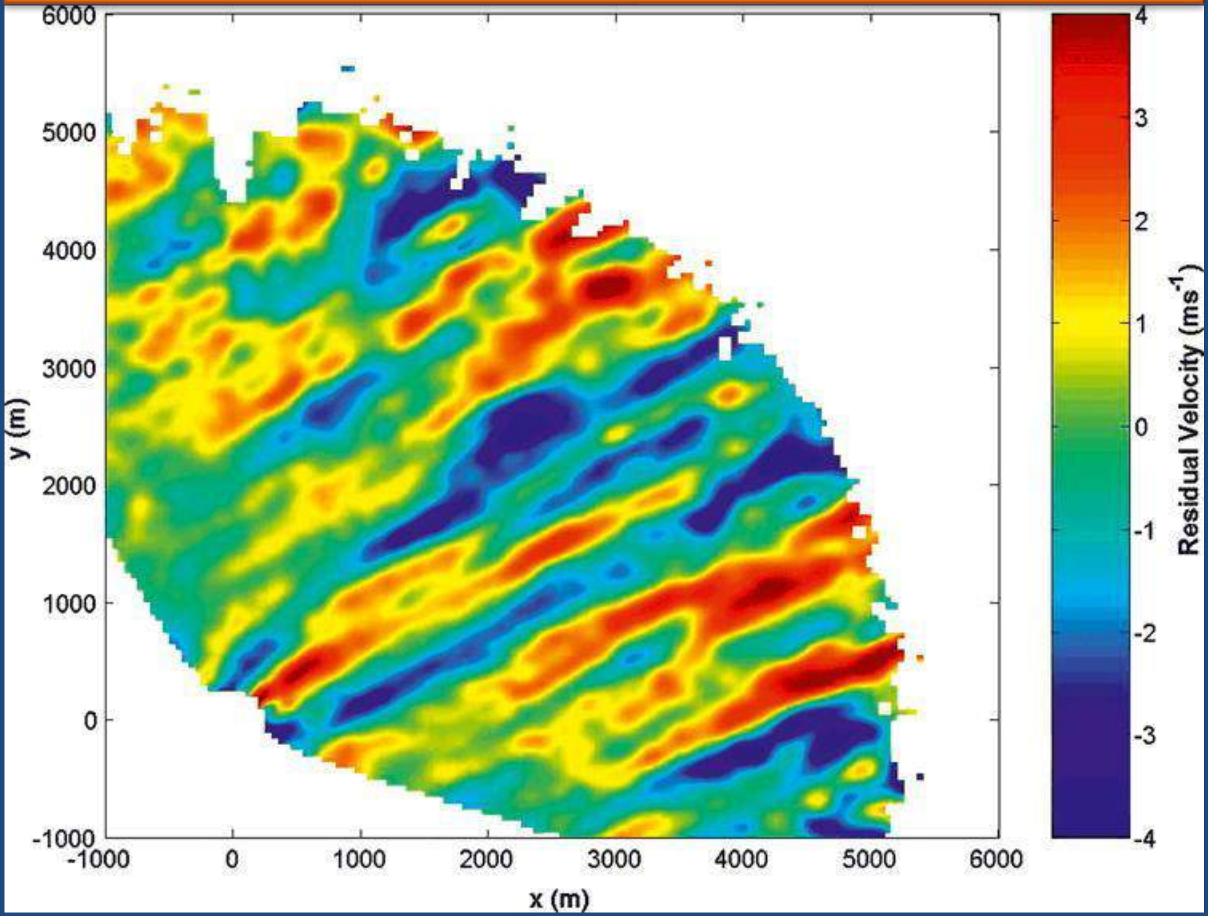
$$\mathrm{TKE} = \frac{1}{2}(u'^2 + v'^2 + w'^2)$$

- The outer core is turbulent within the boundary layer.
- The eyewall is turbulent at all heights, especially in the lowest 2 km.

Rogers et al. (2012)

Boundary Layer Rolls

Perturbation Radial Velocity, z=300 m
Hurricane Frances (2004)

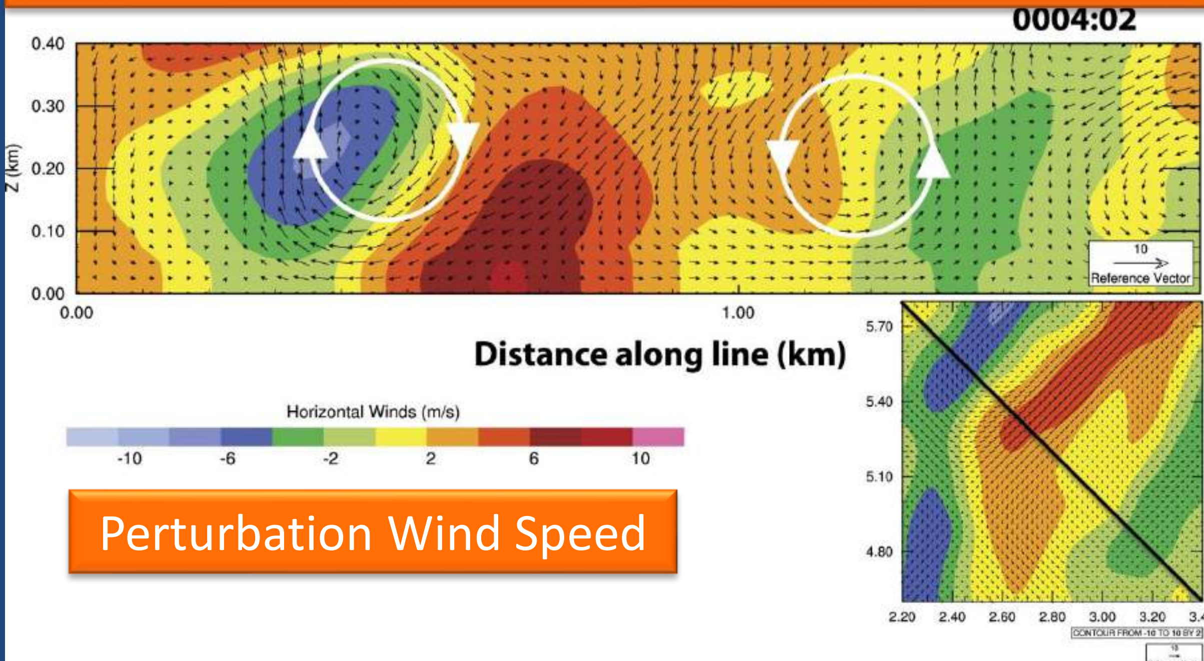


- Roll vortices are very common in the hurricane boundary layer.
- Scales vary, but are generally sub-kilometer.

Lorsolo et al. (2008)

Boundary Layer Rolls

Vertical Cross Section through Roll
Hurricane Frances (2004)



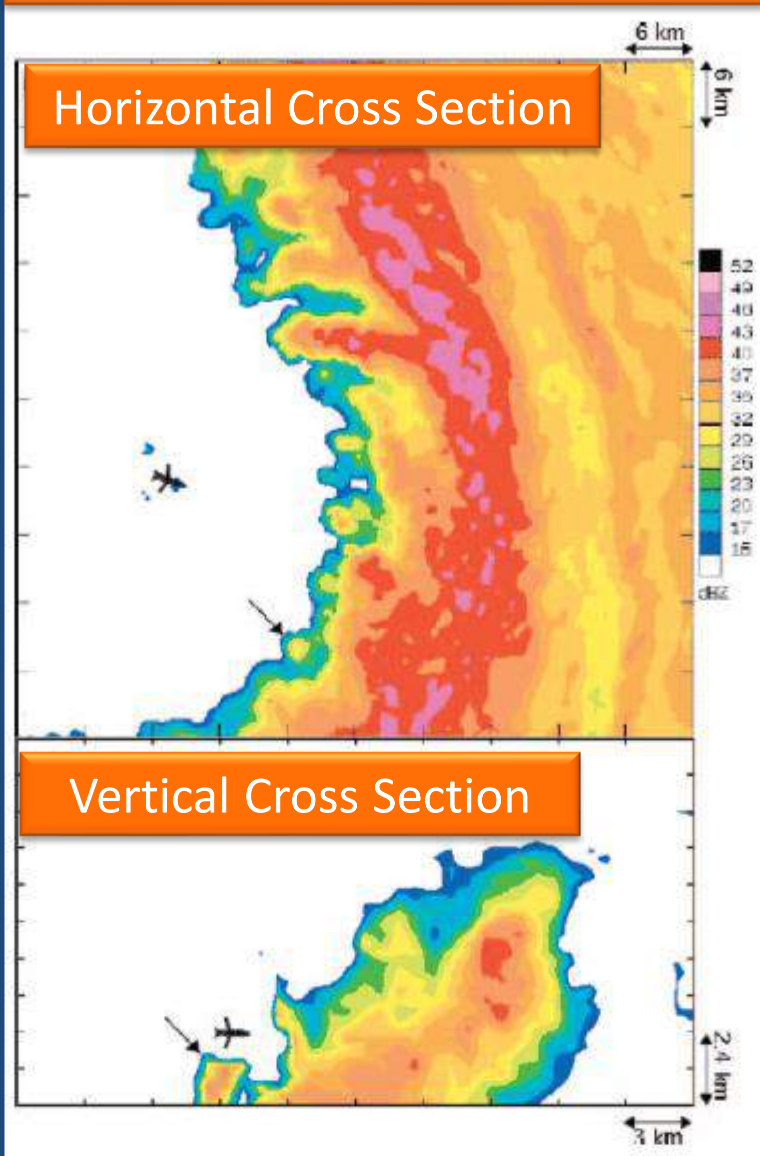
Perturbation Wind Speed

- Rolls tend to transport high momentum air upwards and low momentum air downwards.
- These features are generally unresolved by mesoscale models.

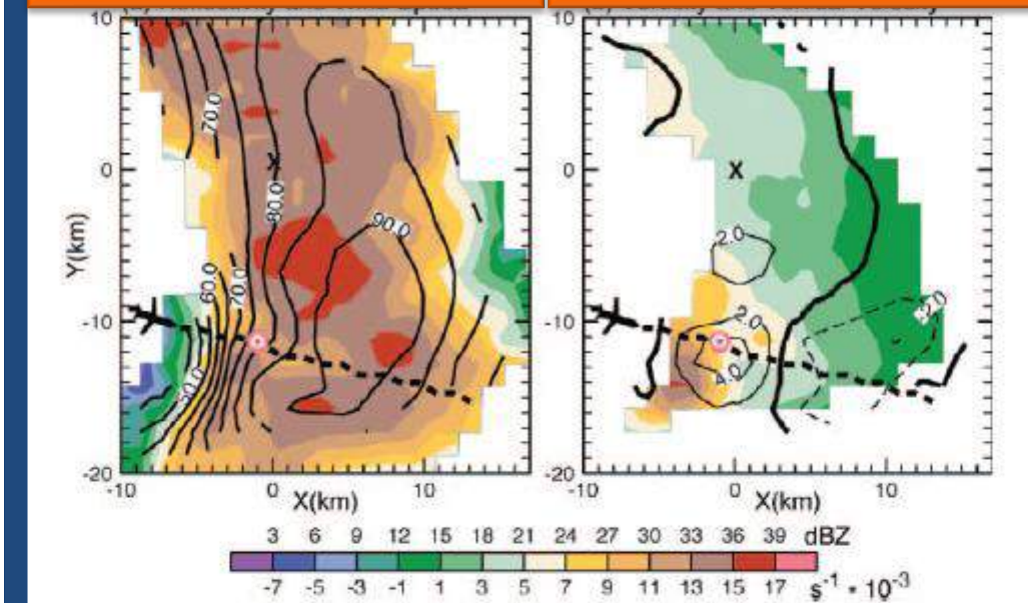
Kosiba and Wurman (2014)

Coherent Eyewall Vortices

Hurricane Isabel (2003)



Reflectivity, Wind Speed | Vorticity, Vert. Velocity



- Observations suggest that small-scale three-dimensional vortices can form on the inner edge of the eyewall.

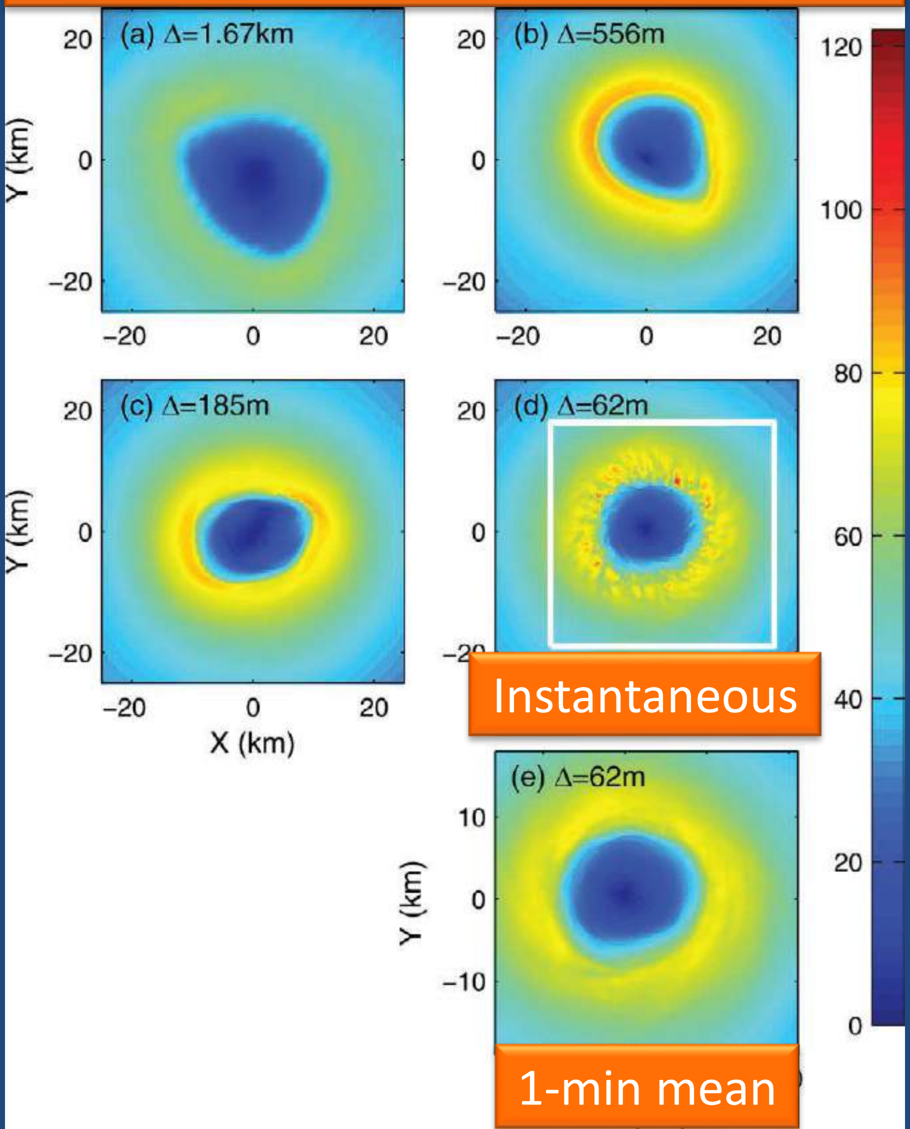
Aberson et al. (2006)

Limitations of Cloud-Permitting Simulations

- Tropical cyclone simulations typically use grid spacing Δx = 1-4 km.
- Important structures (e.g., boundary layer rolls, eyewall vortices) are unresolved at these grid spacings.
- To properly resolve features, grid spacing needs to be at least 4-6 times smaller than the scale of the feature.
- To resolve turbulent structures in TCs, need Δx <~ 100 m.
- At this resolution, the "large eddies" are mostly resolved, and we no longer need to parameterize the boundary layer.

Large Eddy Simulations (LES)

Wind Speed at z=10 m



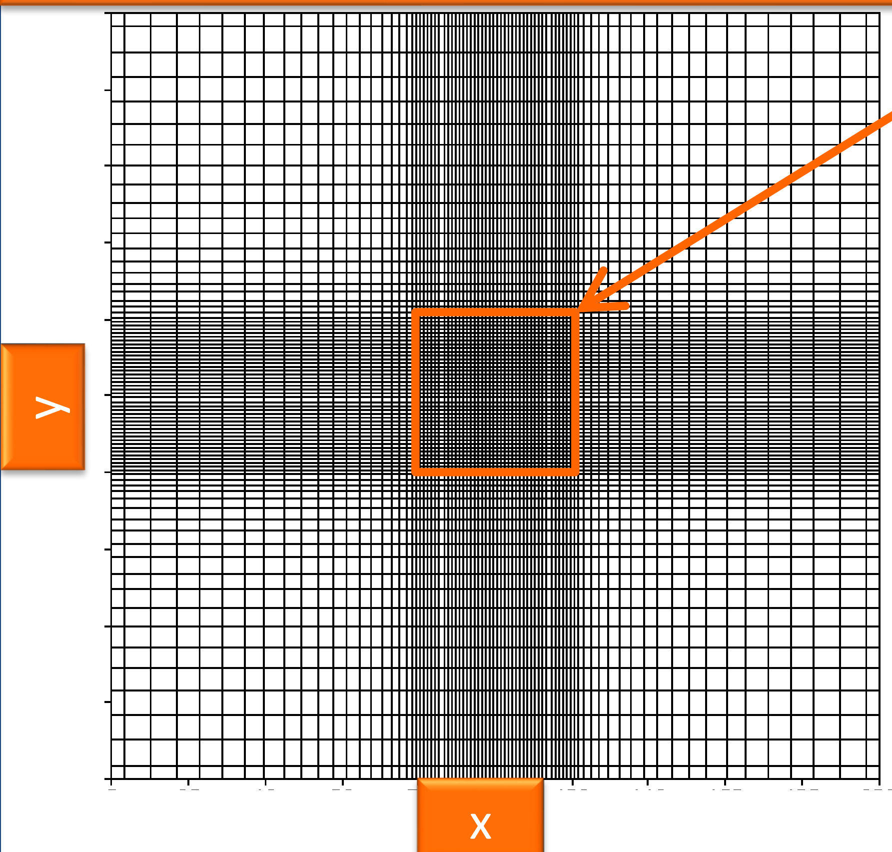
- WRF-LES idealized simulation with nested grids.
- PBL scheme on for Δx=1.67 km, off for finer domains.
- Turbulence develops only when grid spacing < 100 m.
- 1-min average winds are much less than instantaneous winds.

Rotunno et al. (2009)

CM1 Model

- A non-hydrostatic, cloud-resolving model, similar in numerics to WRF
- Utilizes a single domain, with grid stretching
- Can be configured for Large-Eddy Simulations

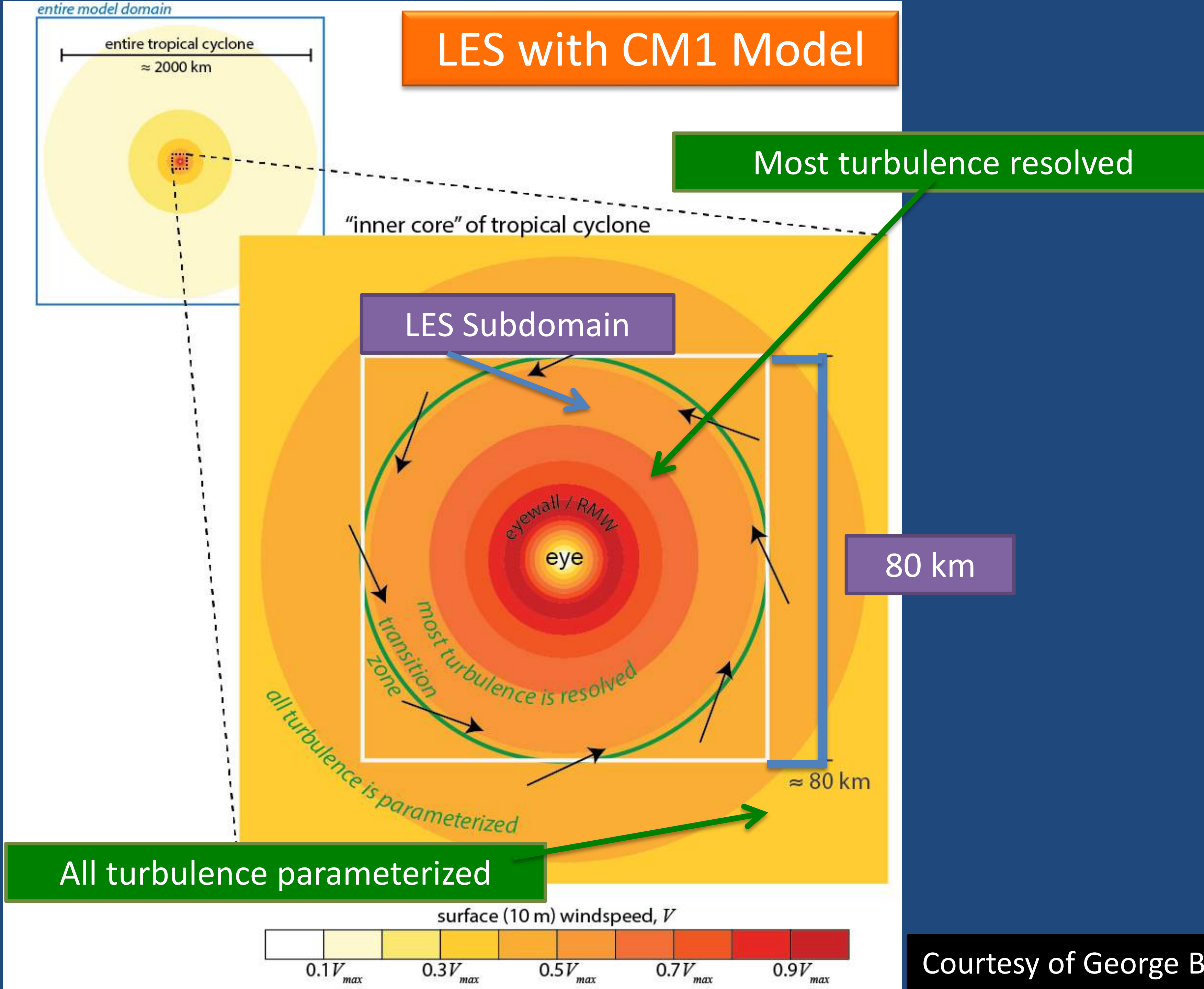
Layout of Horizontal Grid



Fine-mesh part of domain:

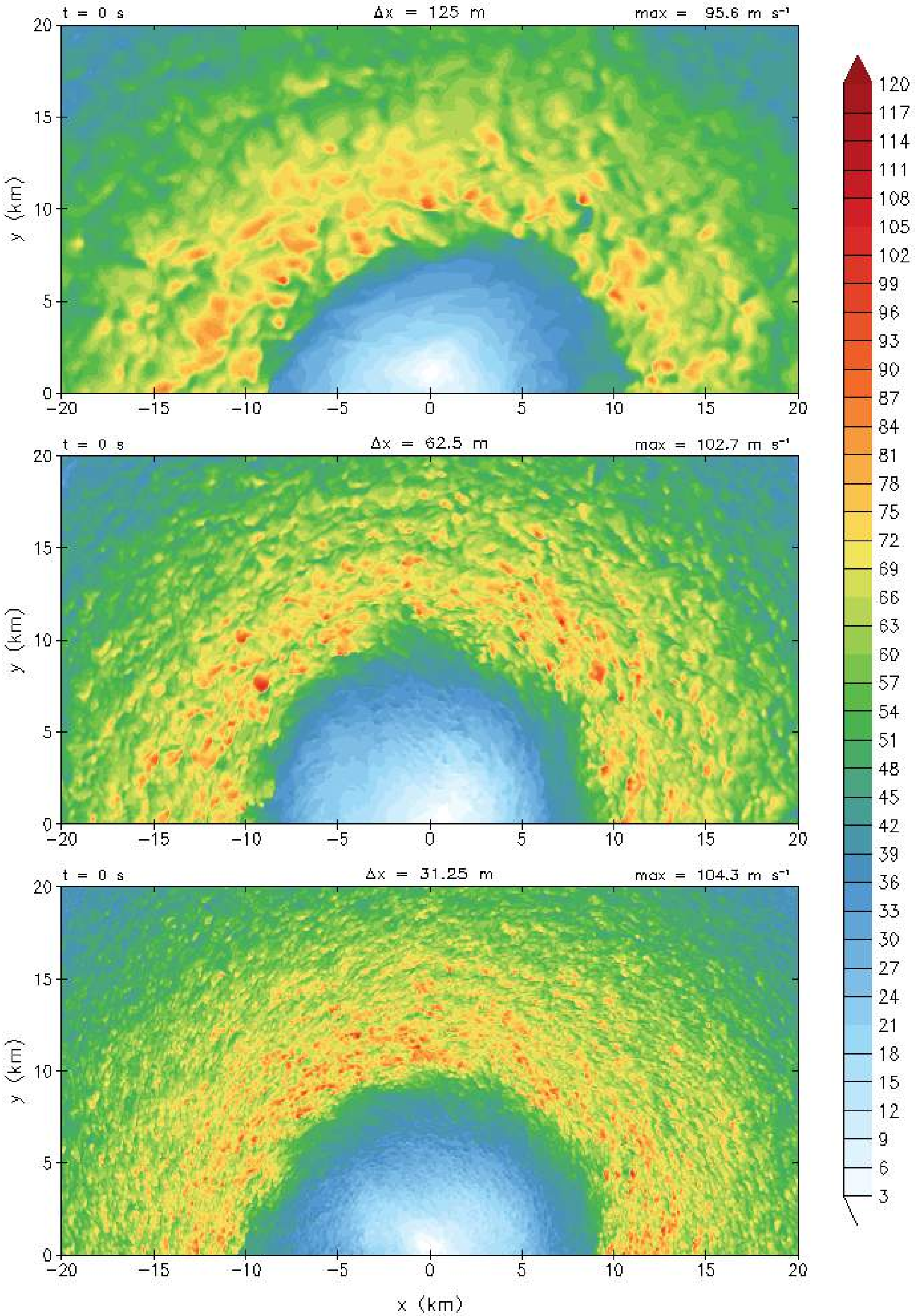
- Fine Mesh Region:
  - 80 km × 80 km × 3 km
  - No PBL Scheme (only LES subgrid model; Deardorff 1980)
- Rest of domain:
  - Δx, Δy, Δz increase gradually
  - Parameterized turbulence (i.e., PBL scheme)

