The National Center for Atmospheric Research (NCAR)
is sponsored by the National Science Foundation (NSF)

EXTREME WIND GUSTS IN LARGE-EDDY SIMULATIONS OF TROPICAL CYCLONES

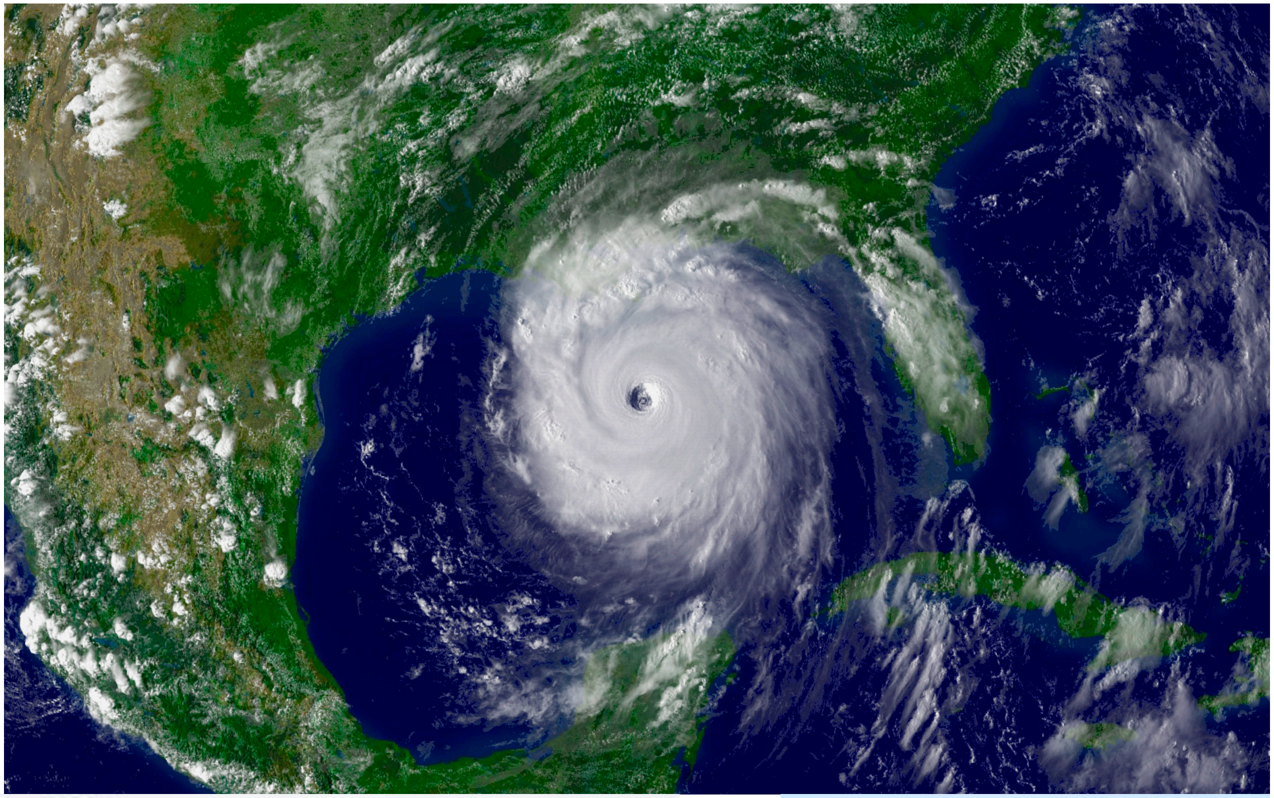
George Bryan

National Center for Atmospheric Research
Boulder, Colorado USA

6th Research Meeting of Ultrahigh Precision Meso-scale Weather Prediction
Kyoto, Japan
7 March 2016