LES with CM1 Model



Courtesy of George Bryan

Wind Speed at z=10 m



Δx=125 m

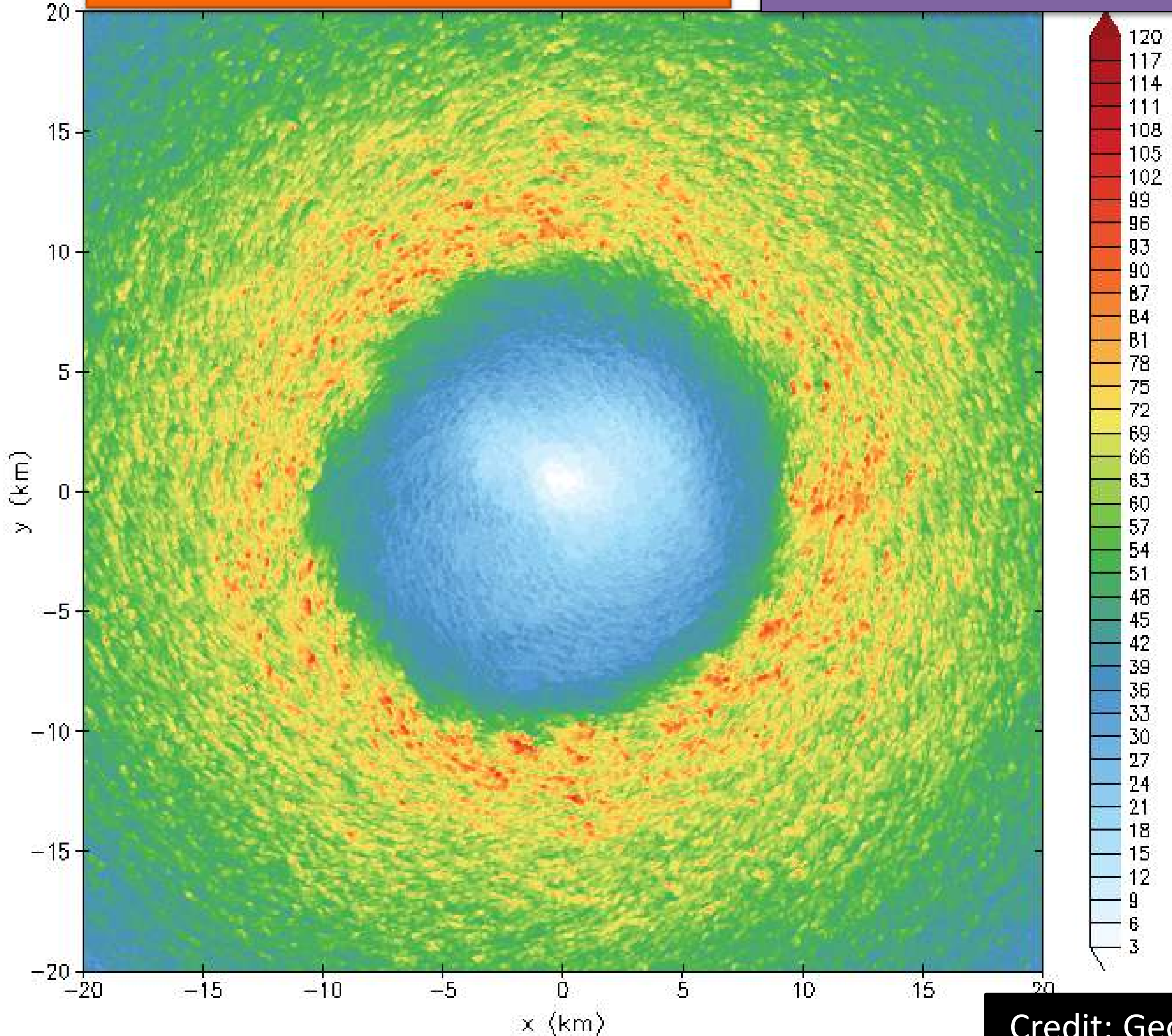
Δx=62.5 m

Δx=31.25 m

Credit: George Bryan

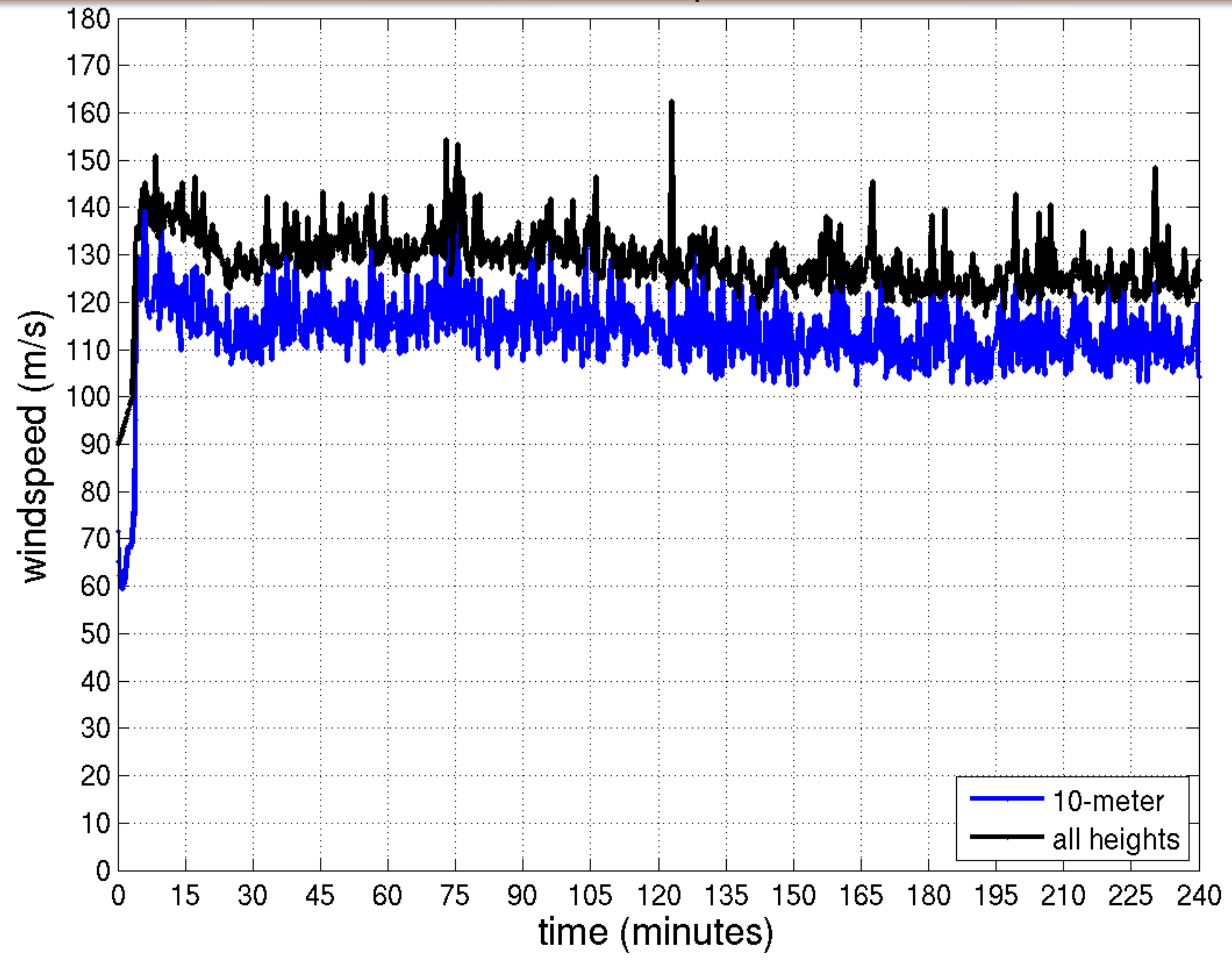
Wind Speed at z=10 m

Δx=31.25 m

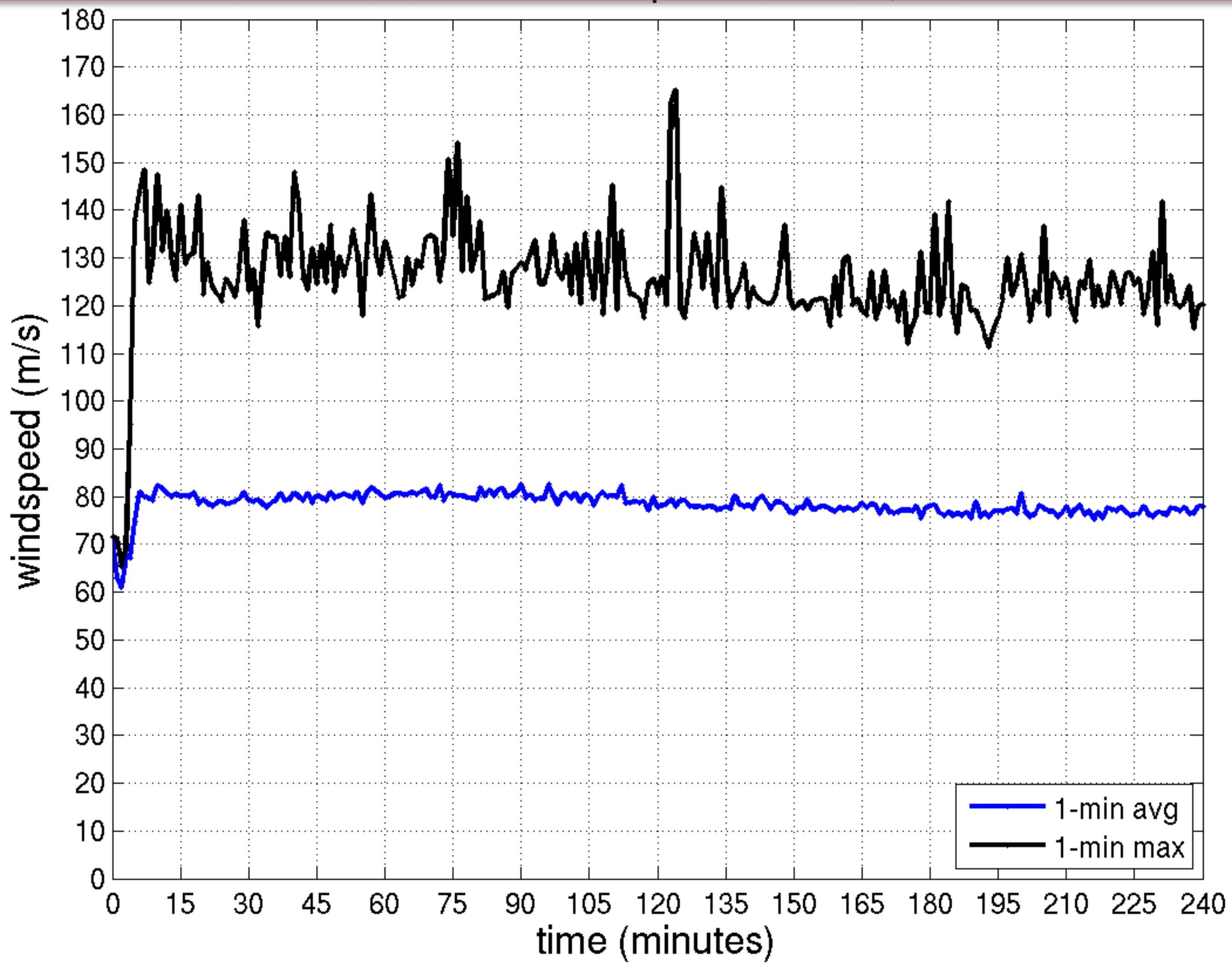


Credit: George Bryan

Peak Instantaneous Wind Speed Vs. Time



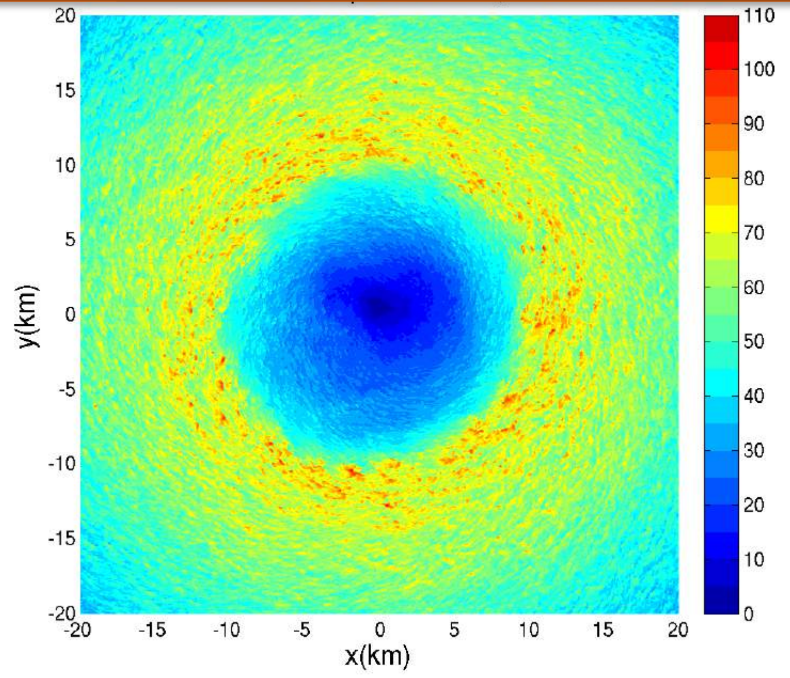
Peak 10-meter Wind Speed Vs. Time



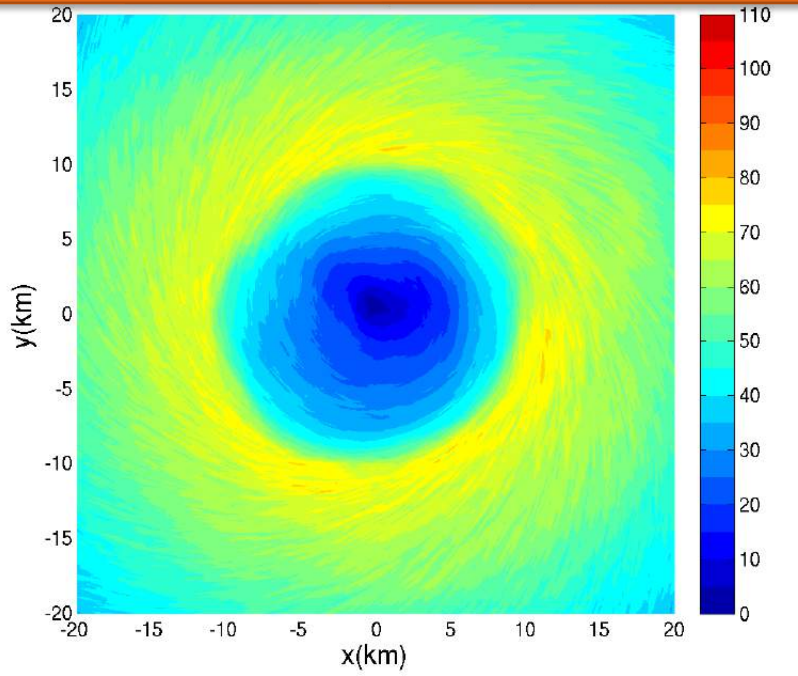
- Instantaneous wind gusts are extremely strong
- Peak 1-min average wind speed is representative of category-5

Wind Speed (ms^{-1}) at z=10 m

Instantaneous Wind Speed

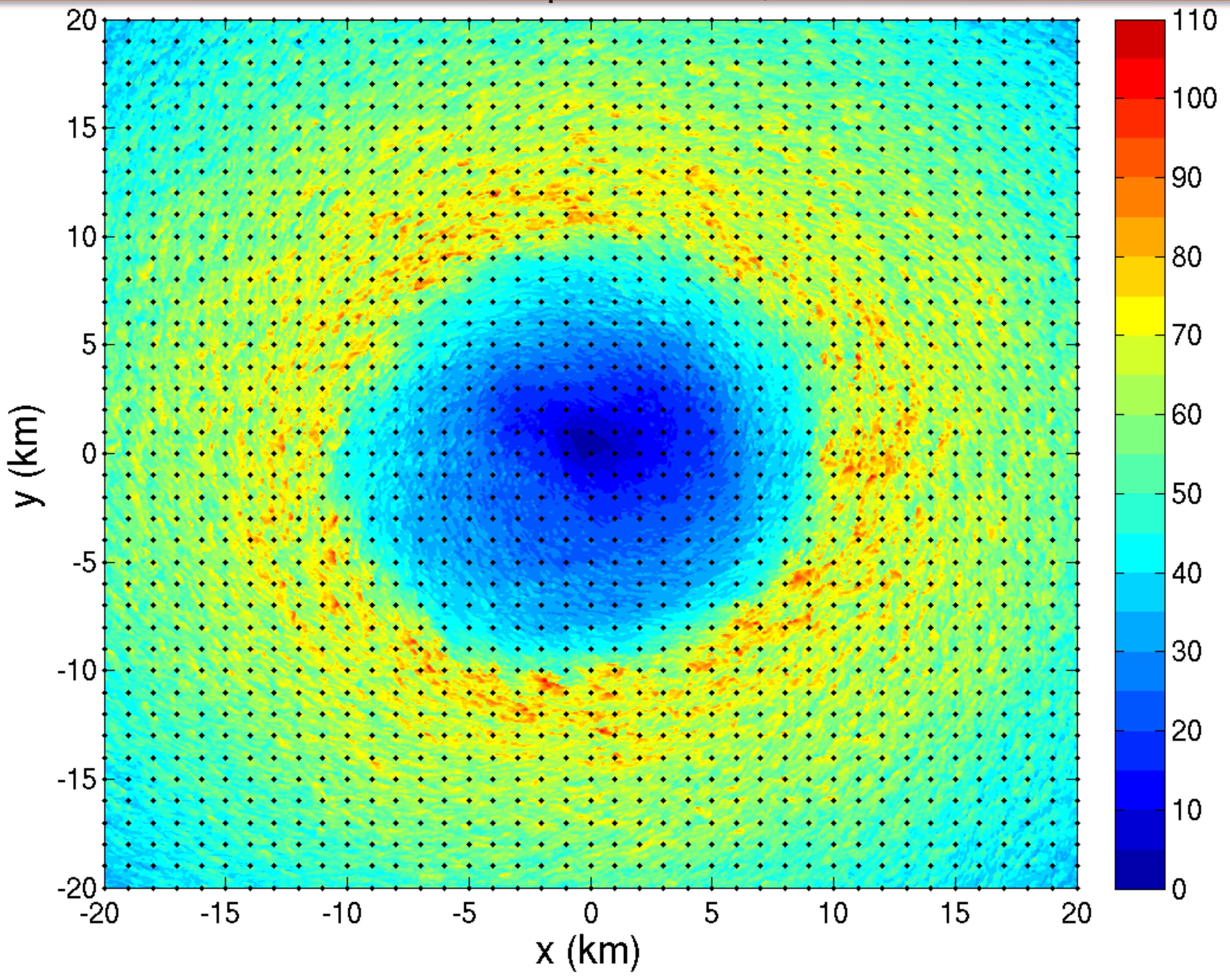


1-min Avg. Wind Speed

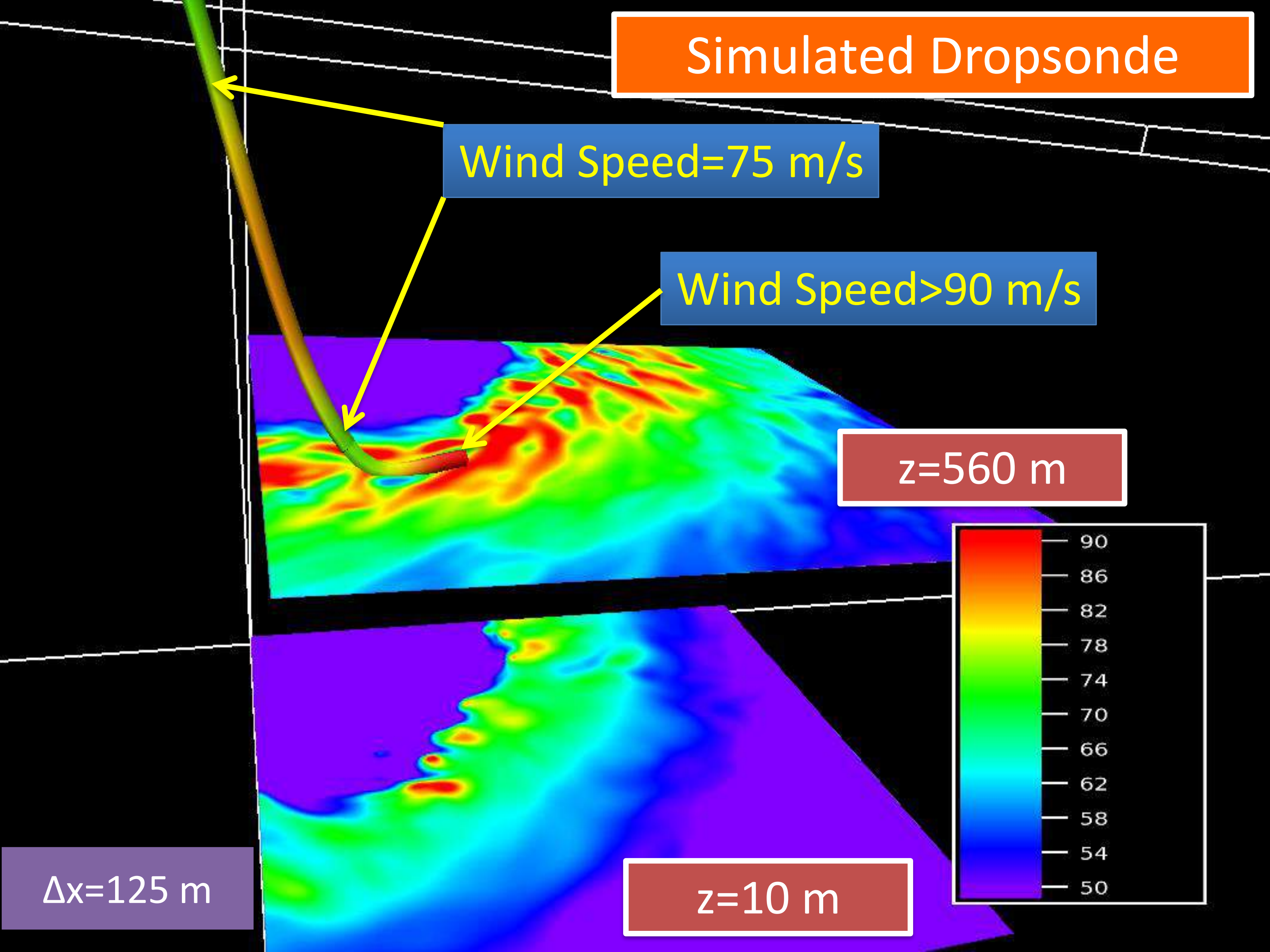


- Numerous instantaneous wind gusts in excess of 100 ms^{-1}
- The 1-min mean wind speed is much weaker, 70-80 ms^{-1} in the eyewall

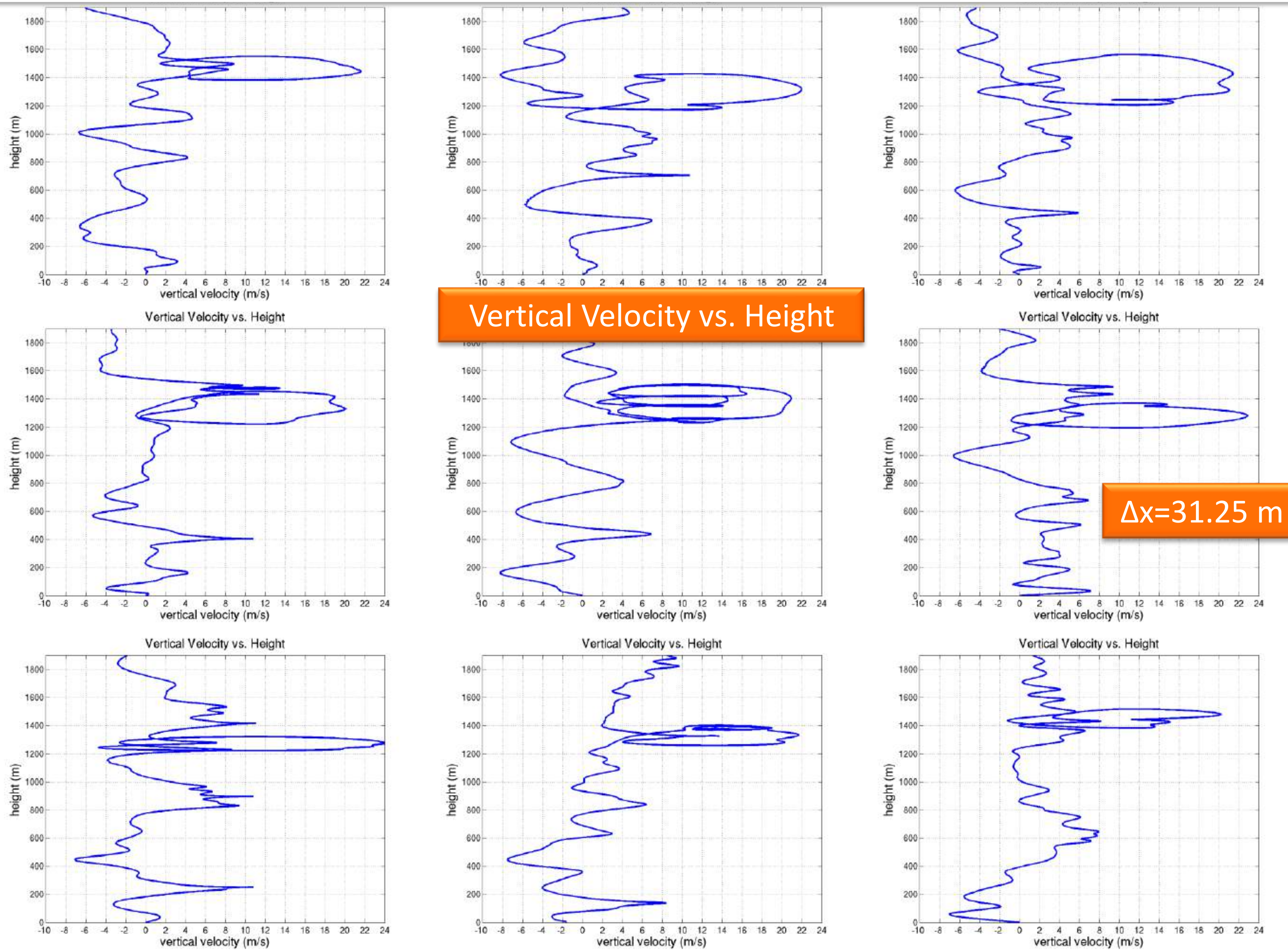
10-m Wind Speed at t=4h; Simulated Dropsondes



- Sondes released every 8 grid points (250 m); every 1 km shown
- 103,041 “virtual” dropsondes


Simulated Dropsonde
Wind Speed=75 m/s
Wind Speed>90 m/s
z=560 m
z=10 m
Δx=125 m
90
86
82
78
74
70
66
62
58
54
50

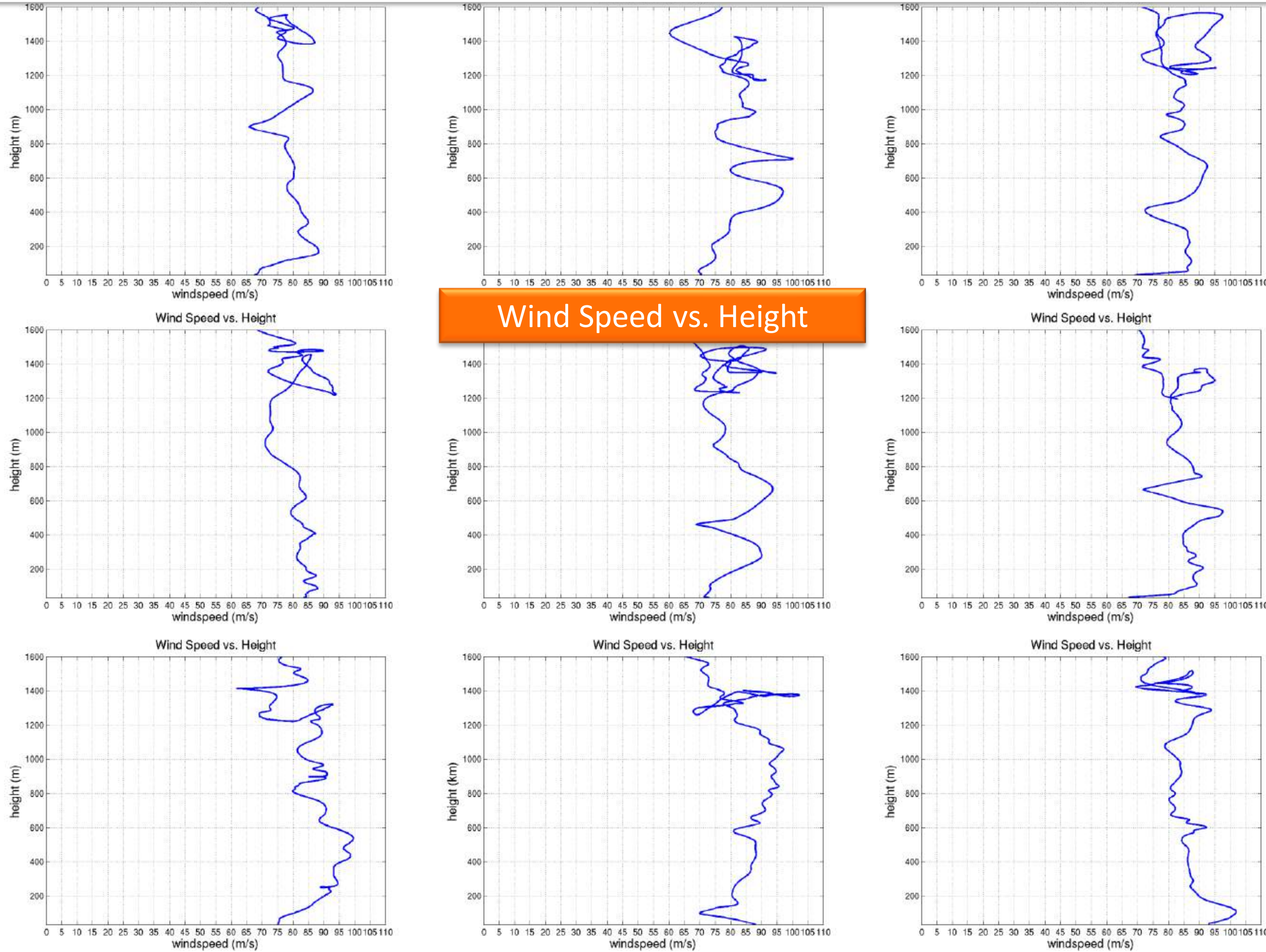
Which is the real dropsonde?



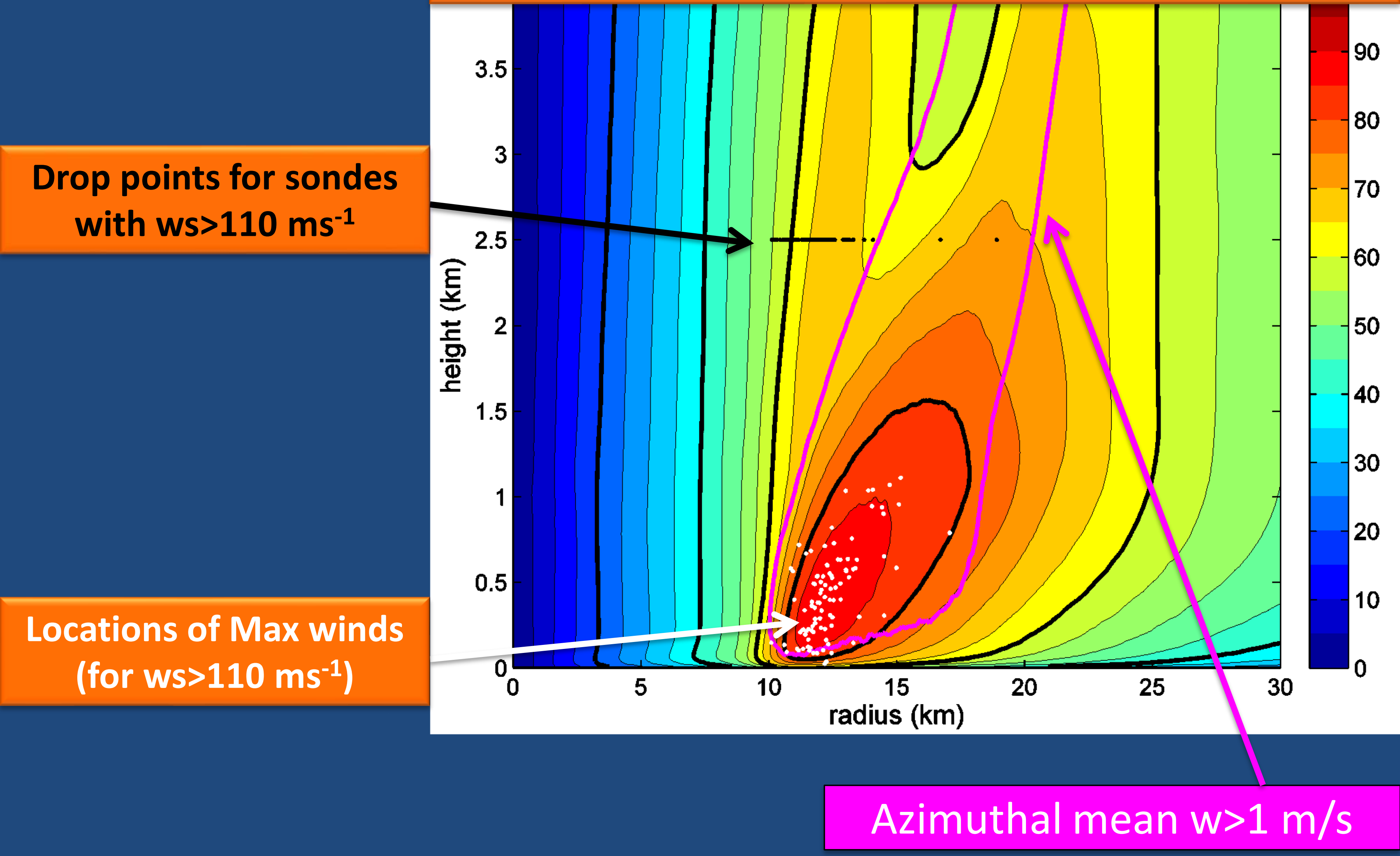
Vertical Velocity vs. Height

Δx=31.25 m

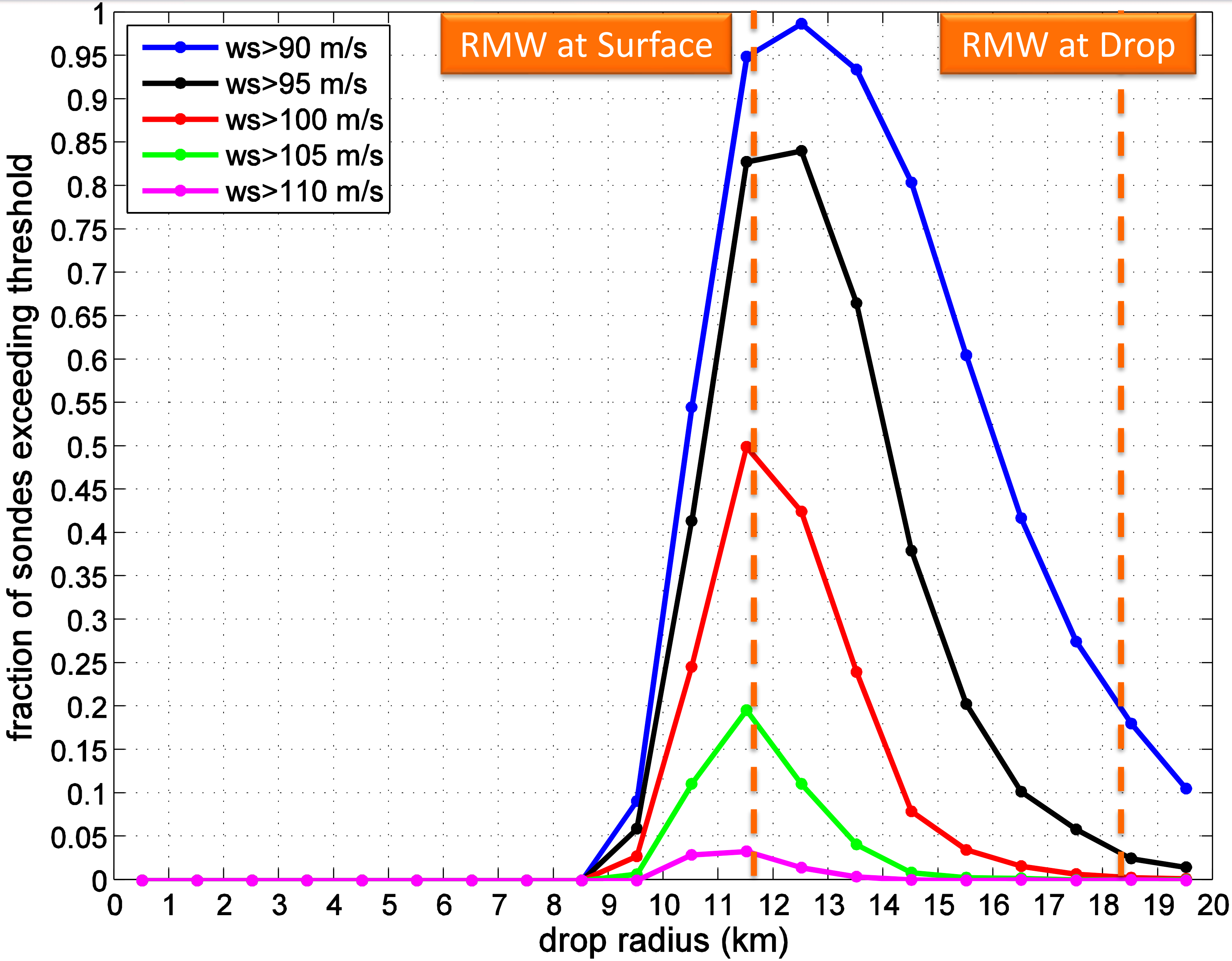
Which is the real dropsonde?



Azimuthal Mean Tangential Wind

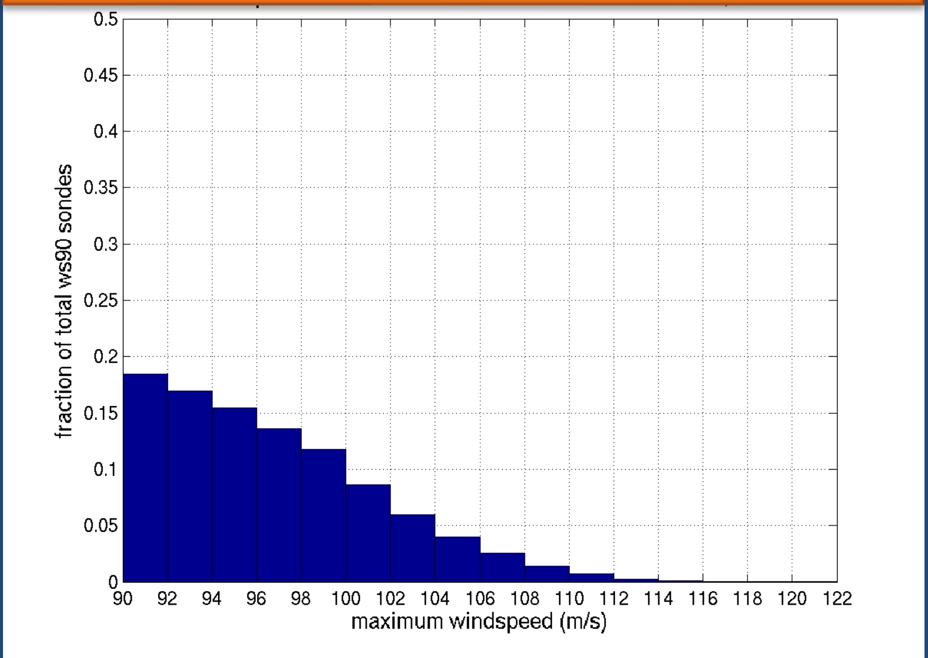


Fraction of Sondes Sampling Extreme Winds

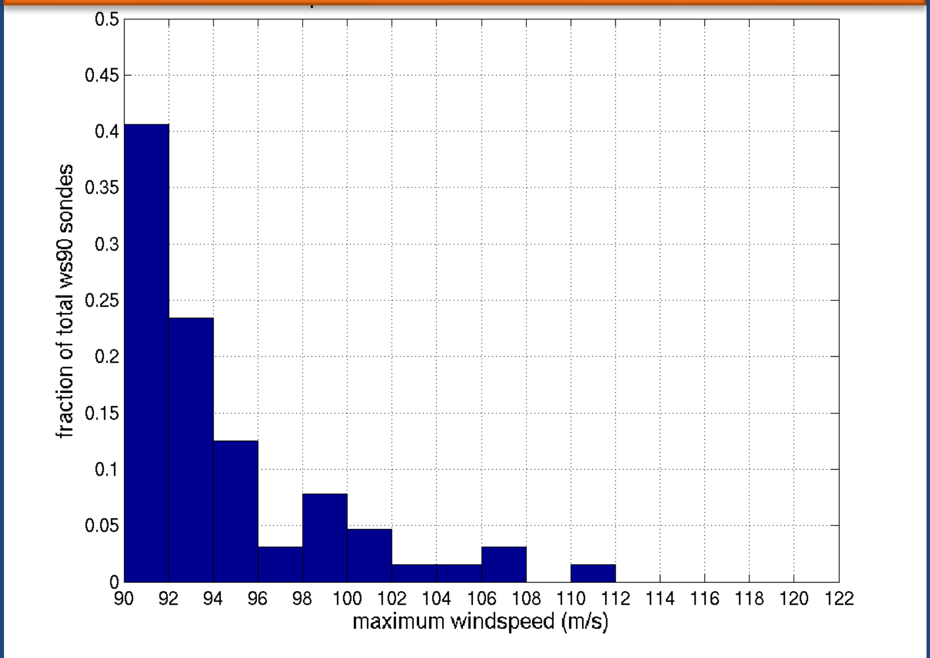


Comparison of Simulated to Observed Dropsondes

Simulated Sonde WS > 90 ms^{-1}

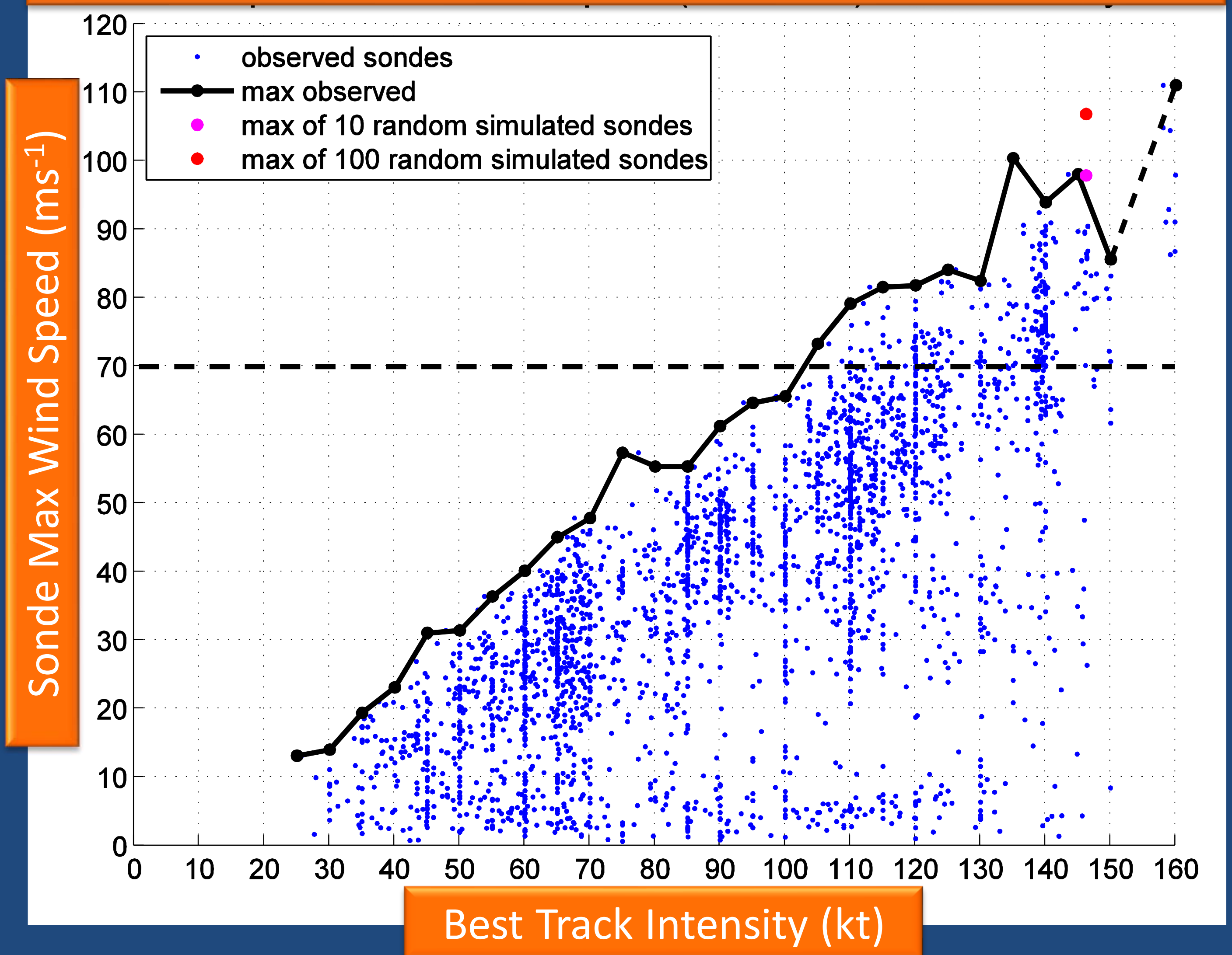


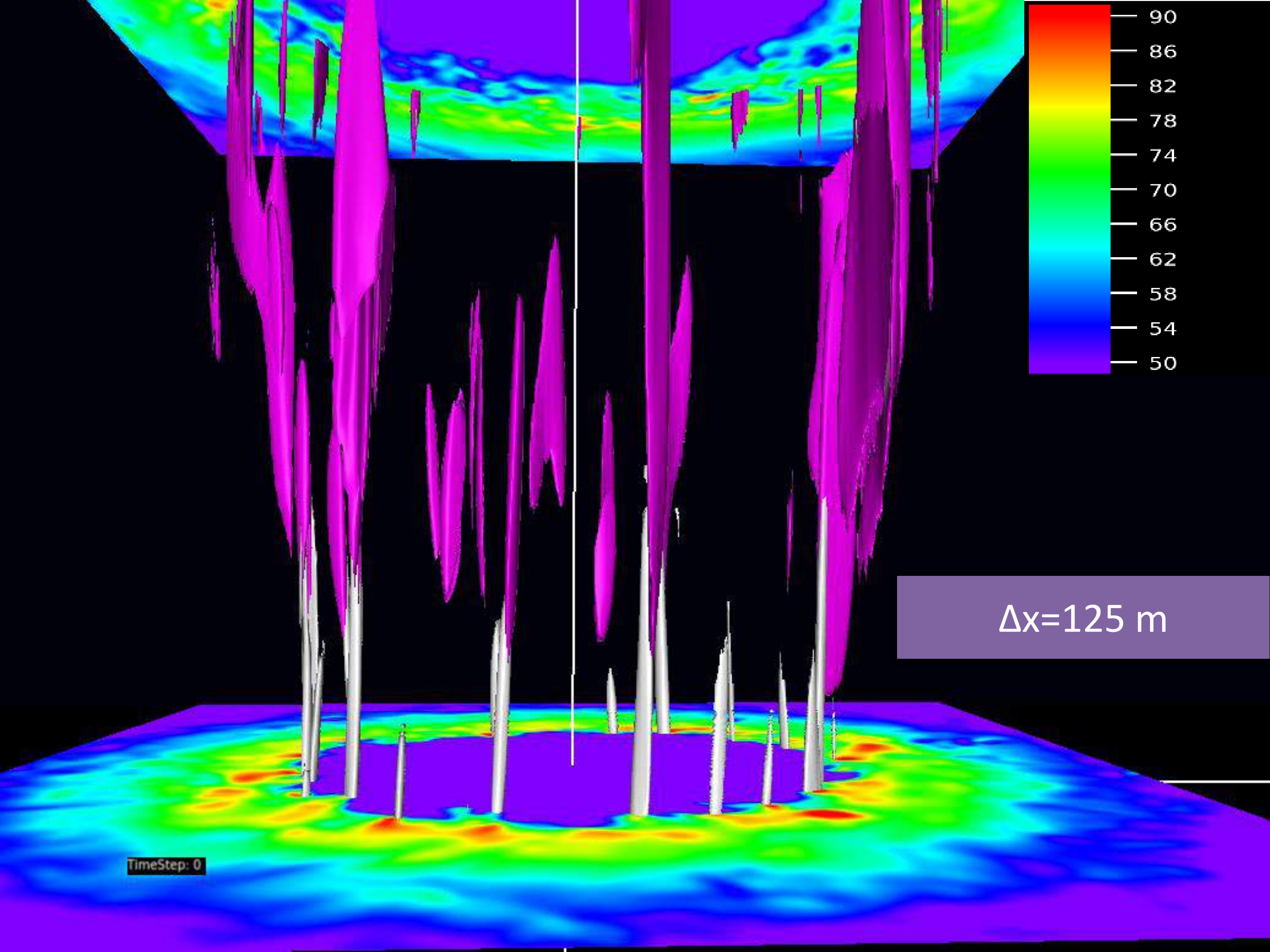
Observed Sonde WS > 90 ms^{-1}

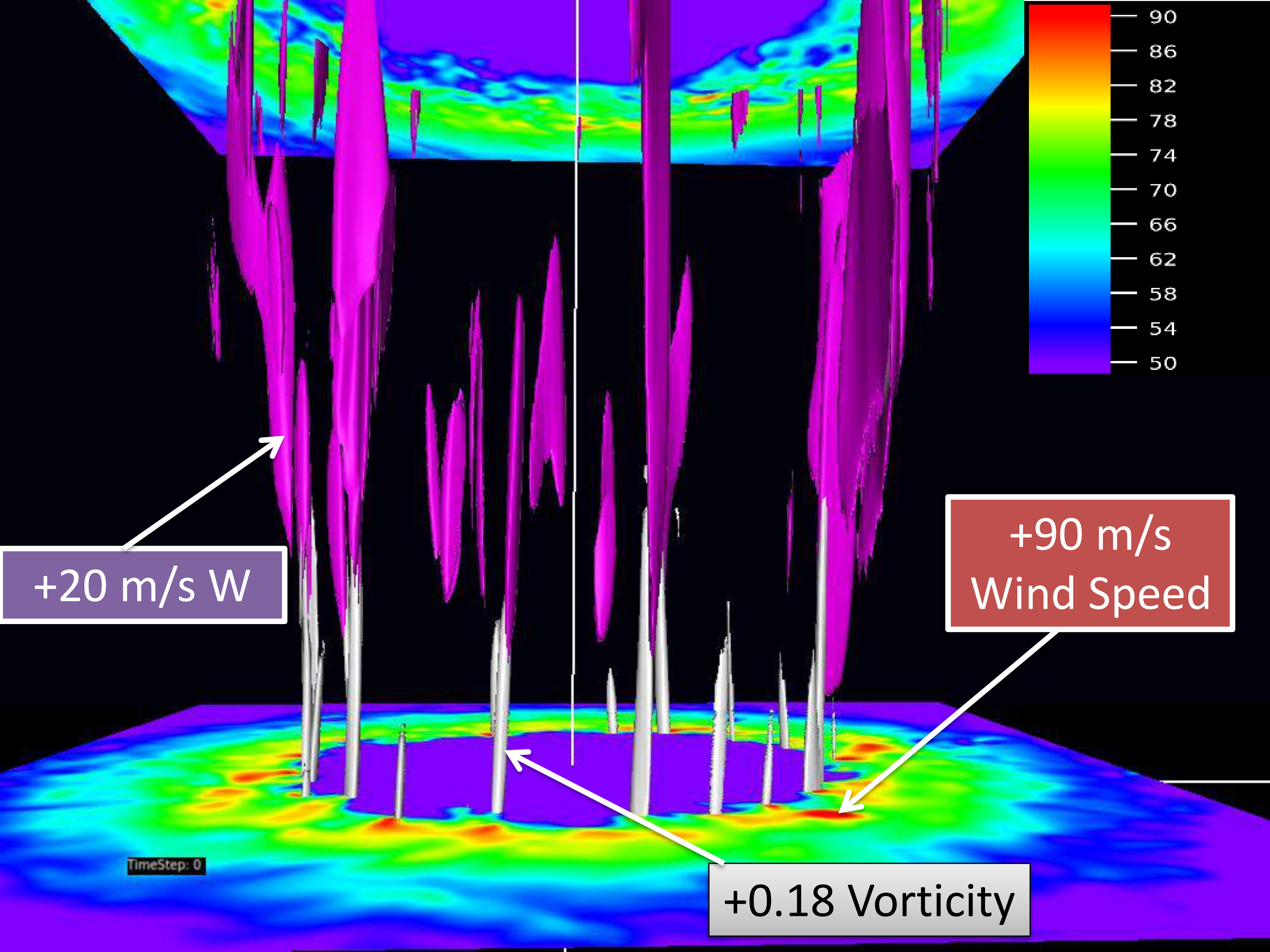


- Magnitude of strongest sampled wind gusts is comparable
- Simulated sondes sample the most extreme values more frequently than observed
- This is likely because the simulated TC is slightly stronger than the average observed TC

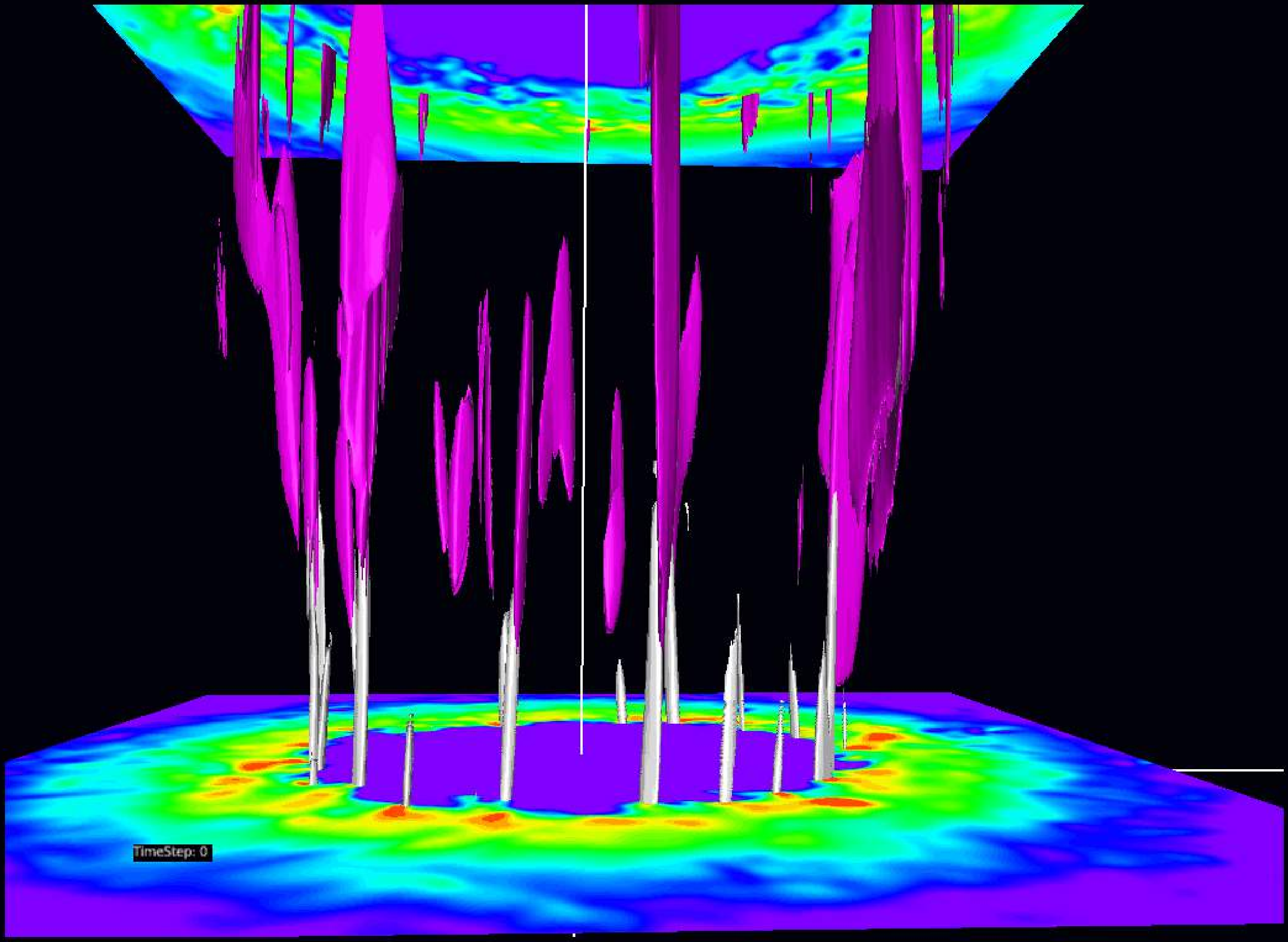
Observed Sonde Max Wind Speed (z=0-200m)



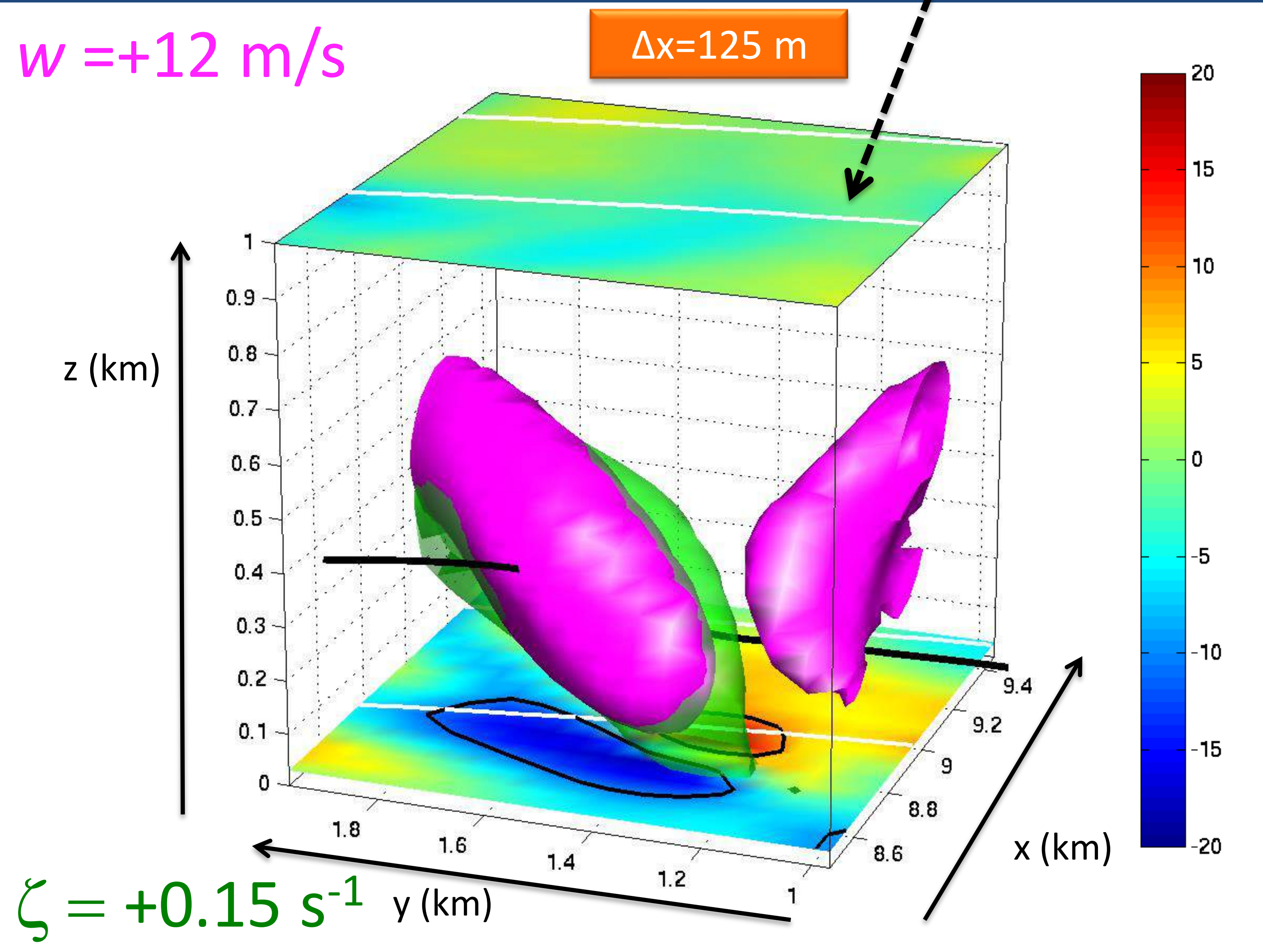

90
86
82
78
74
70
66
62
58
54
50
Δx=125 m
TimeStep: 0



90
86
82
78
74
70
66
62
58
54
50
+20 m/s W
+90 m/s
Wind Speed
TimeStep: 0
+0.18 Vorticity


TimeStep: 0

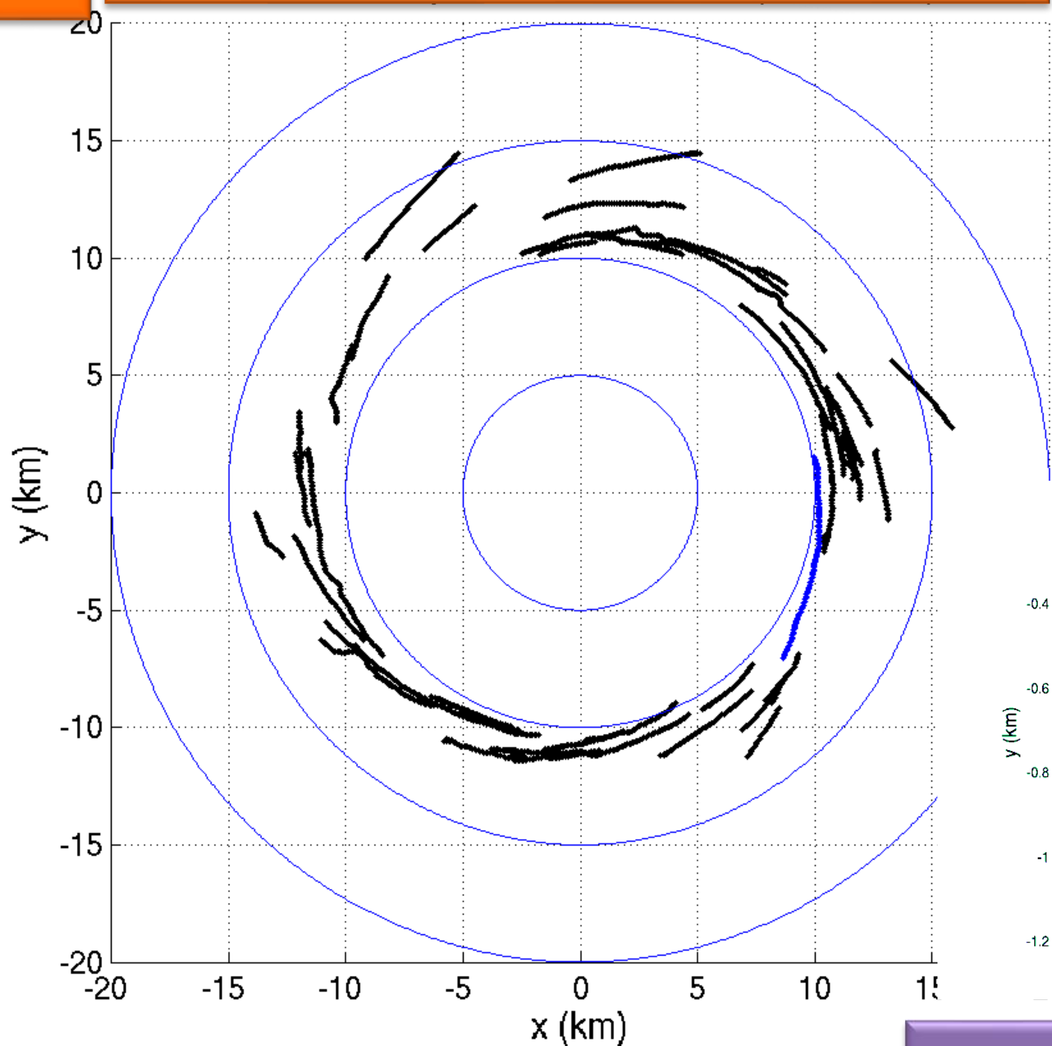
Slices of Perturbation Vt (ms^{-1}; +/- 10 black)

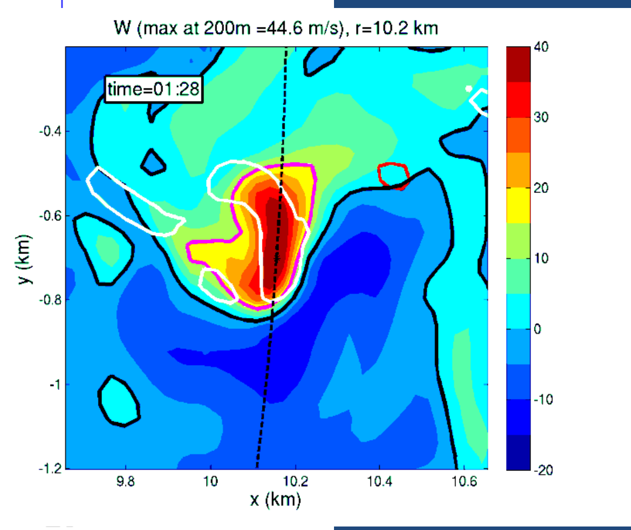


Objective Tracking of Updrafts and Wind Gusts

Δx=31.25 m

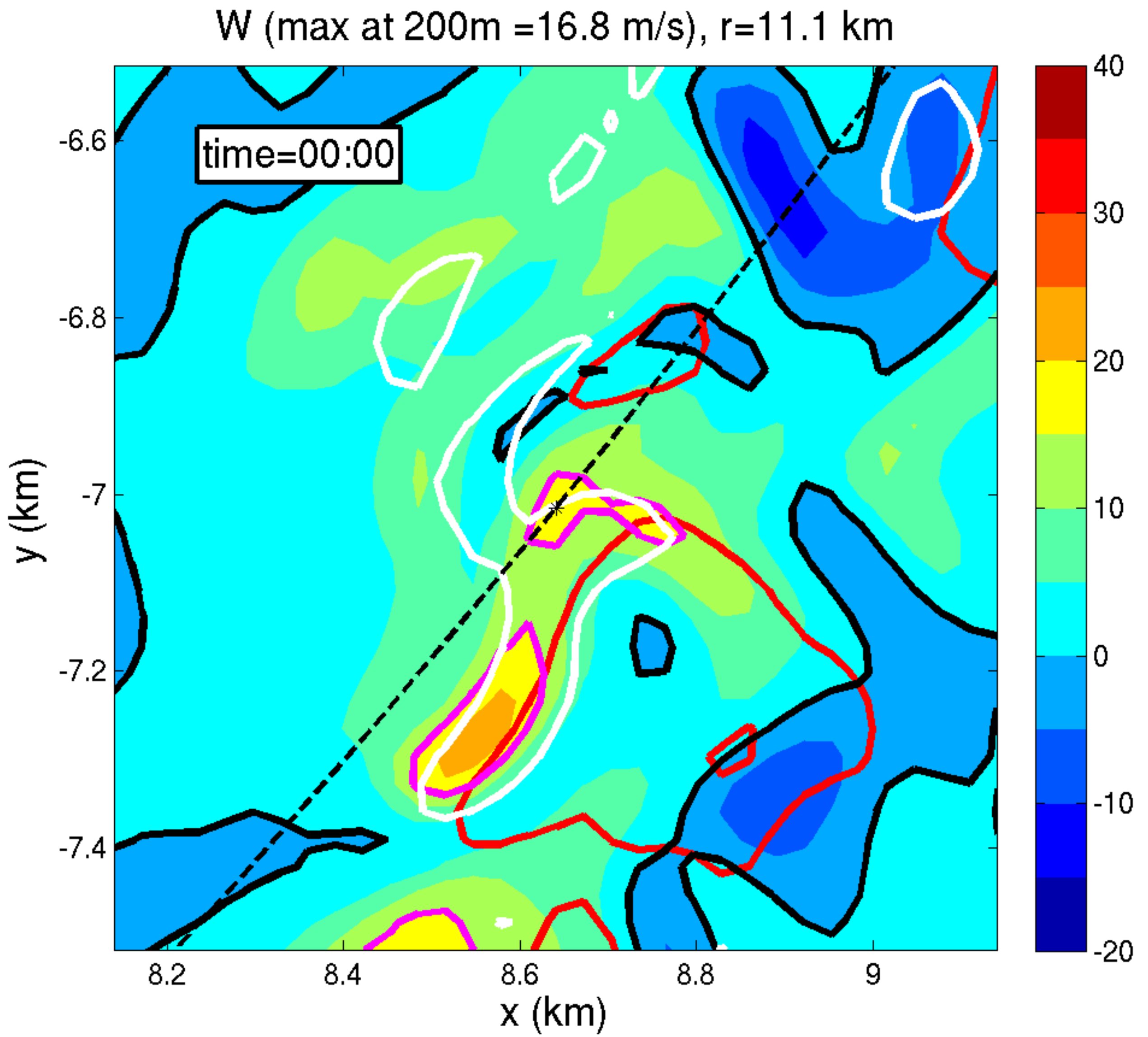
Updrafts > 15 ms^{-1} at z=200 m





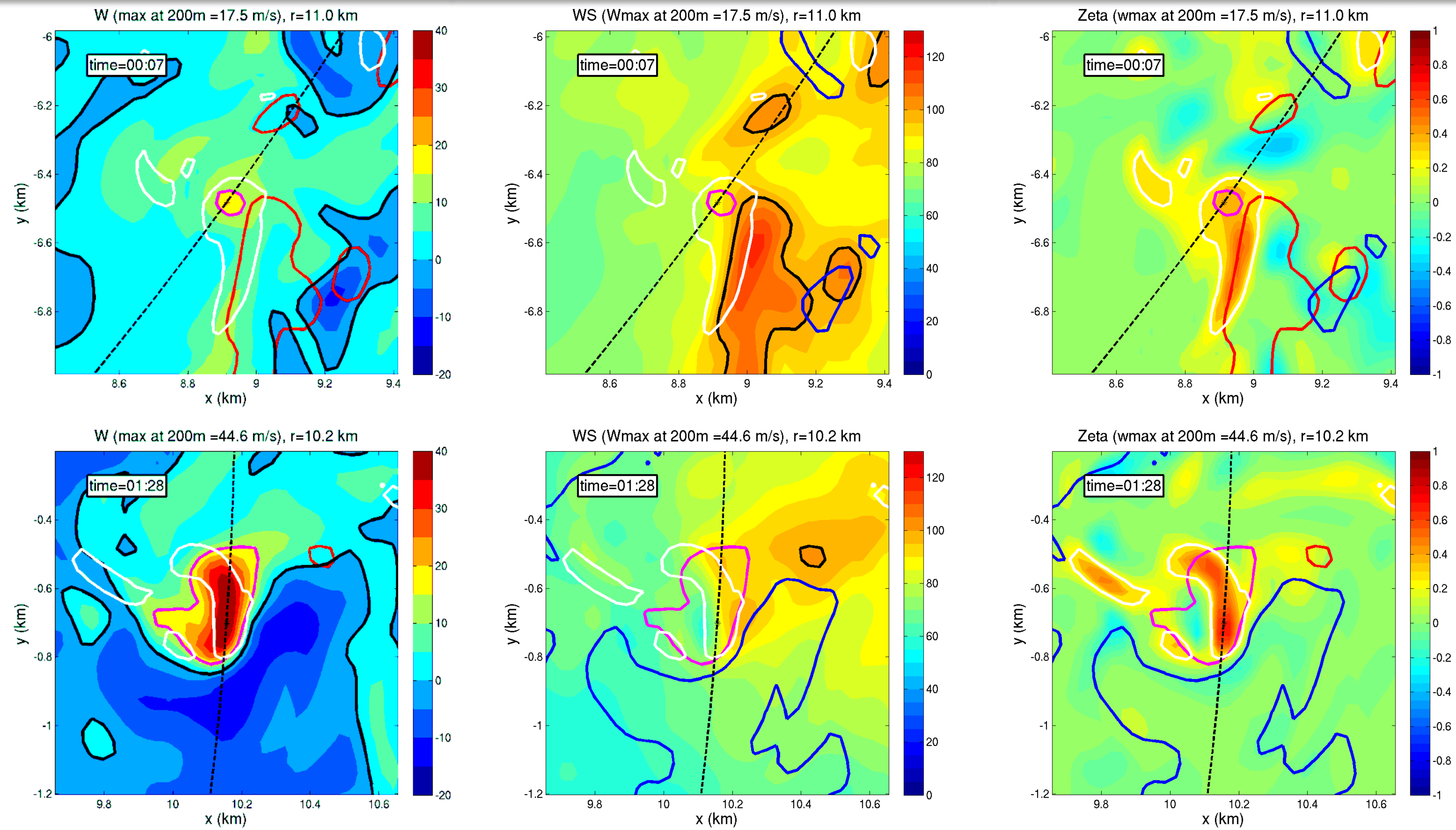
- Azimuthal Translation: 74 ms^{-1}
- Radial Translation: -12 ms^{-1}

Horizontal Cross Section Following Updraft



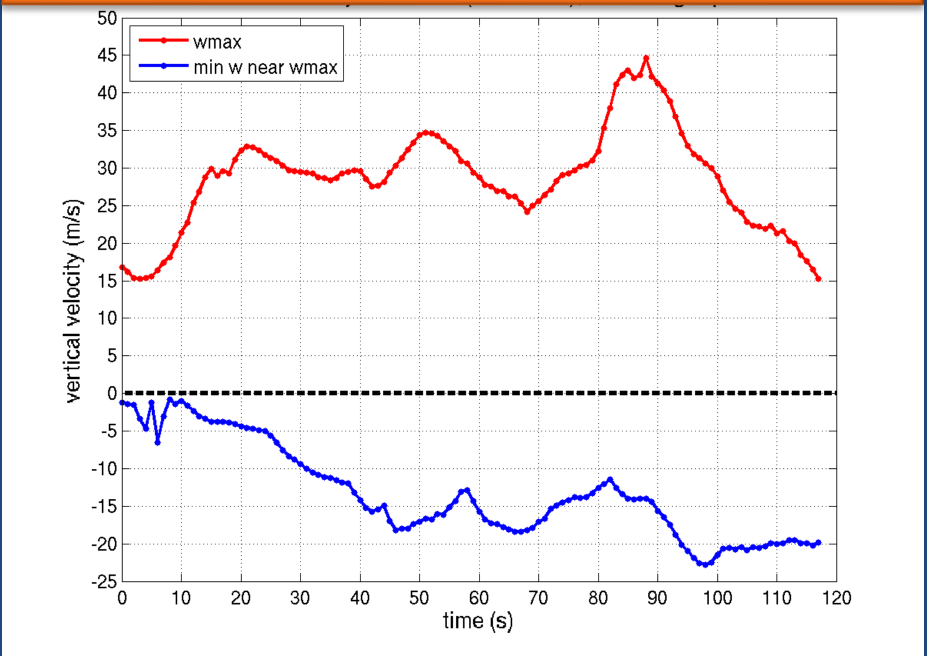
Horizontal Cross Sections at Times of Peak *W*, WSPD

Vertical Velocity	Wind Speed	Vertical Vorticity

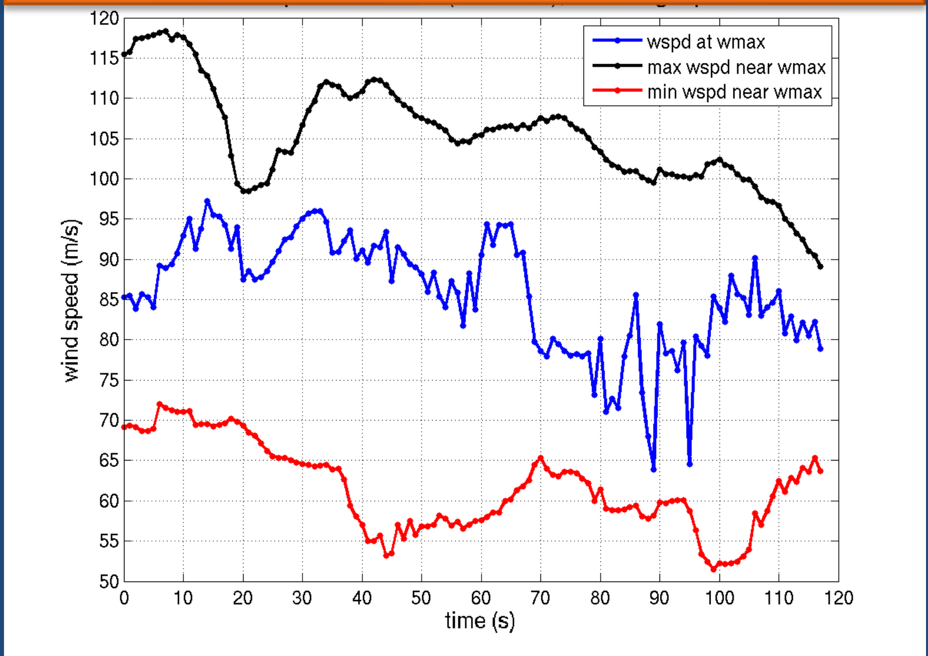


Evolution of Updraft and Wind Gust

Vertical Velocity vs. Time



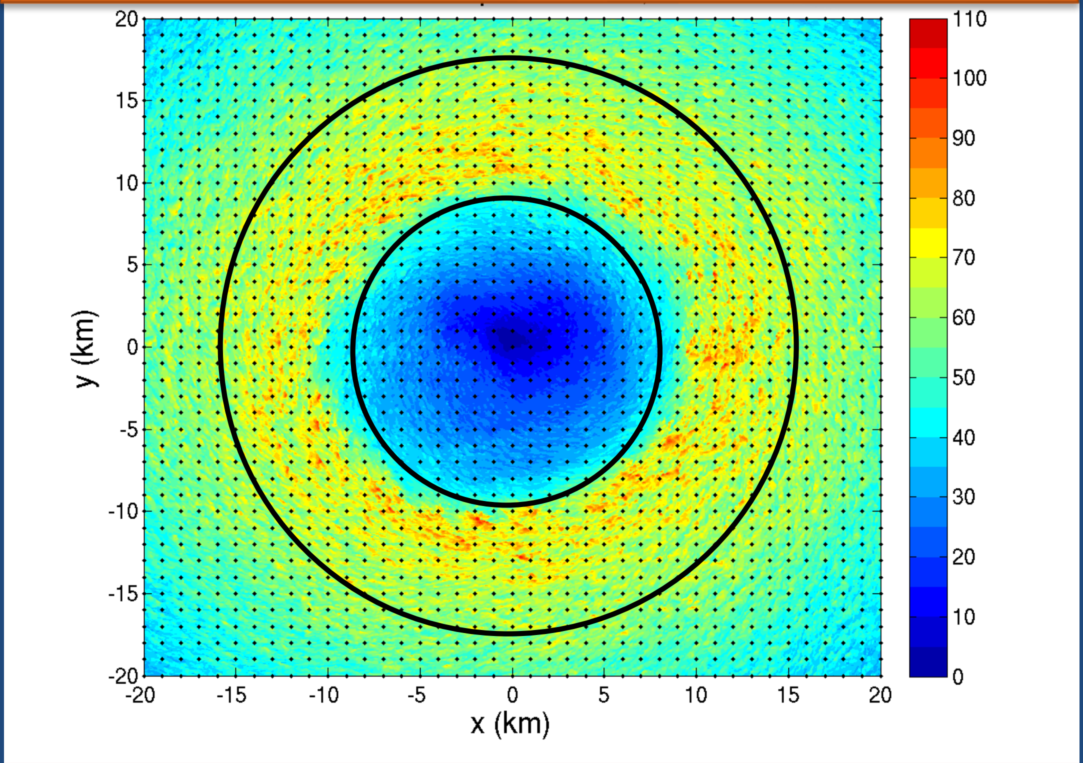
Wind Speed vs. Time



- 118 ms^{-1} gust, remains >100 ms^{-1} for almost two minutes
- Such extreme gusts are unlikely to be sampled observationally.

What is the Maximum *Sampled* Wind Speed?

10-m Wind Speed; Dropsonde Locations

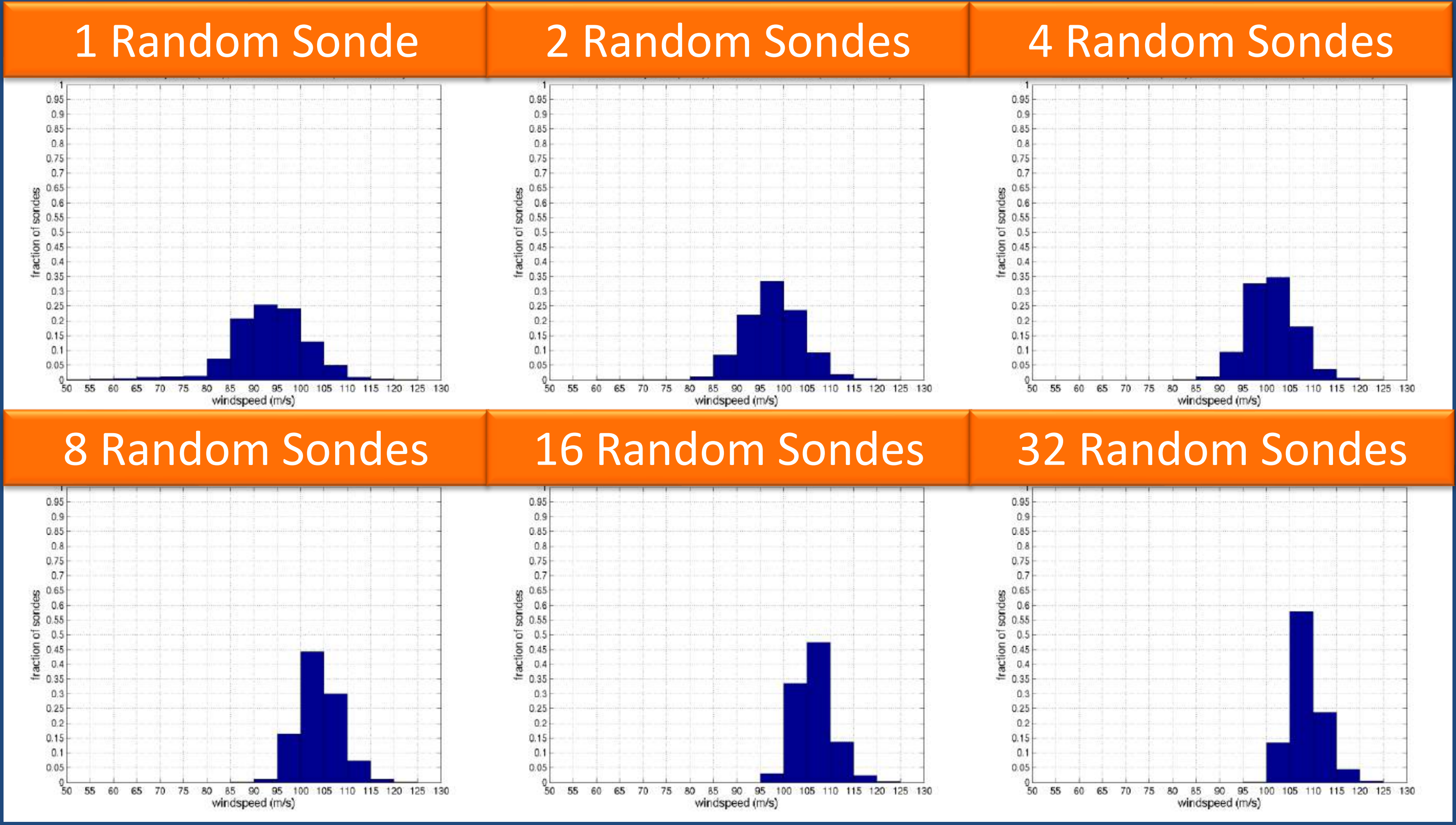


Sonde density is 16 times what is shown

1. Randomly sample combinations of simulated sondes in eyewall
2. Find the maximum wind speed among sondes
3. Repeat 10,000 times to obtain distribution

What is the Maximum *Sampled* Wind Speed?

PDFs of Peak Gust Sampled by Simulated Sondes



Summary

- Observations indicate the existence of small-scale vortices along the eye/eyewall interface, which are associated with extreme updrafts (10-30 ms^{-1}) and wind speeds (90-110 ms^{-1}).

- LES produces these observed structures, and with the simulations, we can learn about dynamics that are difficult to observe.

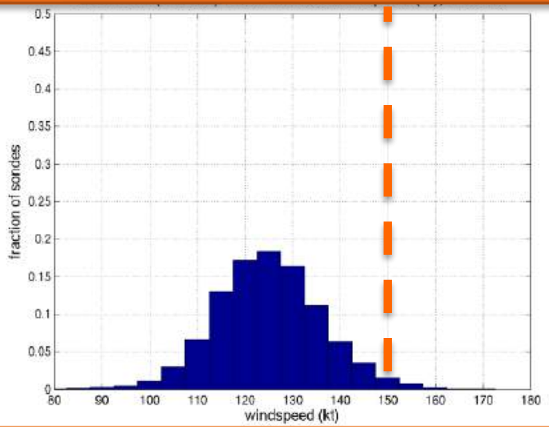
- Gusts of 120-140 ms^{-1} are always present in the simulation, substantially stronger than have ever been observed.

- Such gusts are likely realistic, as simulated dropsondes very rarely sample gusts exceeding 110 ms^{-1}, consistent with observations.

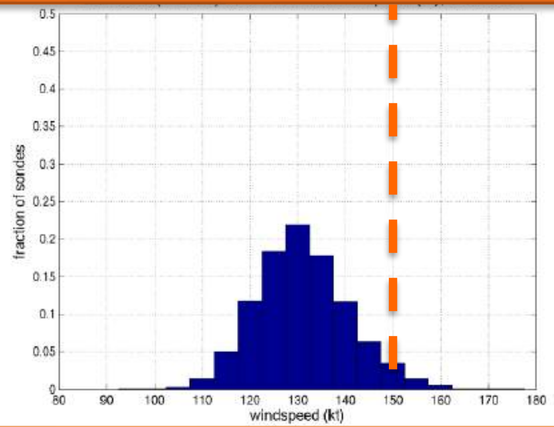
Bonus Slides!

What is the Estimated TC Intensity?

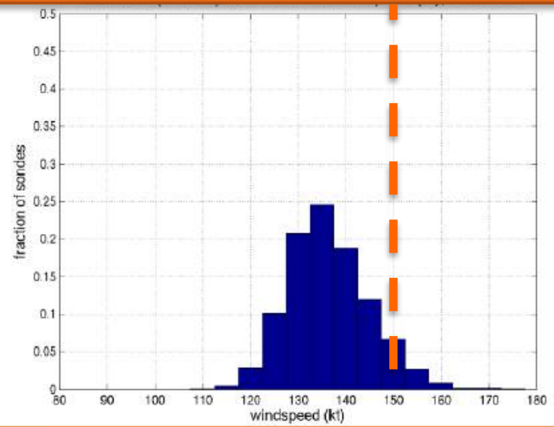
1 Random Sonde



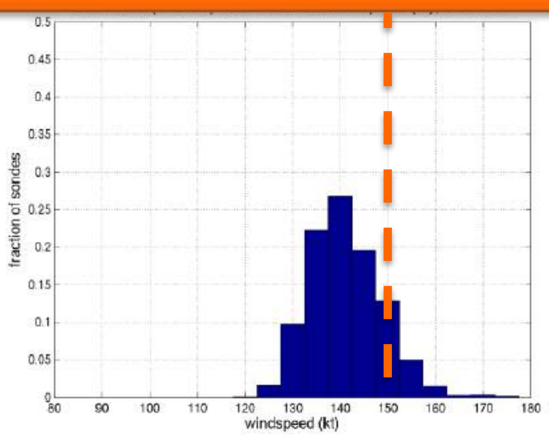
2 Random Sondes



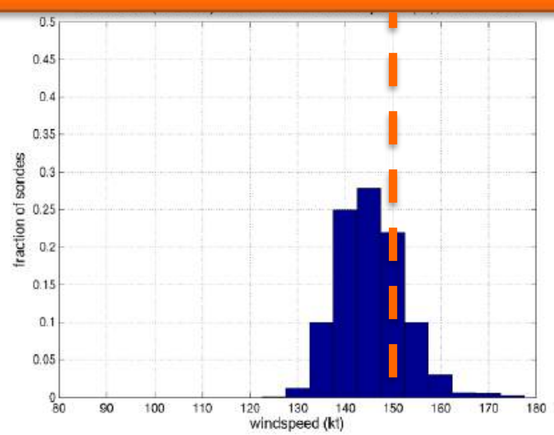
4 Random Sondes



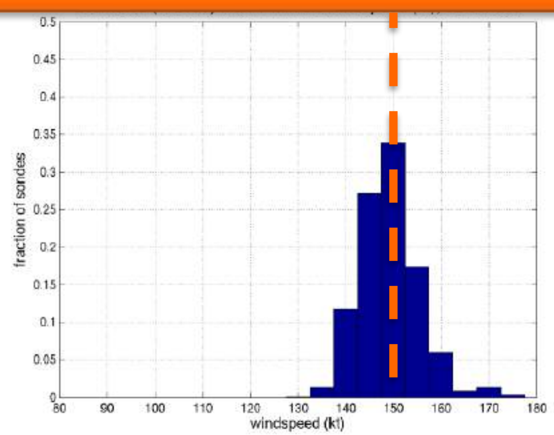
8 Random Sondes



16 Random Sondes

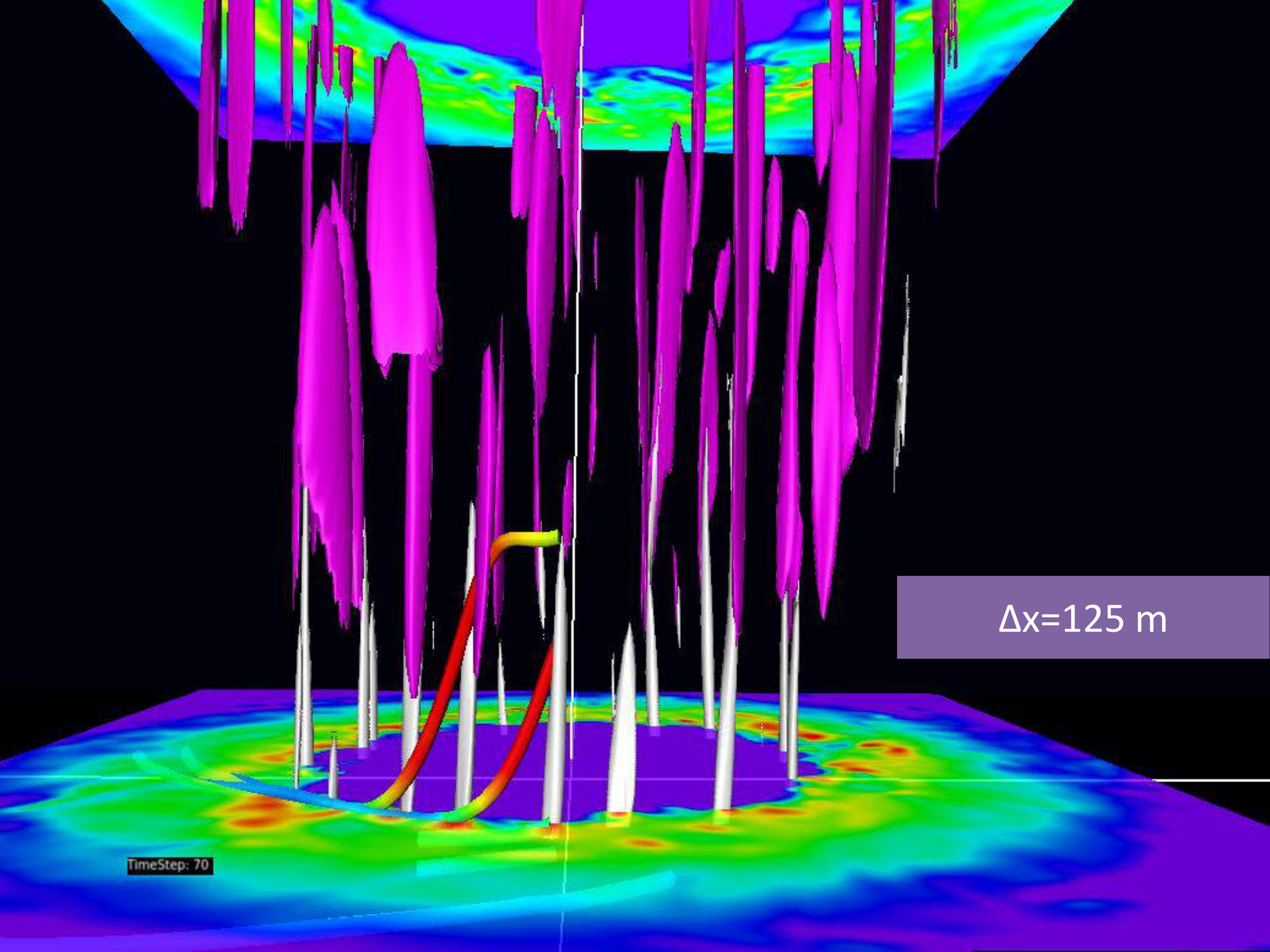


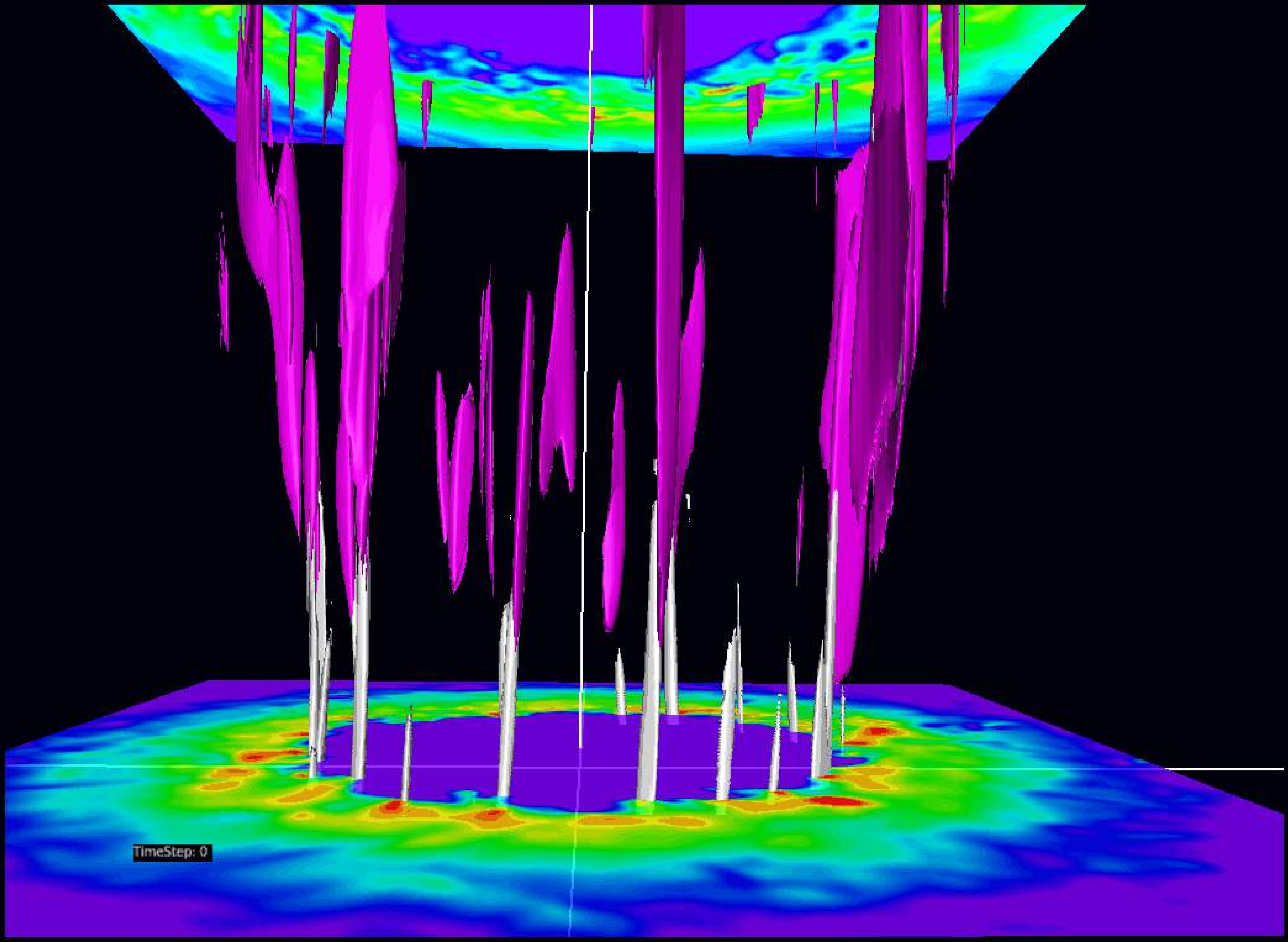
32 Random Sondes



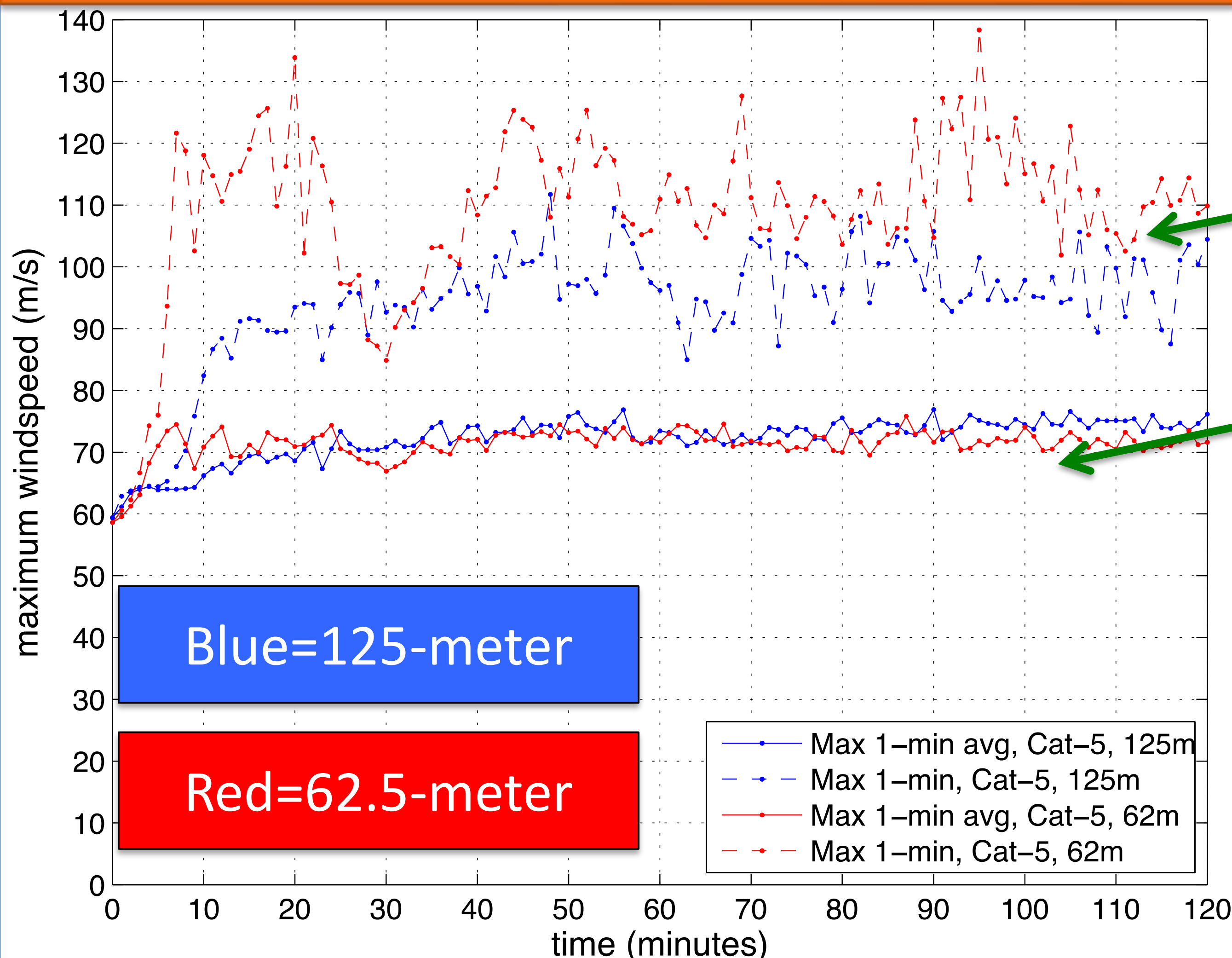
Using Parcel Trajectories to Explore Dynamics

- Calculate backward and forward trajectories for air parcels that enter an extreme low-level updraft.
- We can learn where such parcels originate and how the wind speed changes along the trajectory path.


TimeStep: 70
Δx=125 m


TimeStep: 0

Maximum Surface Wind Speed vs. Time

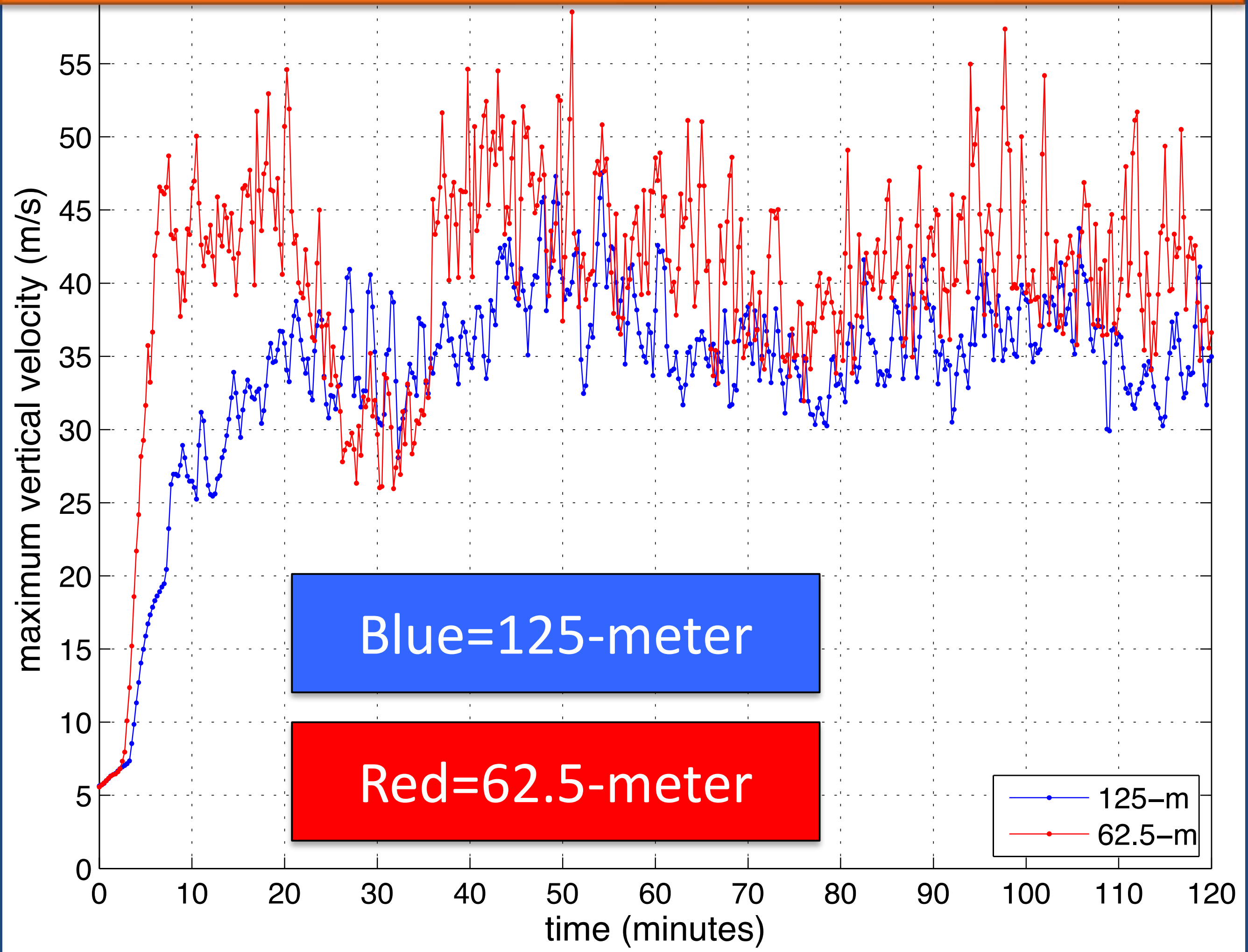


Maximum over previous minute

Average over previous minute

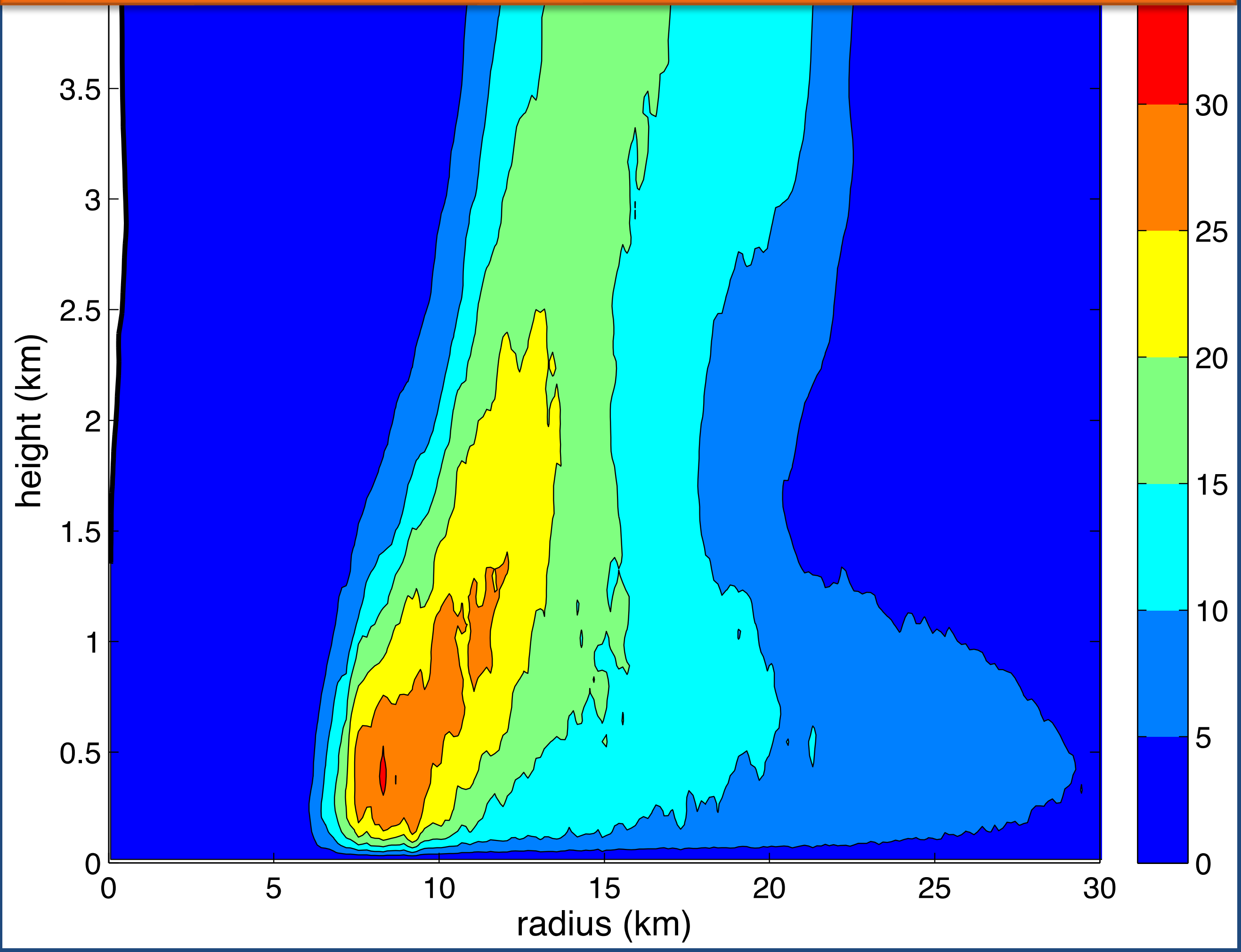
- 1-min mean winds are not that sensitive to grid spacing.
- Instantaneous gusts become stronger with finer resolution.

Maximum Vertical Velocity vs. Time



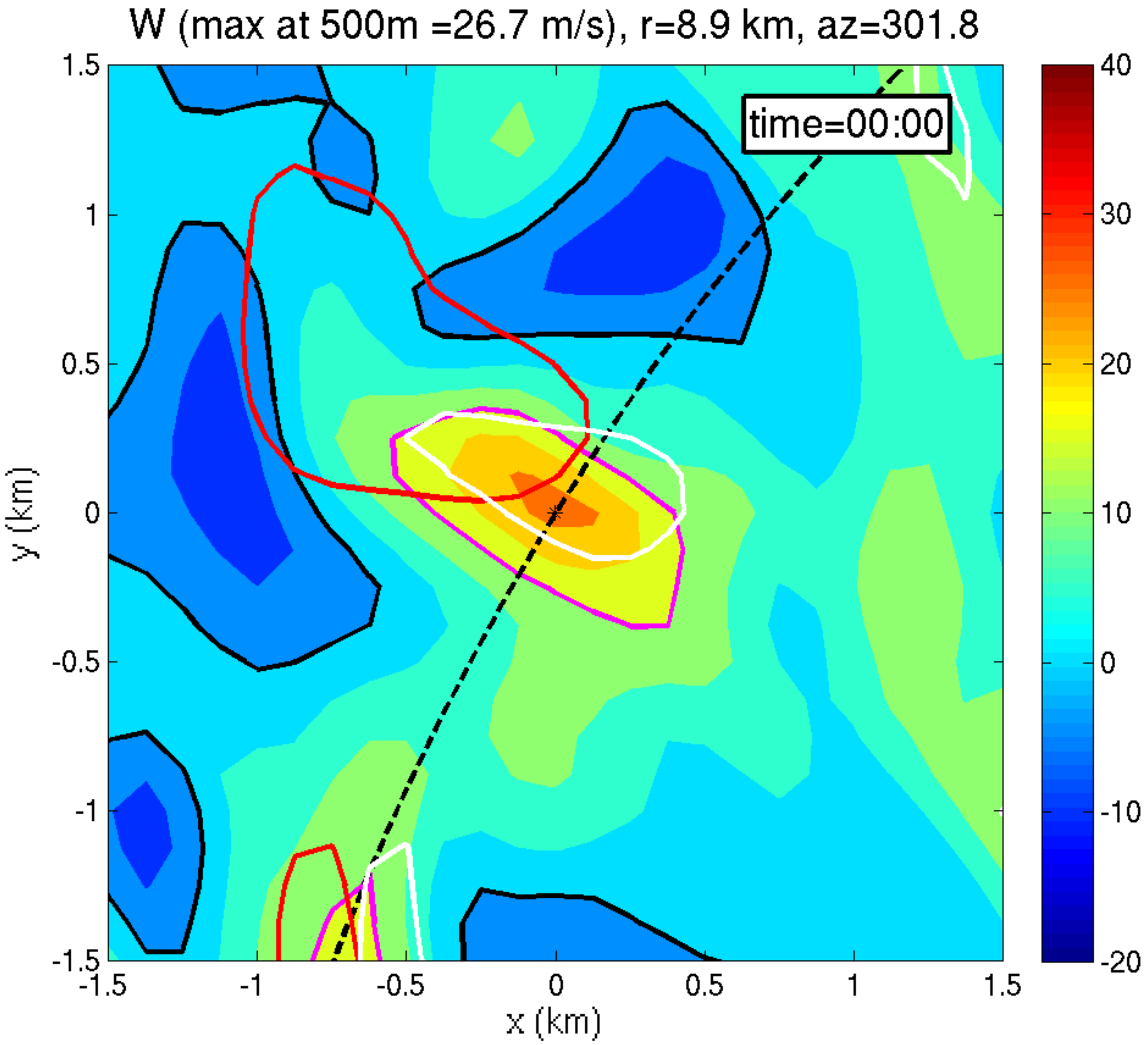
- Starting from an initially axisymmetric state, small-scale extreme updrafts develop quite quickly.
- Updraft strength is sensitive to grid spacing.

Maximum Vertical Velocity

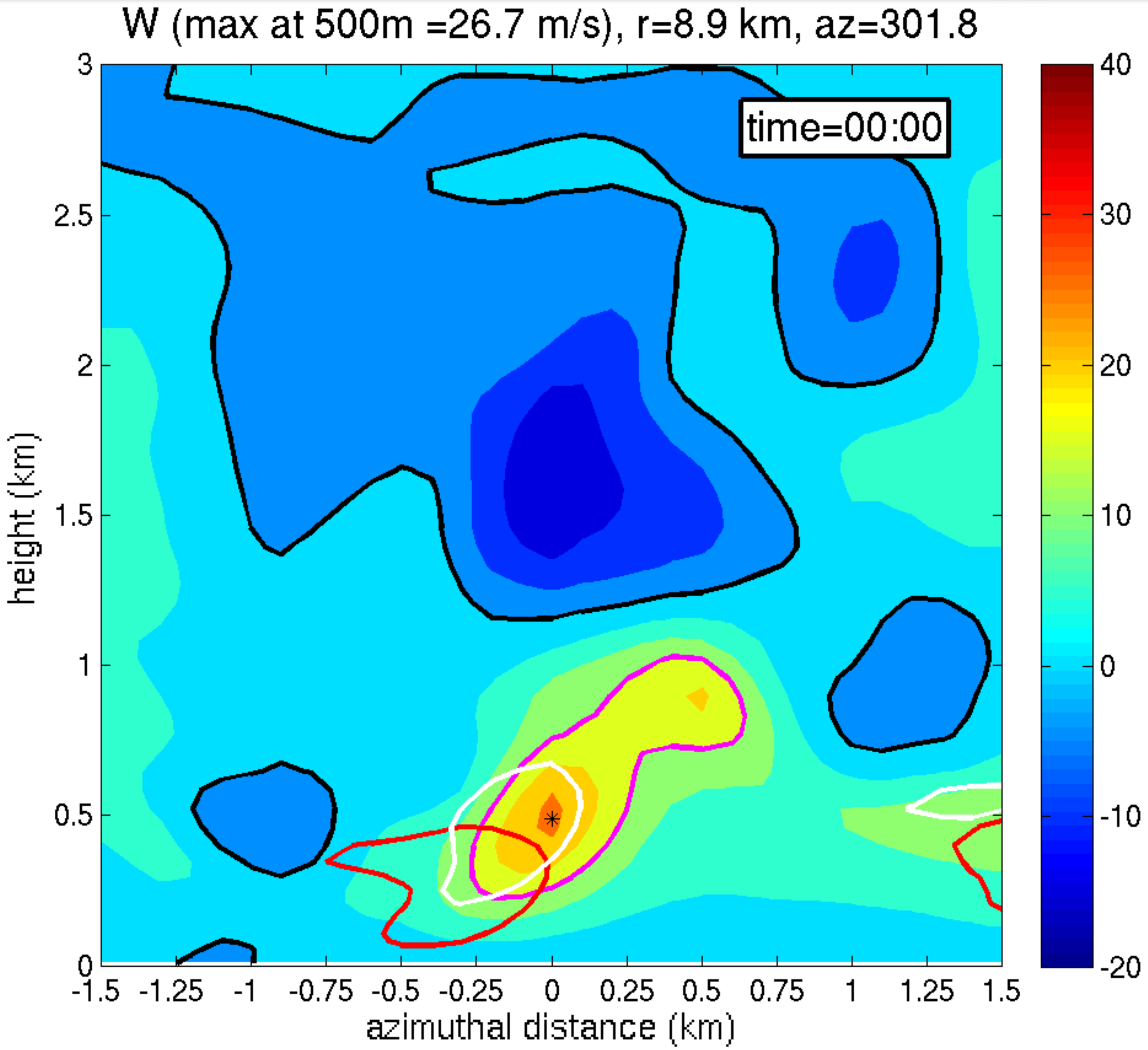


Strongest updrafts are within or just above the boundary layer

Horizontal Cross Section Following Updraft



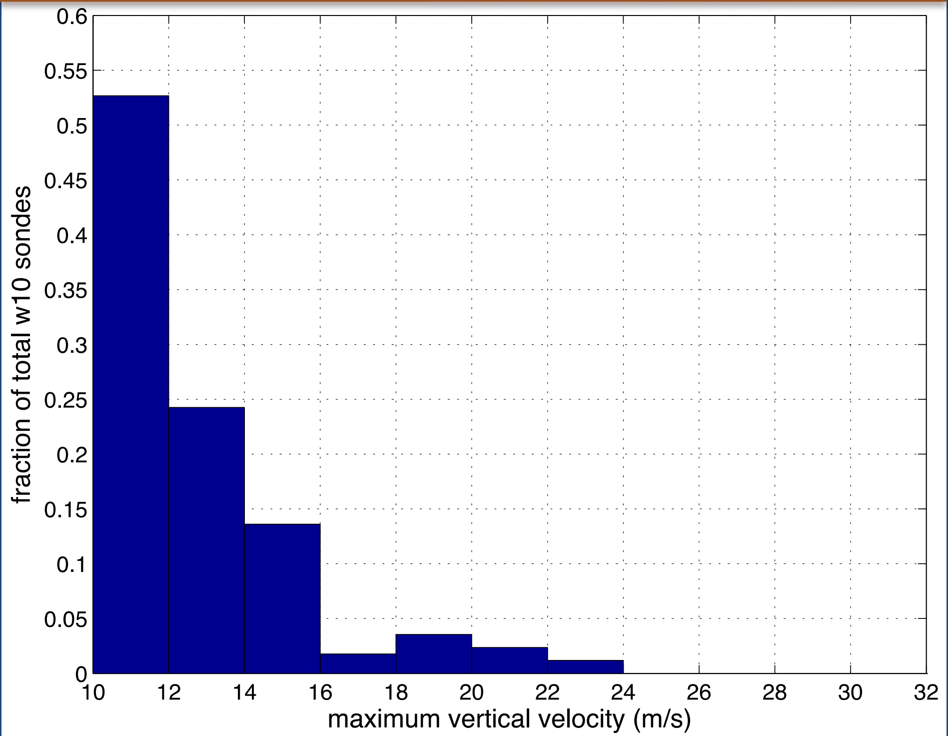
Azimuth-Height Cross Section Following Updraft



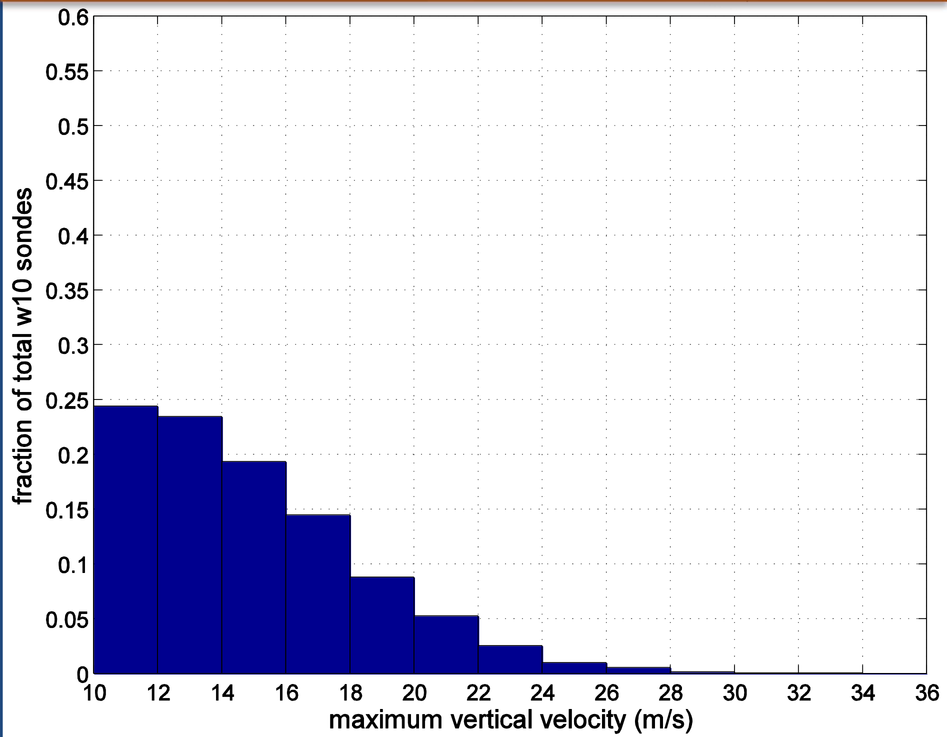
How can we test the realism of the LES?

PDF of Max Vertical Velocity for sondes with *w*>10 m/s

Observed

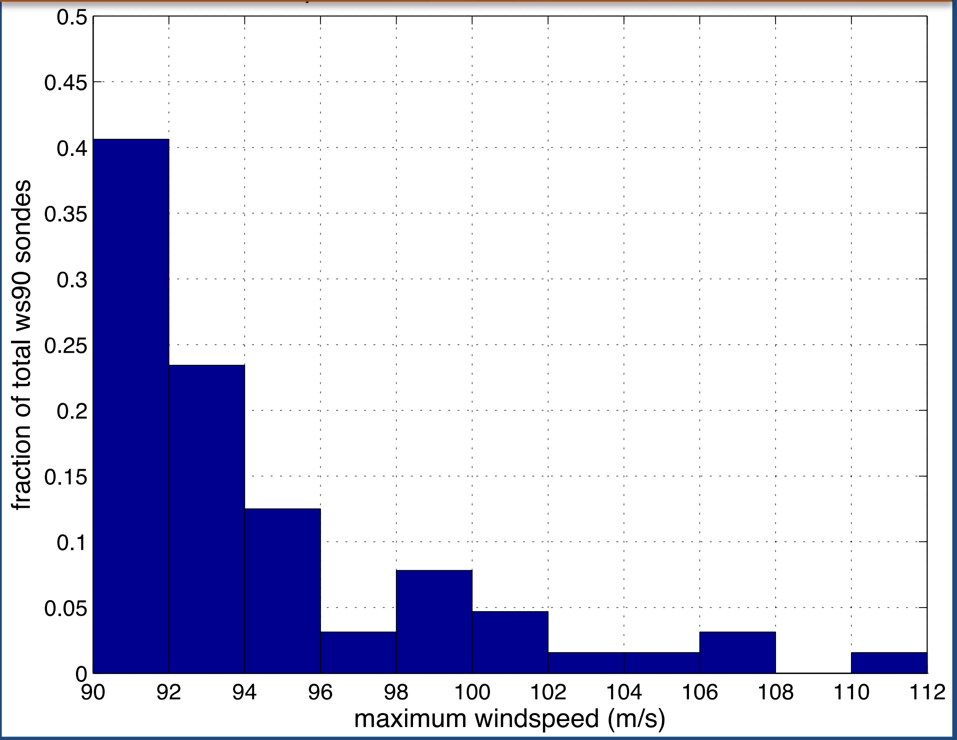


Simulated

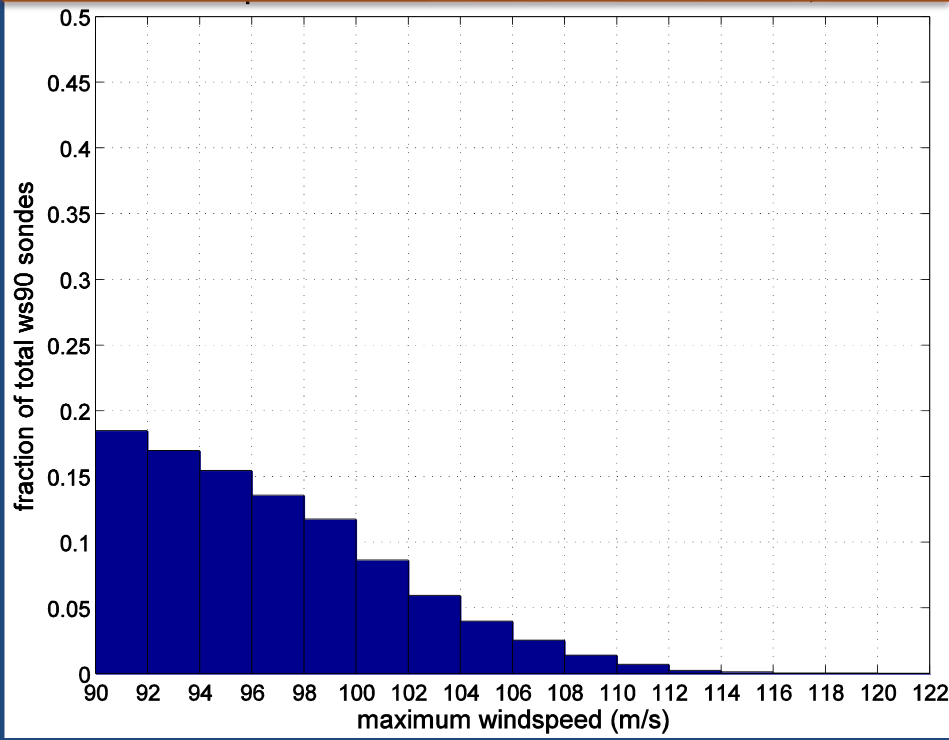


PDF of Max Wind Speed for sondes with WS>90 m/s

Observed

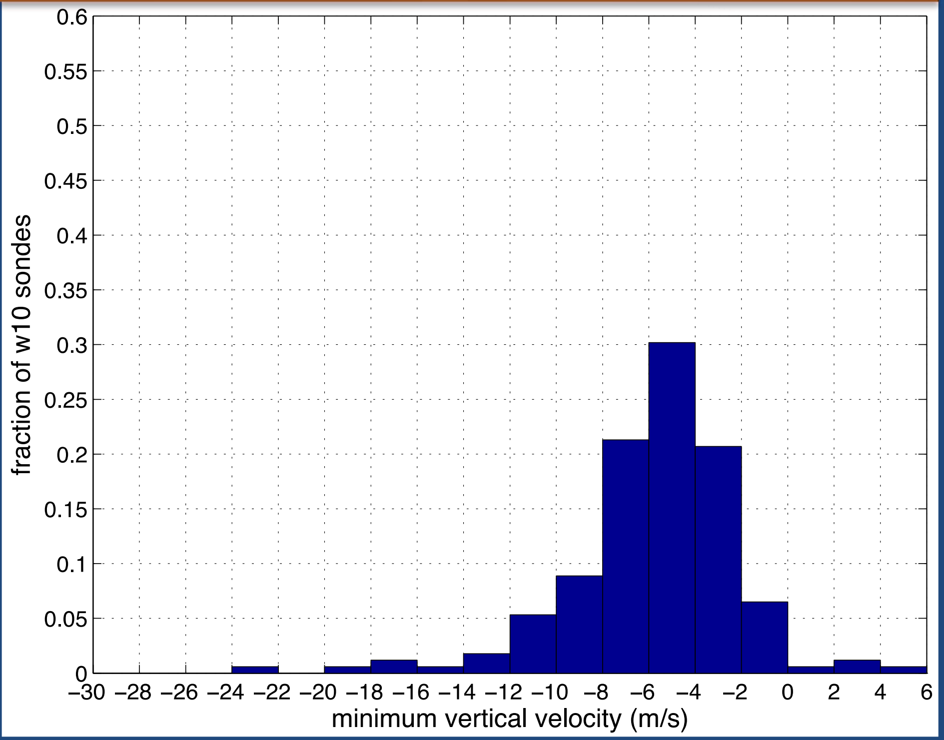


Simulated

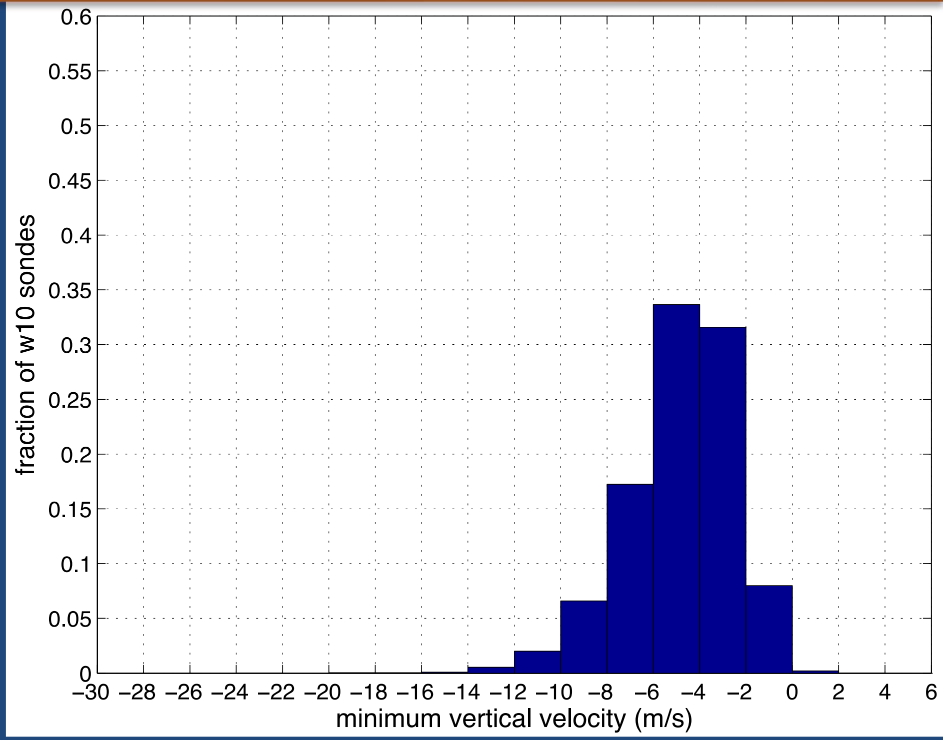


PDF of Min vertical velocity for sondes with *w*>10 m/s

Observed

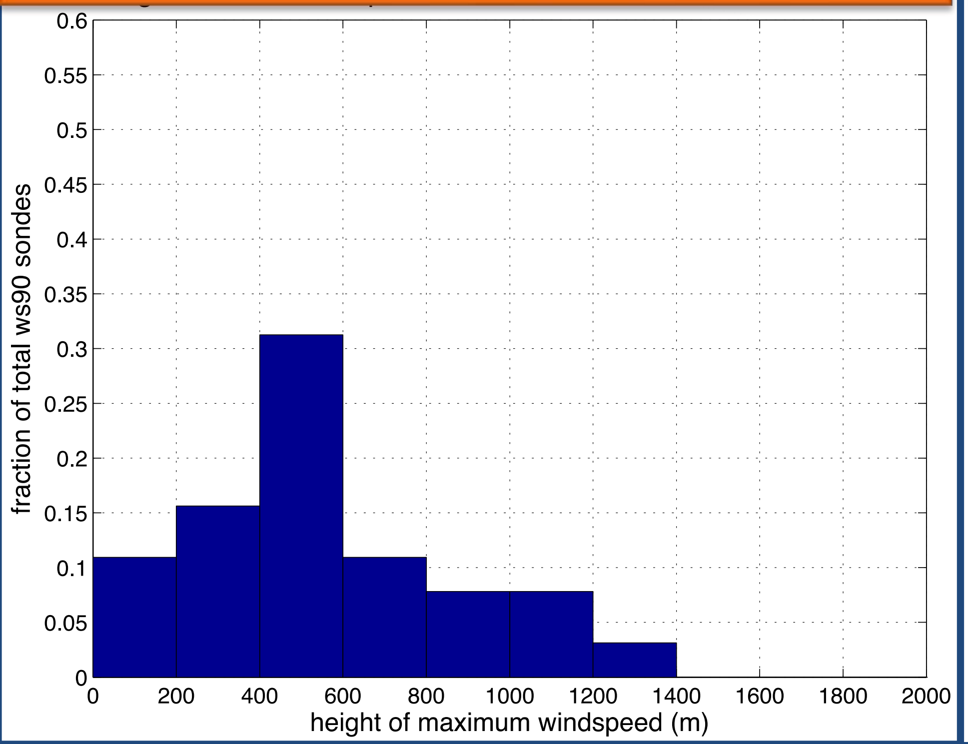


Simulated

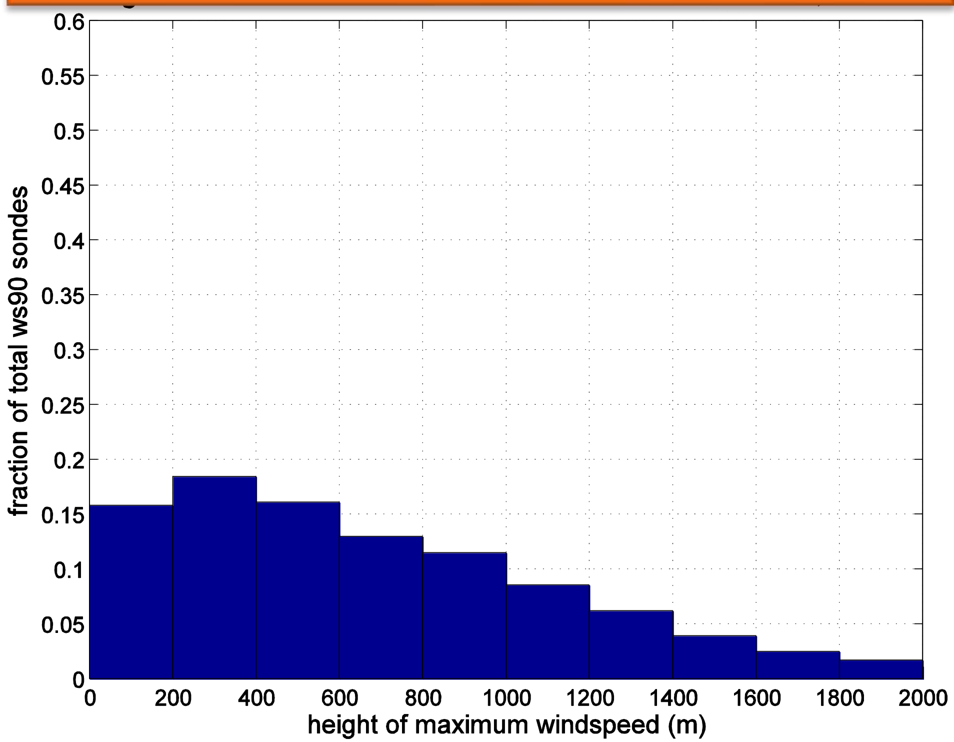


PDF of Height of Max WS for sondes with WS> 90m/s

Observed (WS>90m/s)

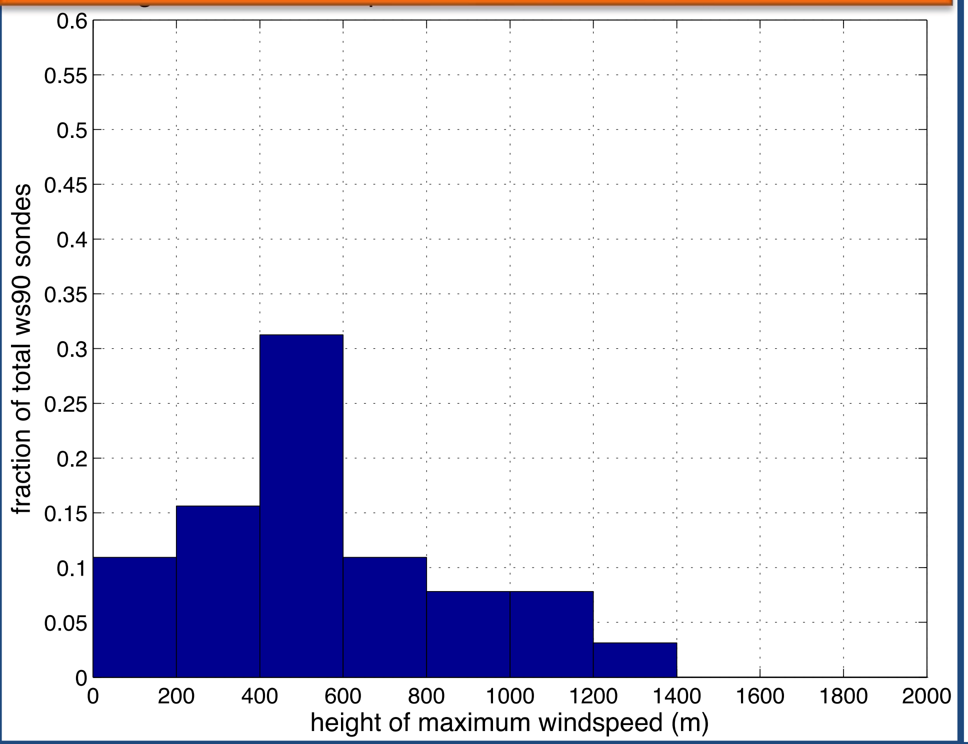


Simulated

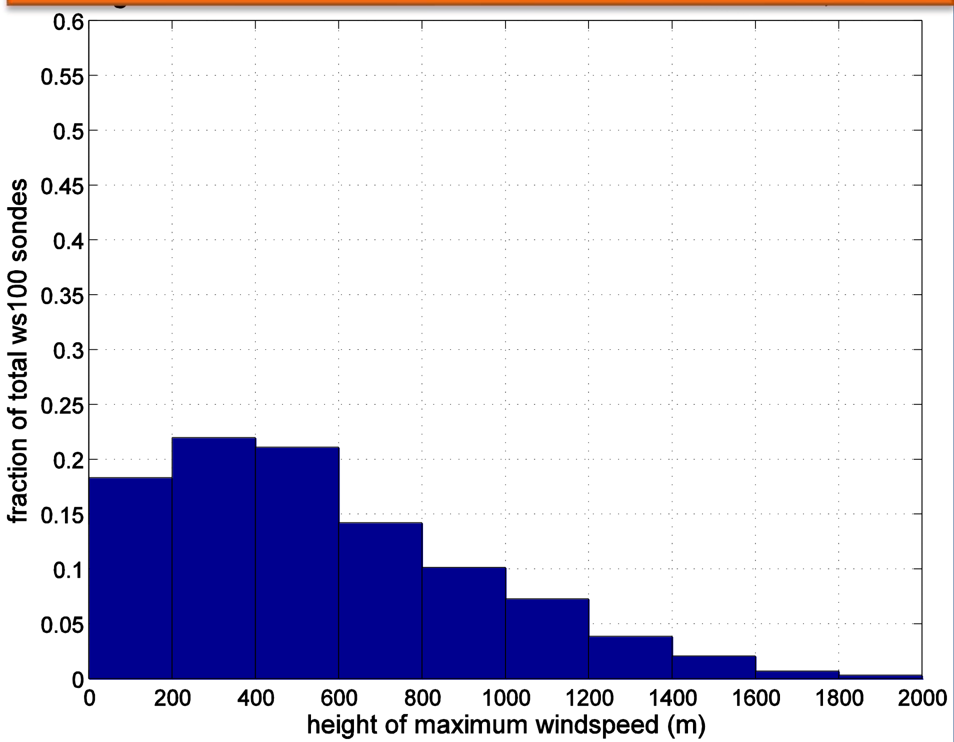


PDF of Height of Max WS for sondes with WS>100 m/s

Observed (WS>90m/s)

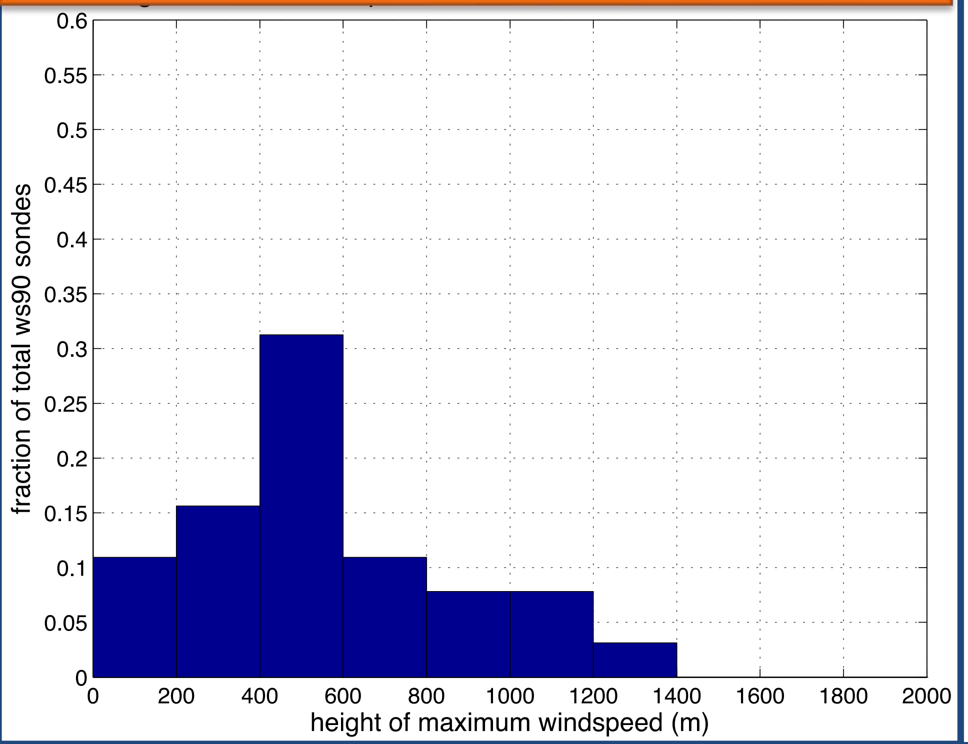


Simulated

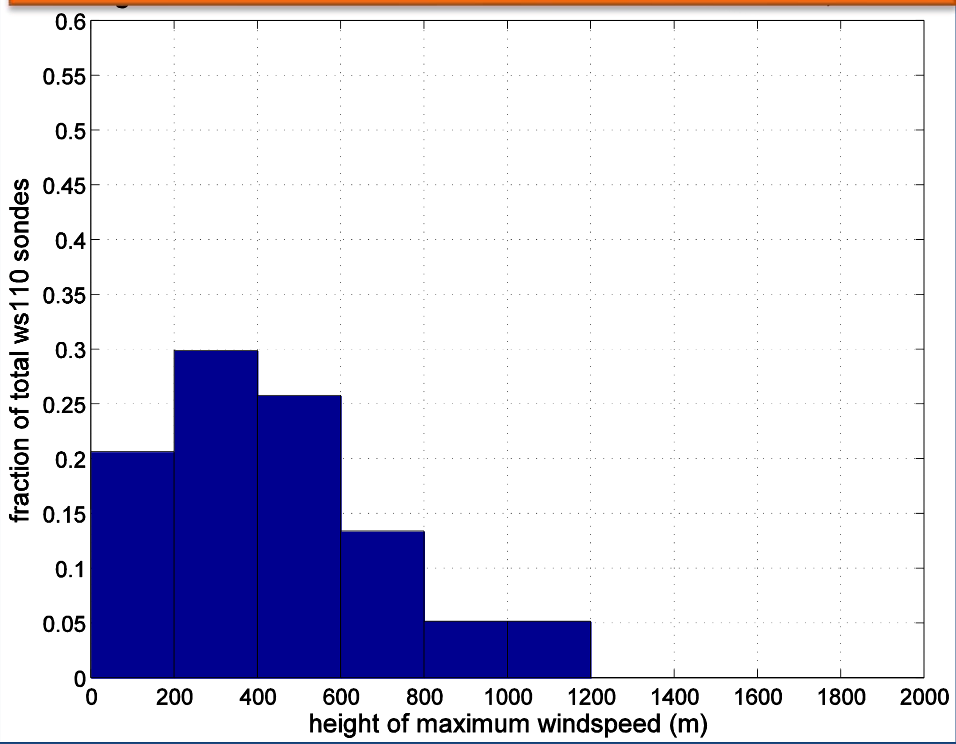


PDF of Height of Max WS for sondes with WS>110 m/s

Observed (WS>90m/s)

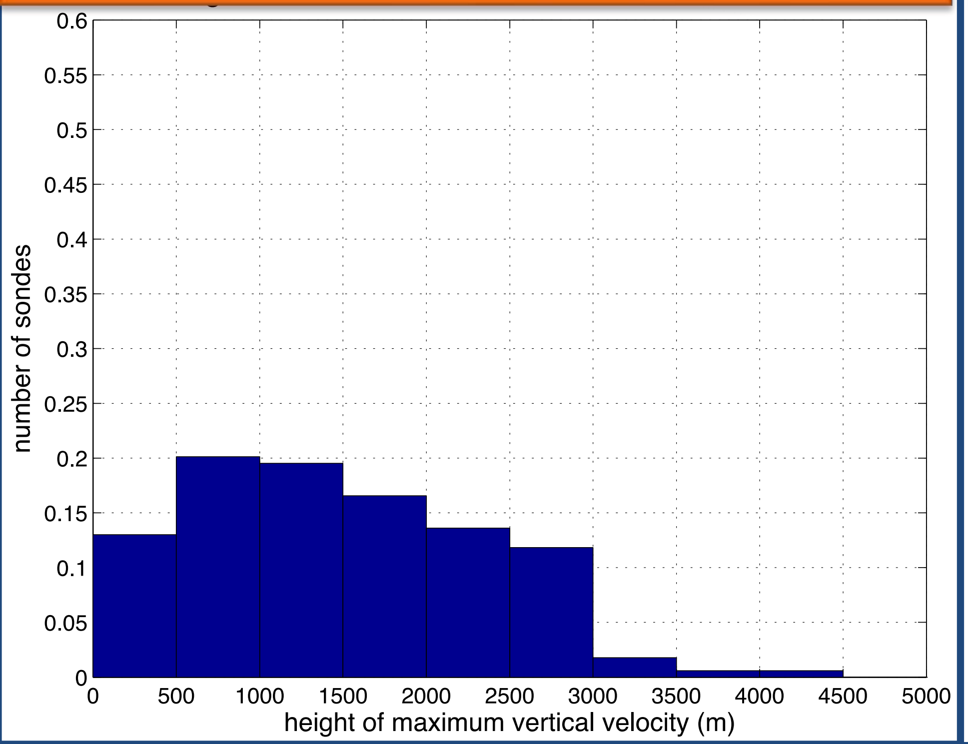


Simulated

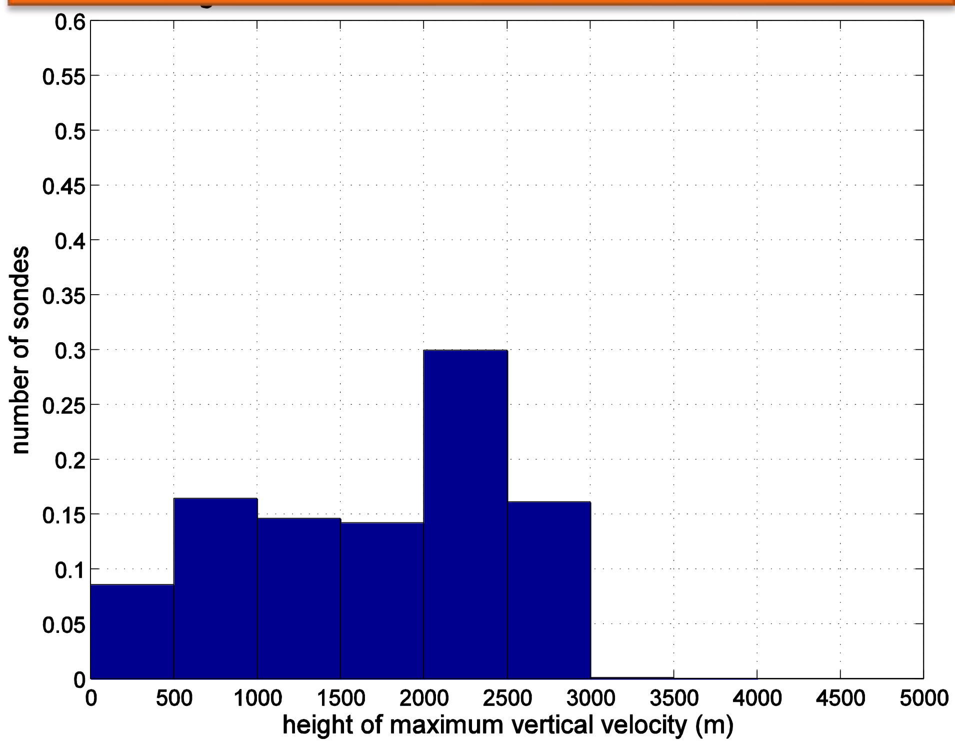


PDF of Height of Max *w* for sondes with *w*>10 m/s

Observed

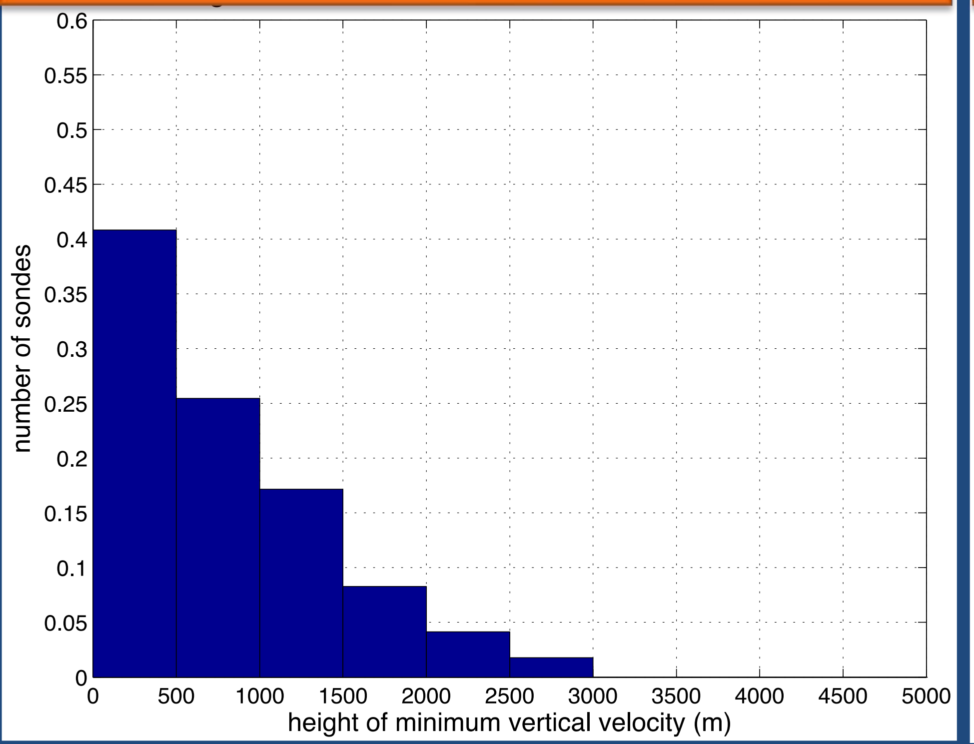


Simulated

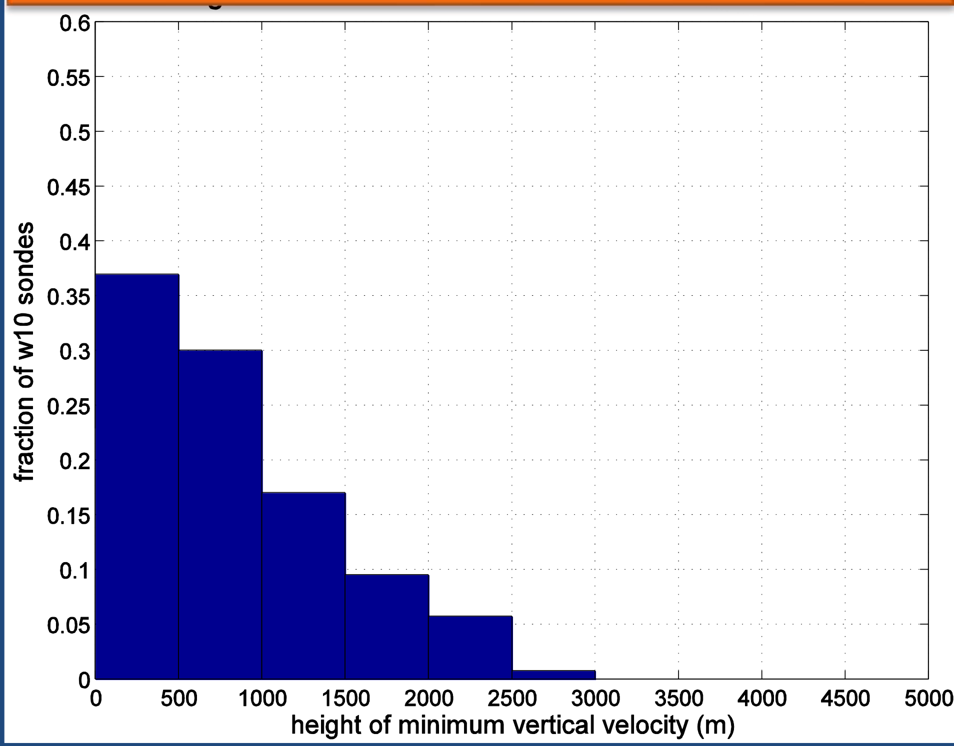


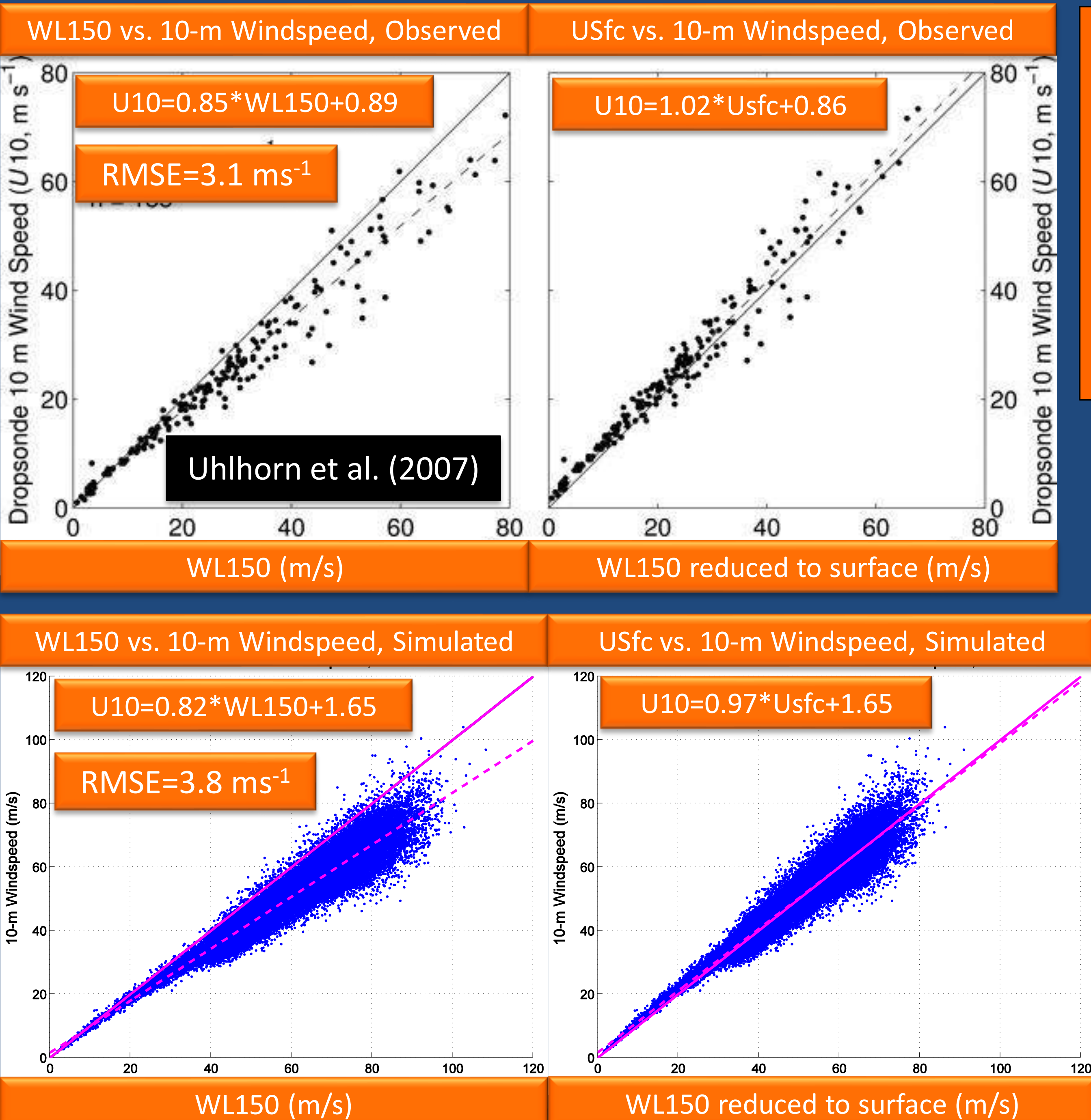
PDF of Height of Min *w* for sondes with *w*>10 m/s

Observed



Simulated



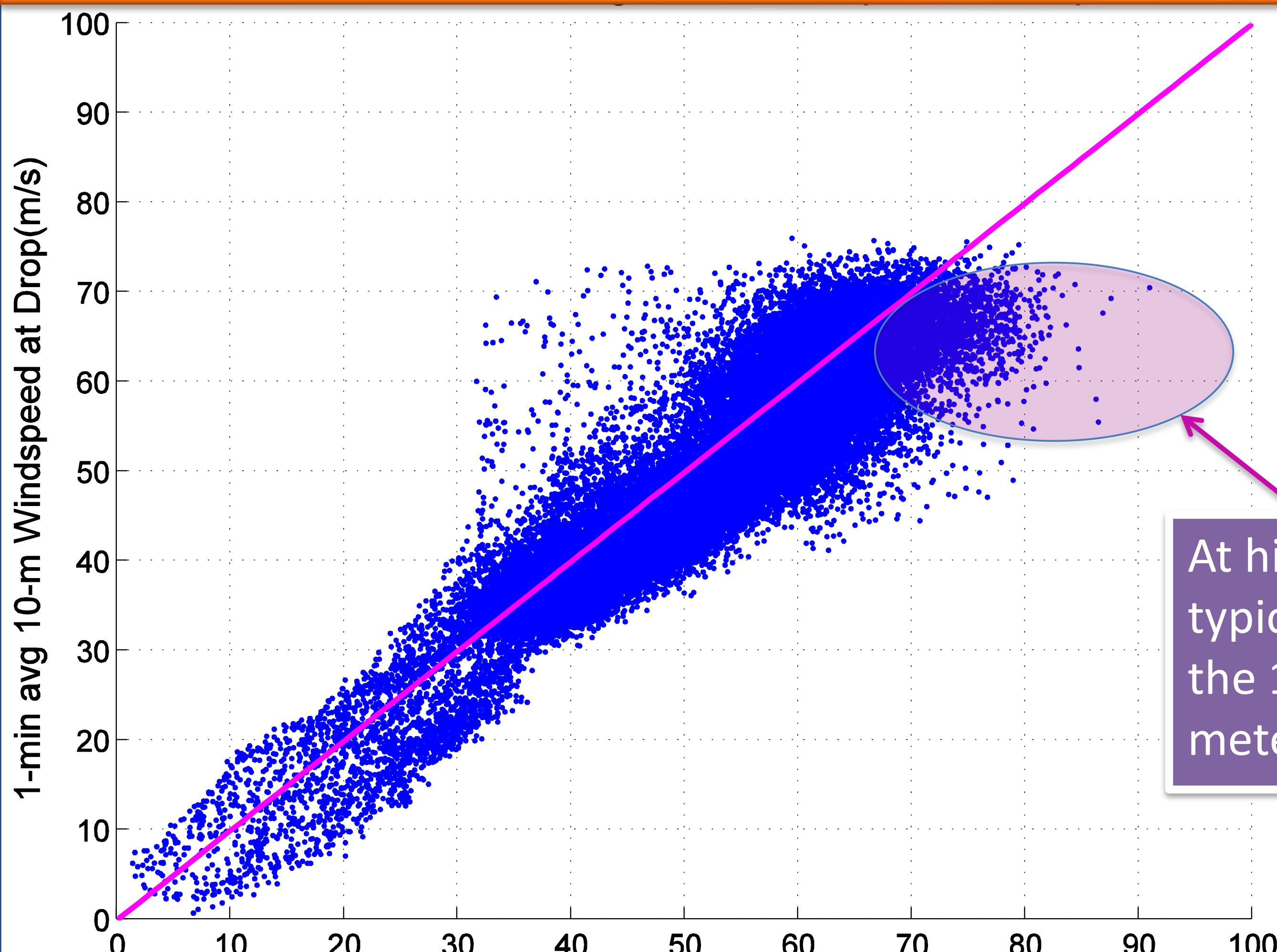


WL150: Mean wind speed in lowest 150 meters.

Usfc: Estimate of surface wind speed from WL150.

U10: Actual instantaneous 10-meter wind speed.

USfc vs. 1-minute mean 10-m Windspeed, Simulated



WL150 reduced to surface (m/s)

At high wind speeds, Usfc is typically an *overestimate* of the 1-minute average 10-meter wind speed.

Using Parcel Trajectories to Explore Dynamics

- Calculate backward and forward trajectories for air parcels that enter an extreme low-level updraft.

- We can learn where such parcels originate and how the wind speed changes along the trajectory path.

Is Buoyancy Important for Forcing the Acceleration of Low-Level Updrafts?

We can determine the total vertical acceleration, and partition it into two parts:

1. A **"thermodynamic"** acceleration, associated with buoyancy

2. A "**dynamic**" acceleration, associated with the perturbation pressure gradient force.

Is Buoyancy Important?

Momentum equation (neglecting Coriolis and diffusion):

$$\frac{dw}{dt} = -c_p \theta_v \frac{\partial \pi'}{\partial z} + B$$

$$\pi = \left(\frac{p}{p_0}\right)^{\frac{R_d}{c_p}}$$

$$B = g\left(\frac{\theta - \theta_0}{\theta_0} + 0.61(q_v - q_{v0}) - q_h\right)$$

θ : Potential Temperature

$\theta_0(z)$: Base State Potential Temperature

q_v : Water Vapor Mixing Ratio

q_h : Hydrometeor Mixing Ratio

Note: *p* is the perturbation pressure, after a hydrostatic basic state has been removed.

We can decompose pressure into a buoyant and a dynamic part:

Momentum equation (neglecting Coriolis and diffusion):

$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0} \nabla p + B\vec{k} - \vec{v} \cdot \nabla \vec{v}$$

Multiplying by density and taking divergence:

$$\frac{\partial}{\partial t}(\nabla \cdot \rho_0 \vec{v}) = -\nabla^2 p + \frac{\partial}{\partial z}(\rho_0 B) - \nabla(\rho_0 \vec{v} \cdot \nabla v)$$

We can decompose pressure into a buoyant and a dynamic part:

Momentum equation (neglecting Coriolis and diffusion):

$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0}\nabla p + B\vec{k} - \vec{v}\cdot\nabla\vec{v}$$

$$\rho_0 = \rho_0(z)$$

Anelastic approximation

Multiplying by density and taking divergence:

$$\frac{\partial}{\partial t}(\nabla \cdot \rho_0\vec{v}) = -\nabla^2 p + \frac{\partial}{\partial z}(\rho_0 B) - \nabla(\rho_0\vec{v}\cdot\nabla v)$$

$$\nabla \cdot \rho_0\vec{v} = 0$$

Divergence of 3D Mass Flux is Zero

We can decompose pressure into a buoyant and a dynamic part:

Momentum equation (neglecting Coriolis and diffusion):

$$\frac{\partial \vec{v}}{\partial t} = -\frac{1}{\rho_0}\nabla p + B\vec{k} - \vec{v}\cdot\nabla\vec{v}$$

Multiplying by density and taking divergence:

$$\frac{\partial}{\partial t}(\nabla\cdot\rho_0\vec{v}) = -\nabla^2 p + \frac{\partial}{\partial z}(\rho_0 B) - \nabla(\rho_0\vec{v}\cdot\nabla\vec{v})$$

$$\nabla^2 p = F_B + F_D$$

$$F_B = \frac{\partial}{\partial z}(\rho_0 B)$$

$$F_D = -\nabla(\rho_0\vec{v}\cdot\nabla\vec{v})$$

We can decompose pressure into a buoyant and a dynamic part:

$$\nabla^2 p = F_B + F_D$$

$$F_B = \frac{\partial}{\partial z}(\rho_0 B)$$

$$F_D = -\nabla(\rho_0 \vec{v} \cdot \nabla \vec{v})$$

Buoyancy Source

Dynamic Source

$$p = p_B + p_D$$

$$\nabla^2 p_B = F_B$$

$$\nabla^2 p_D = F_D$$

PB and PD can be solved for numerically, from which the pressure gradient forces, PGB and PGD can be found.

$$\text{PGB} = -\frac{1}{\rho}\frac{\partial p_B}{\partial z}$$

$$\text{PGD} = -\frac{1}{\rho}\frac{\partial p_D}{\partial z}$$

We can decompose pressure into a buoyant and a dynamic part:

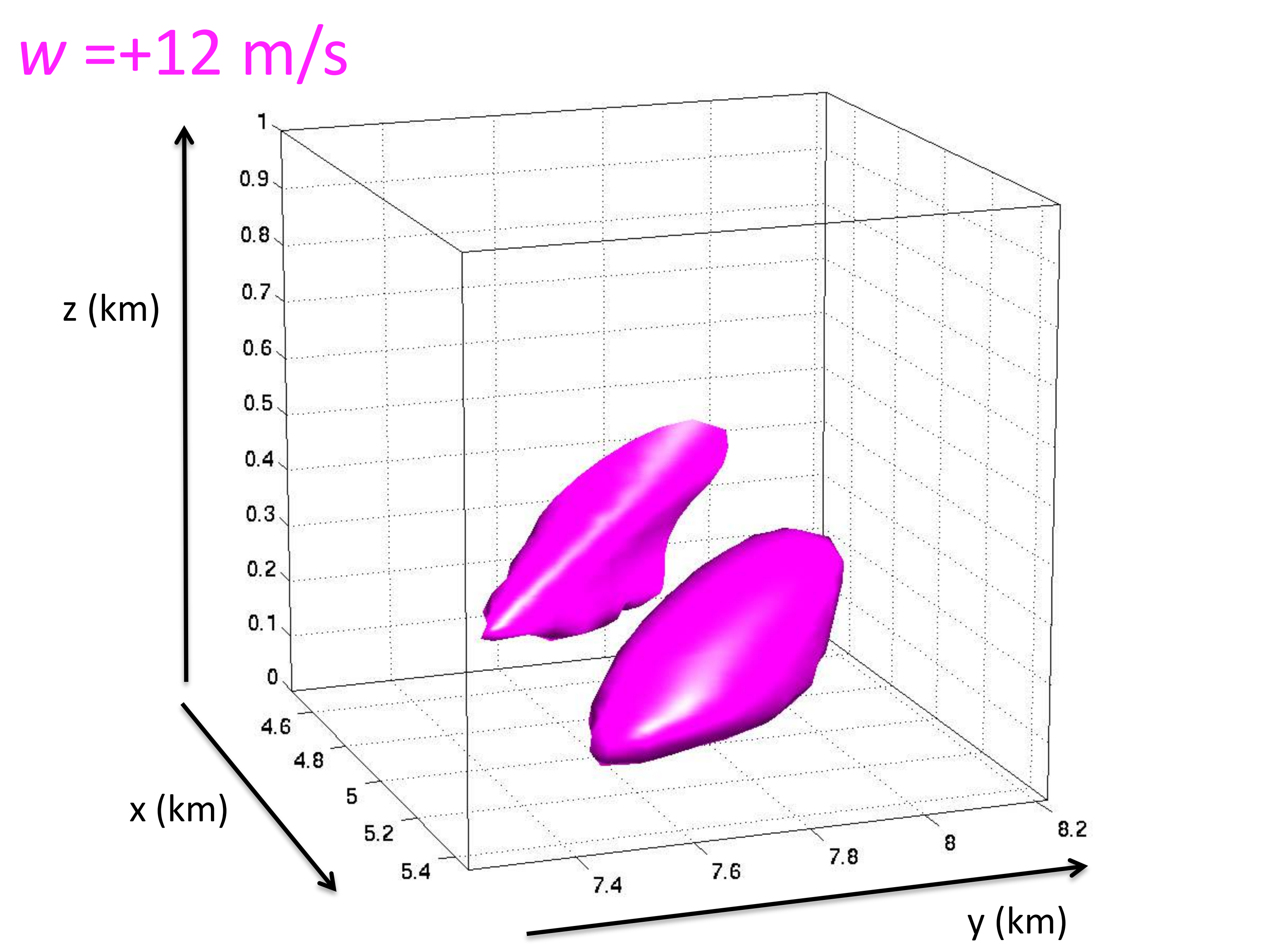
$$\frac{dw}{dt} = (B + \mathrm{PGB}) + \mathrm{PGD}$$

$$\mathrm{PGB} = -\frac{1}{\rho}\frac{\partial p_B}{\partial z}$$

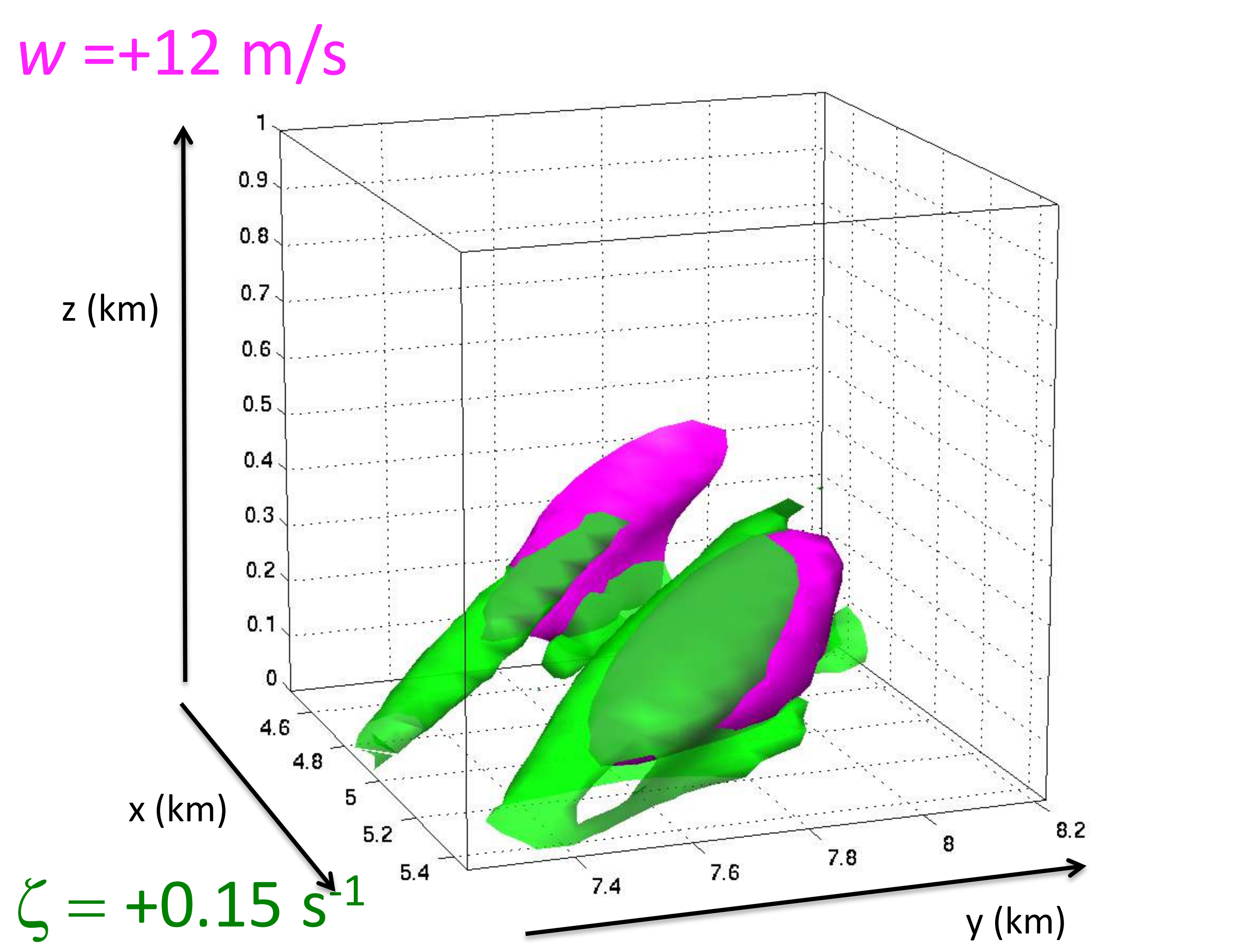
$$\mathrm{PGD} = -\frac{1}{\rho}\frac{\partial p_D}{\partial z}$$

- B and PGB are each strongly dependent on the choice of reference state, but their sum is not.
- So we combine B and PGB into one term, and compare this to PGD.

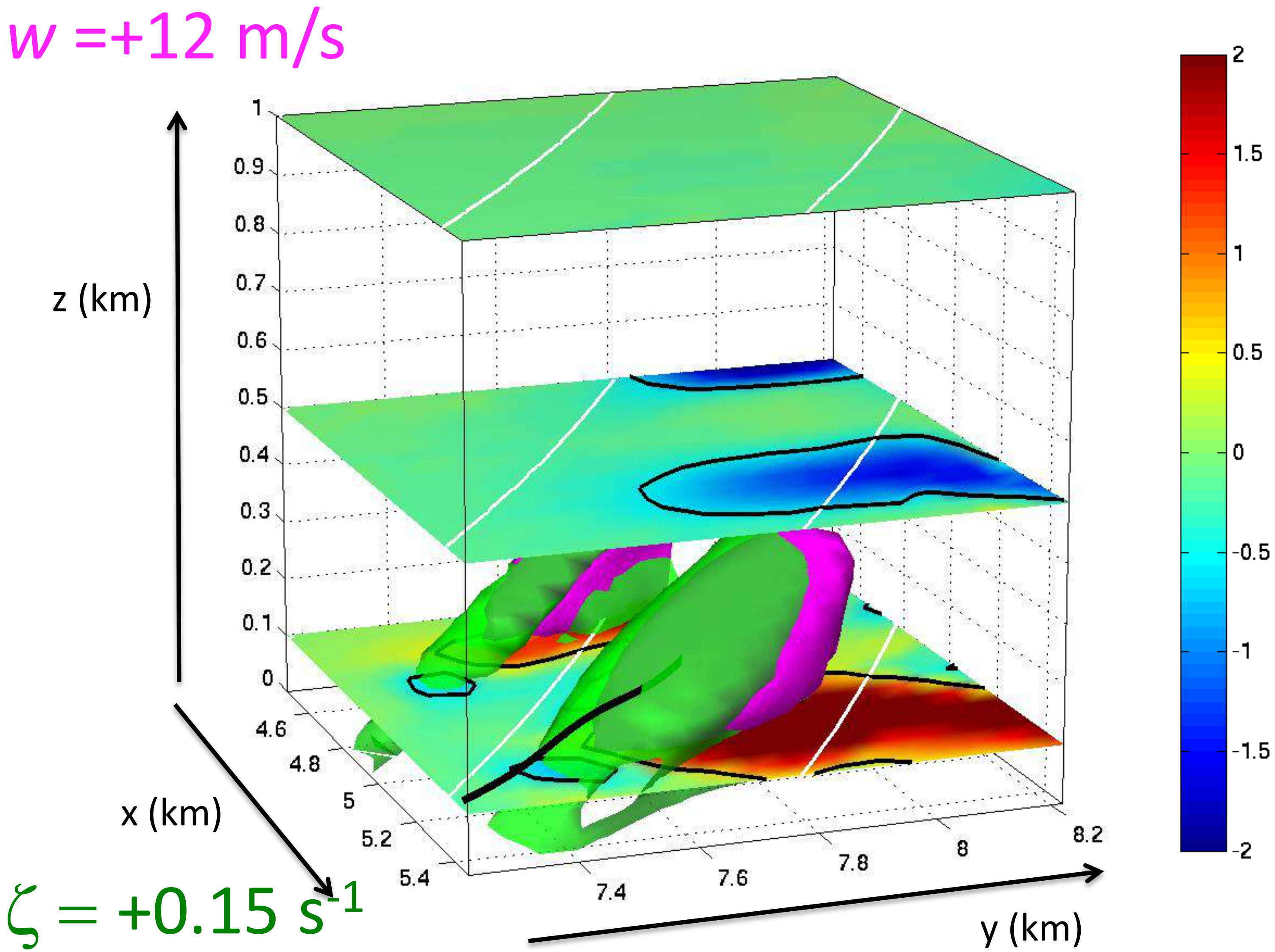
Examine updraft in a 1x1x1 km cube



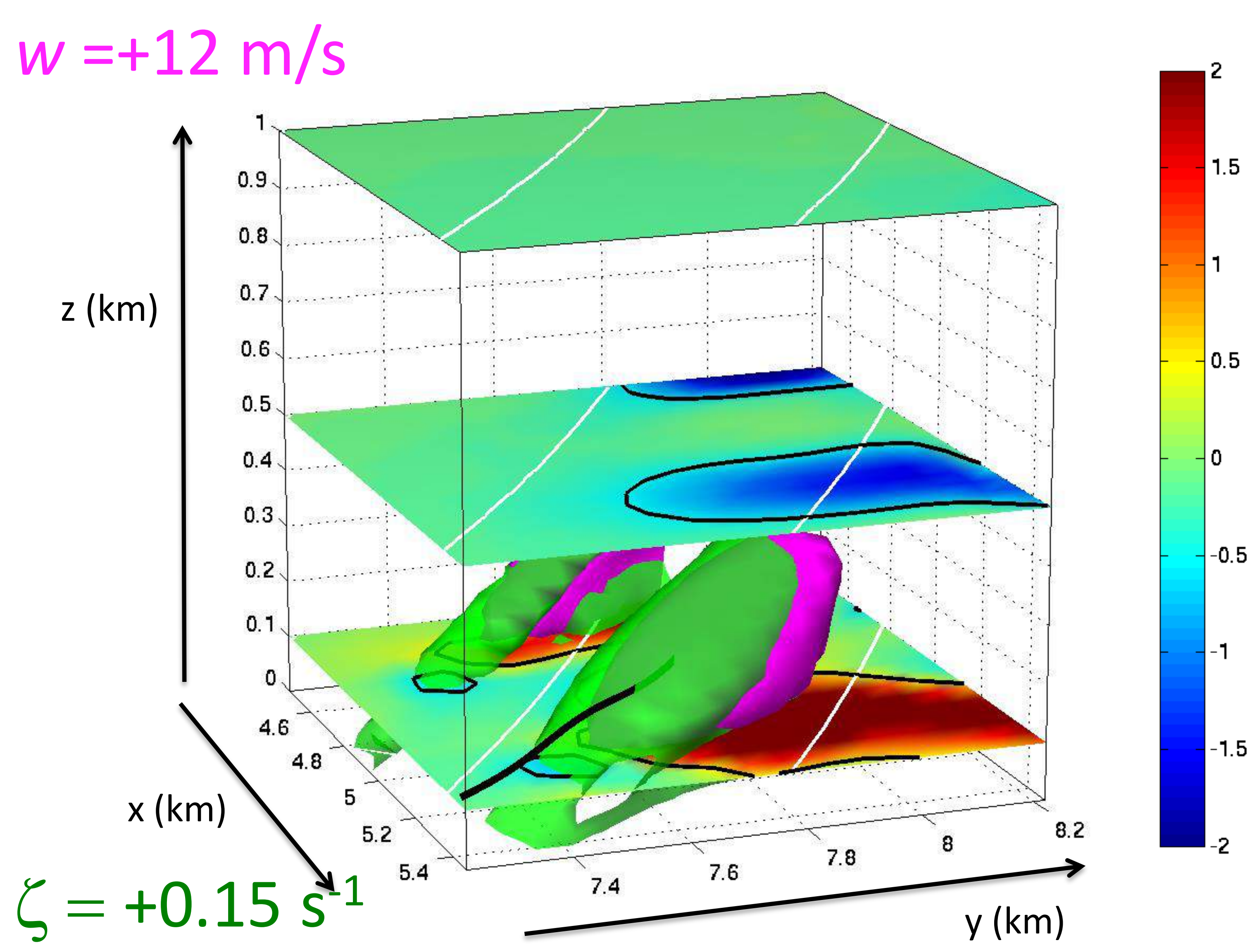
Add Vorticity Isosurface



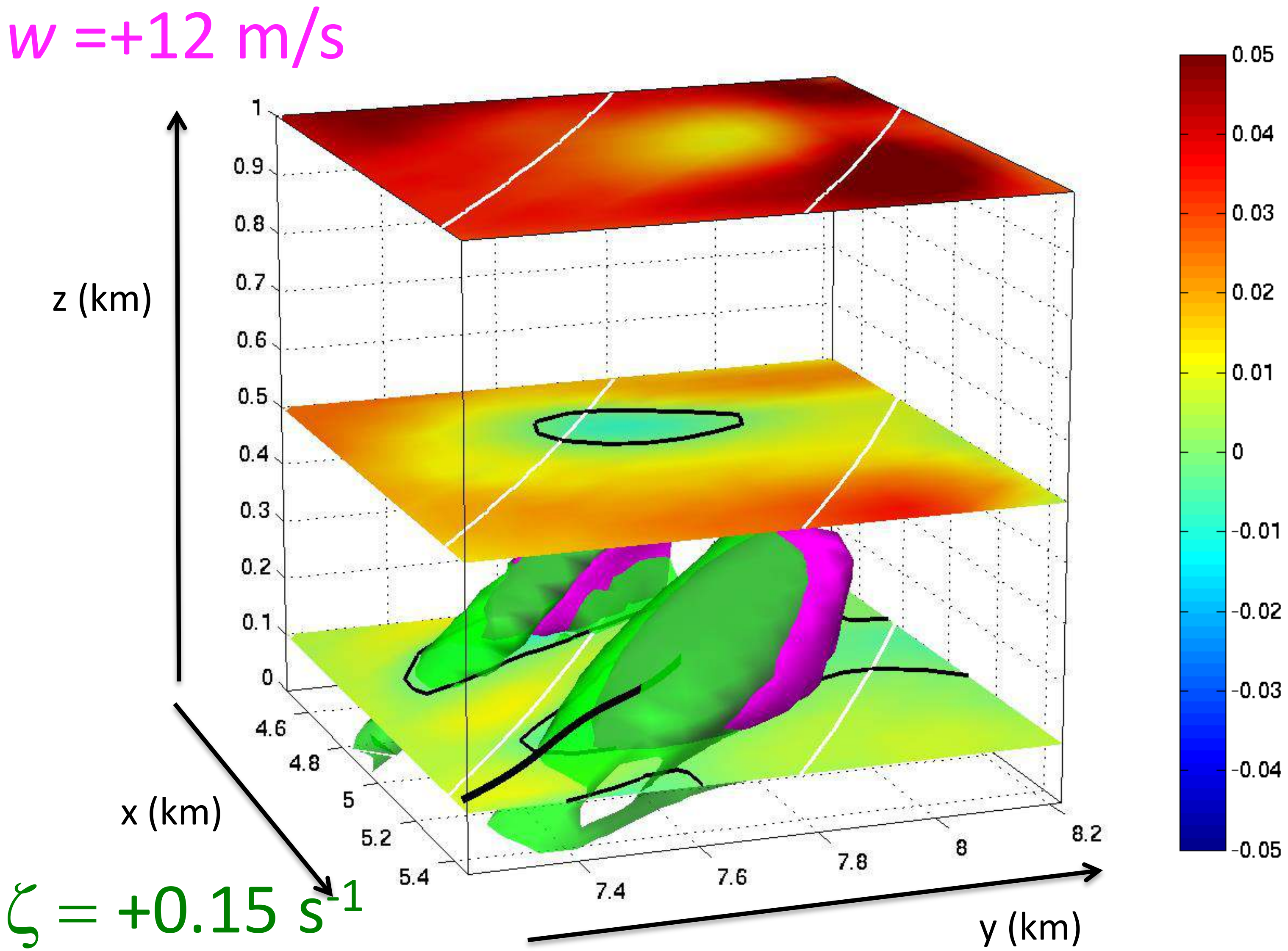
Total Acceleration (ms^{-2}; +/- 0.5 black)



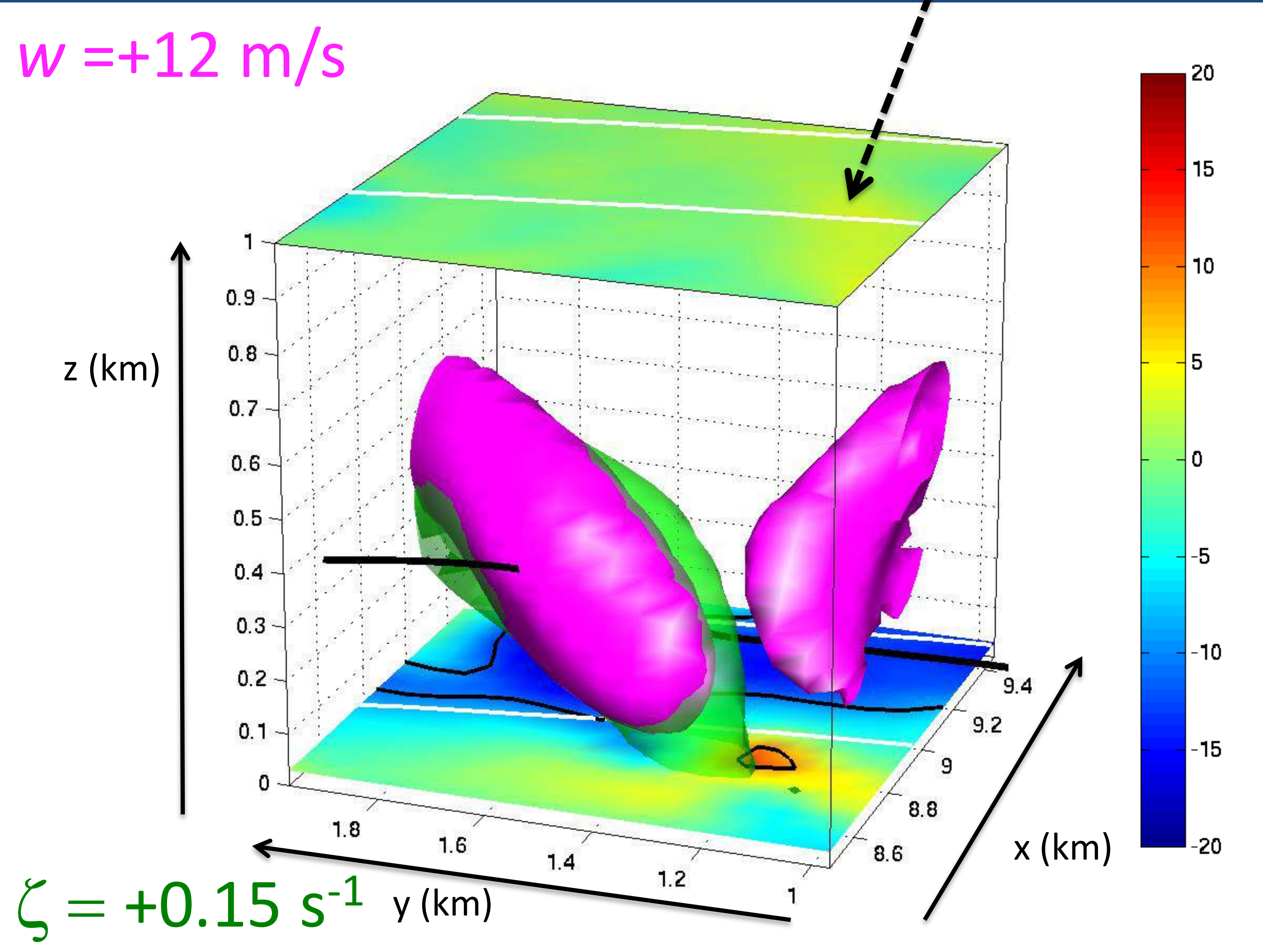
Dynamic Acceleration (ms^{-2}; +/- 0.5 black)



Buoyant Acceleration (ms^{-2}; 0 black)



Slices of Perturbation Vr (ms^{-1}; +/- 10 black)



Is there a *systematic* relationship between the updraft, horizontal winds, and vorticity?

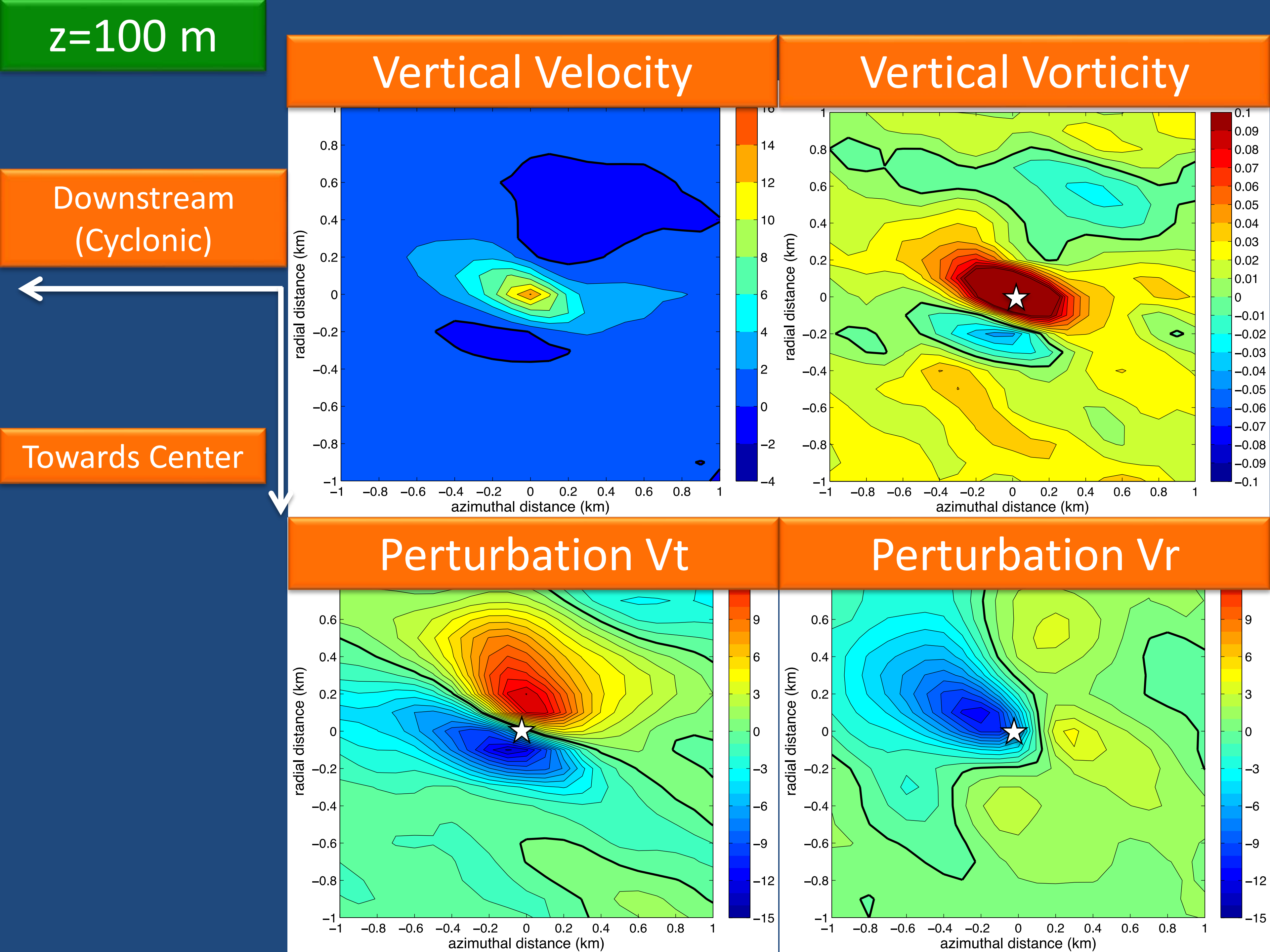
We can examine composite fields from many updrafts:

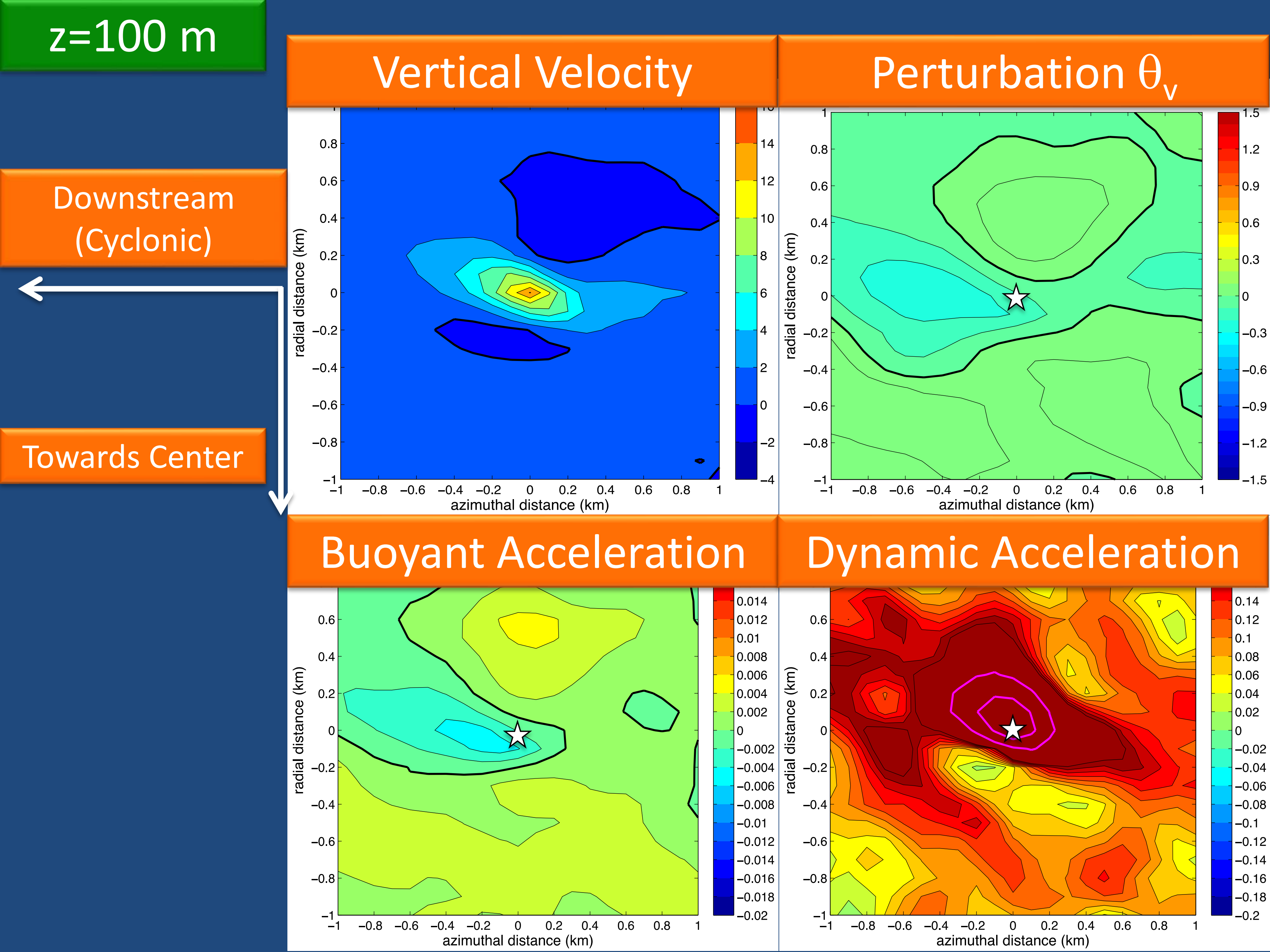
1. At a given level, find all points where w >= 12 m/s.

2. Interpolate to cylindrical coordinates.

3. Take a 2x2 km box (in radius/azimuth) around each point.

4. Average all such boxes.


z=100 m
Downstream (Cyclonic)
Towards Center
Vertical Velocity
Vertical Vorticity
Perturbation Vt
Perturbation Vr
radial distance (km)
azimuthal distance (km)



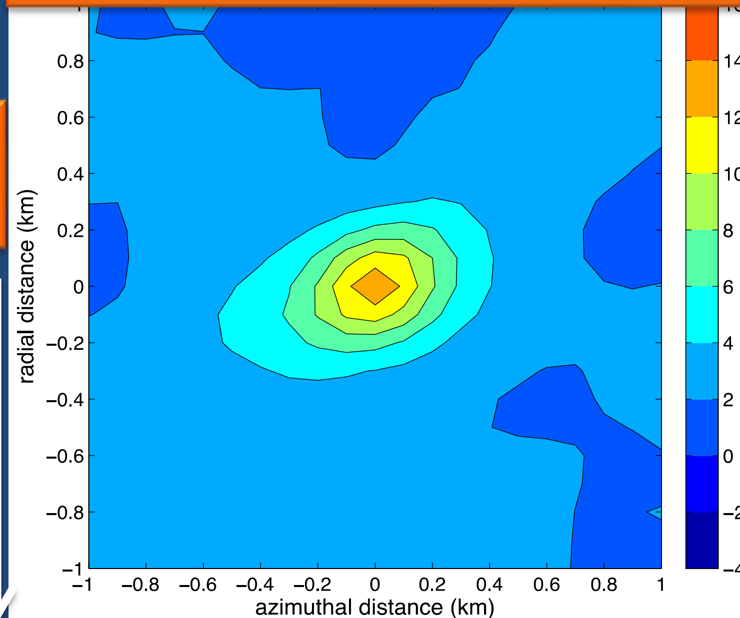
z=100 m
Downstream (Cyclonic)
Towards Center
Vertical Velocity
Perturbation θv
Buoyant Acceleration
Dynamic Acceleration
radial distance (km)
azimuthal distance (km)

Z=1000 m

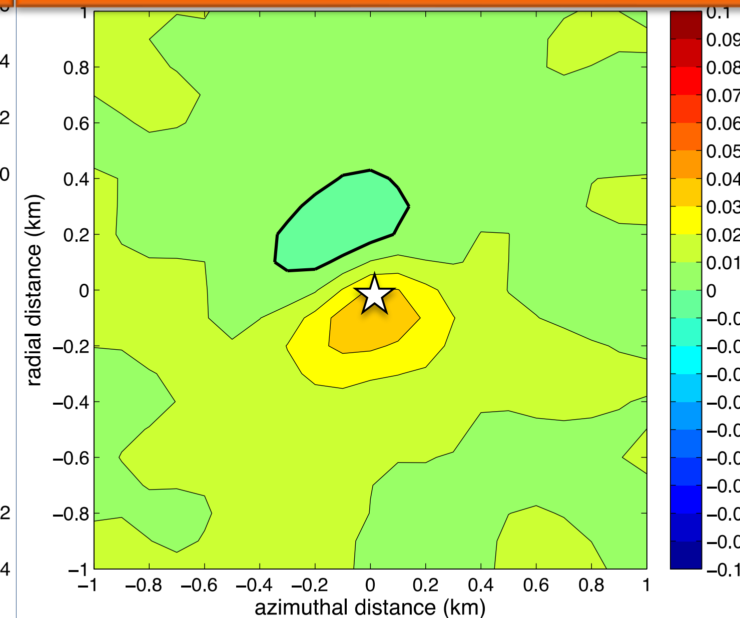
Downstream (Cyclonic)

Towards Center

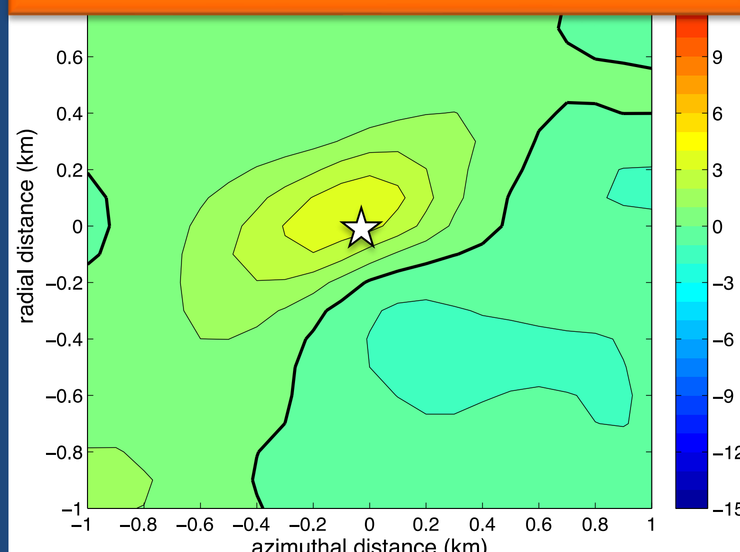
Vertical Velocity



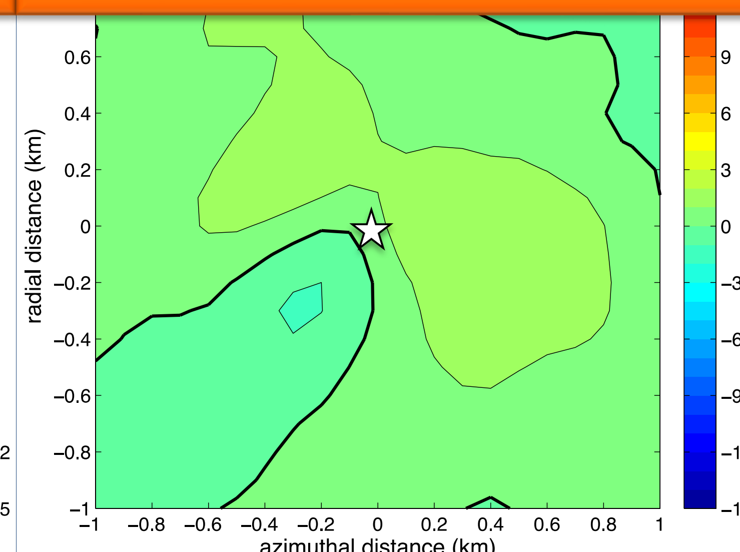
Vertical Vorticity

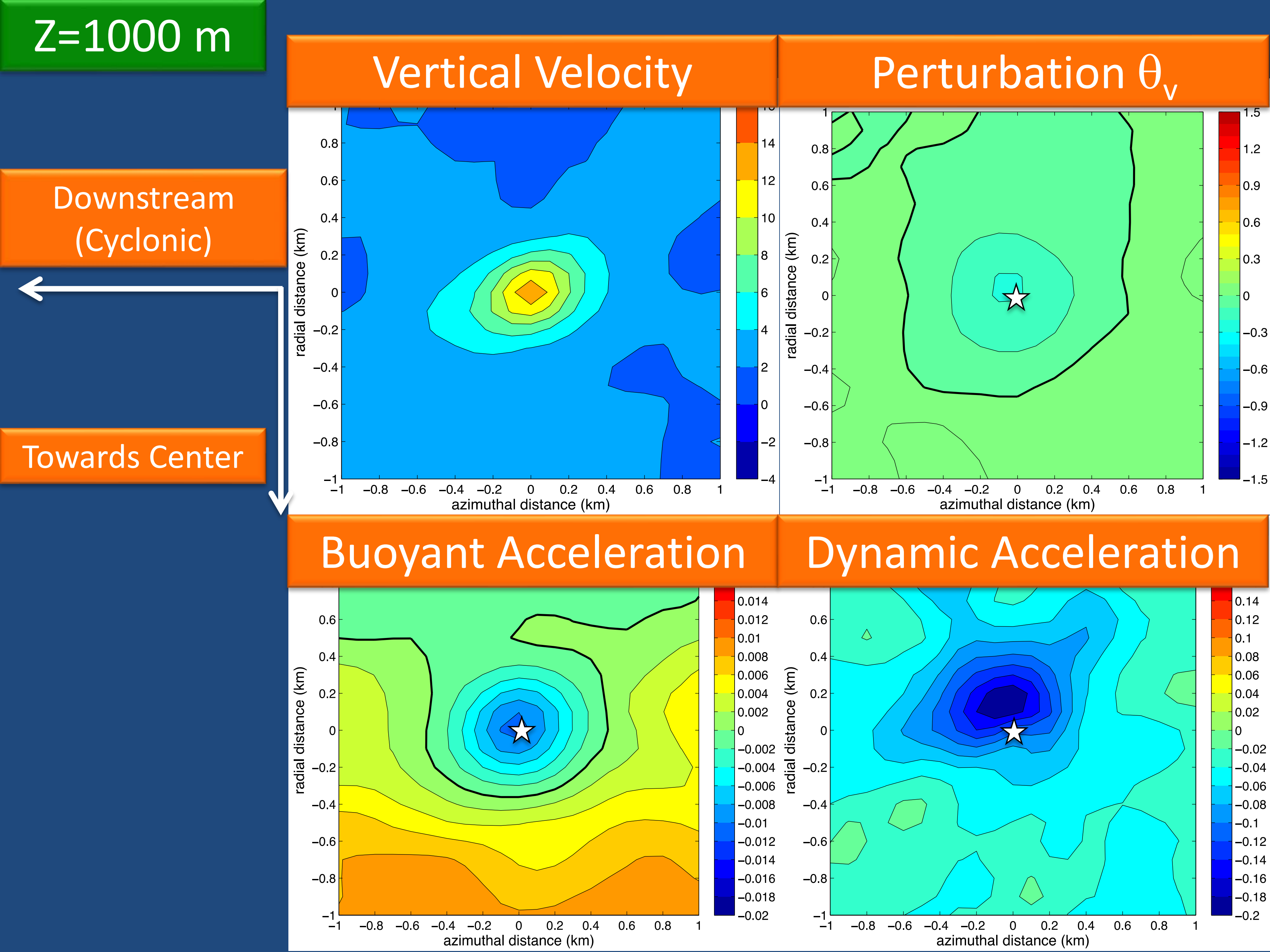


Perturbation Vt



Perturbation Vr




Z=1000 m
Vertical Velocity
Perturbation θv
Downstream (Cyclonic)
Towards Center
Buoyant Acceleration
Dynamic Acceleration
radial distance (km)
azimuthal distance (km)