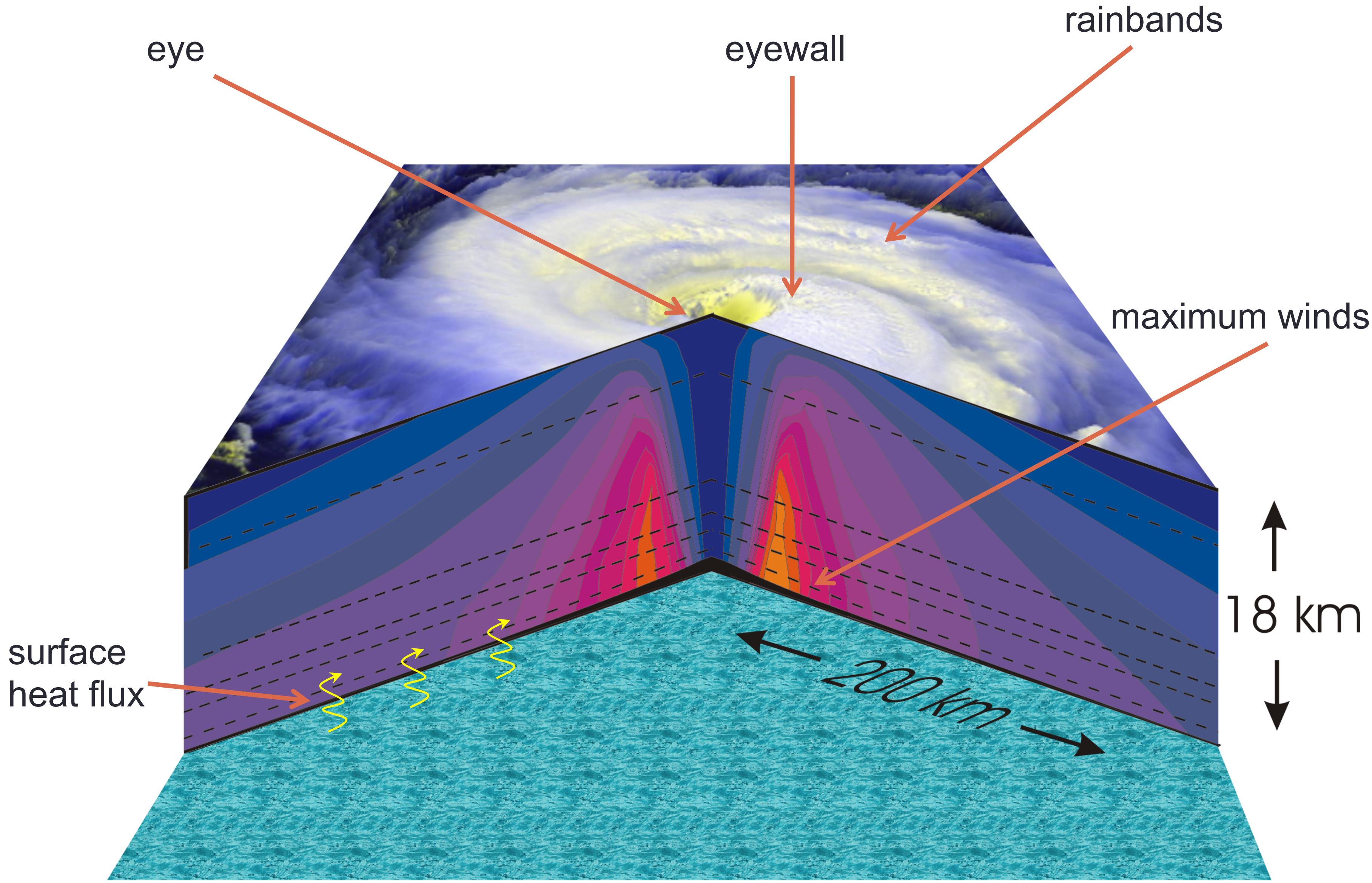
Tropical Cyclone (TC)

(i.e., Hurricane)
(i.e., Typhoon)
(台風)



Hurricane Katrina (2005)

Components of a tropical cyclone



Emanuel (2005)

Observations in Hurricanes

- Aircraft *in situ* measurements
  - High frequency (40 Hz windspeed)

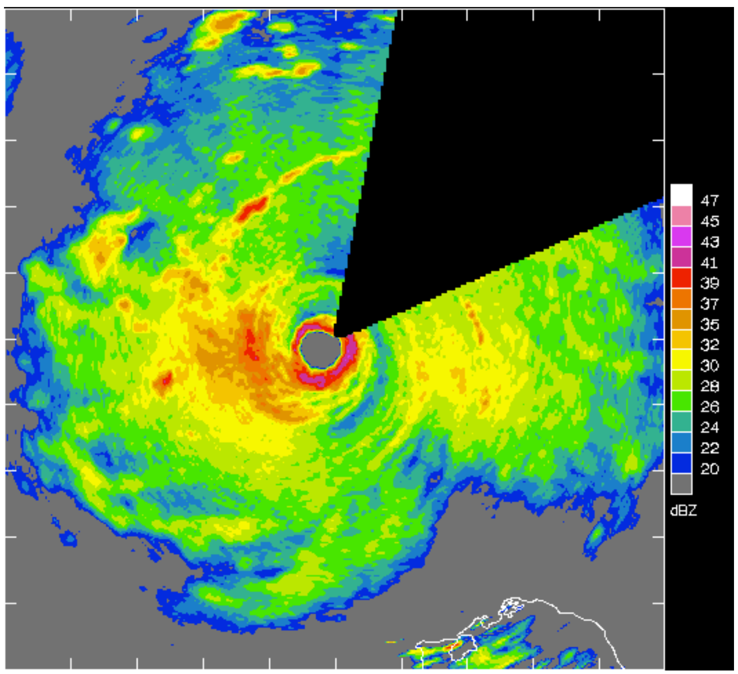
- Dropsondes
  - High vertical resolution

Images courtesy NOAA

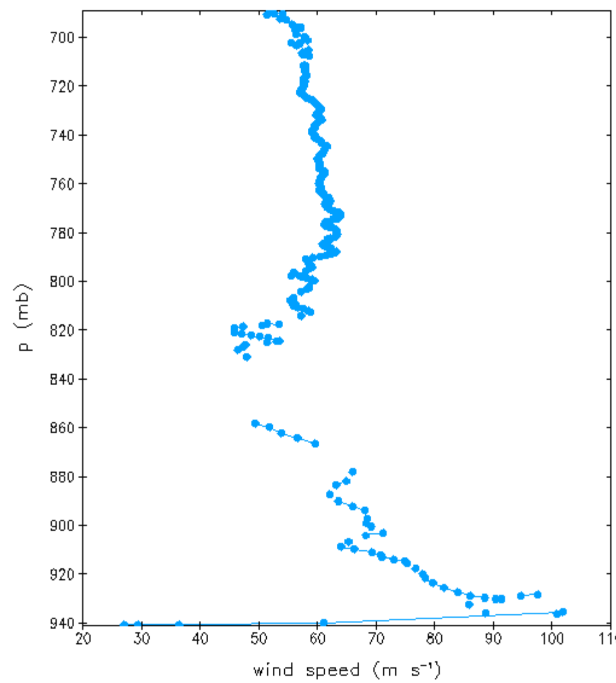
Hurricane Felix (2007)

National Hurricane Center best track intensity: V_{max} = 77 m s^{-1}

"maximum intensity … has greater than normal uncertainty"

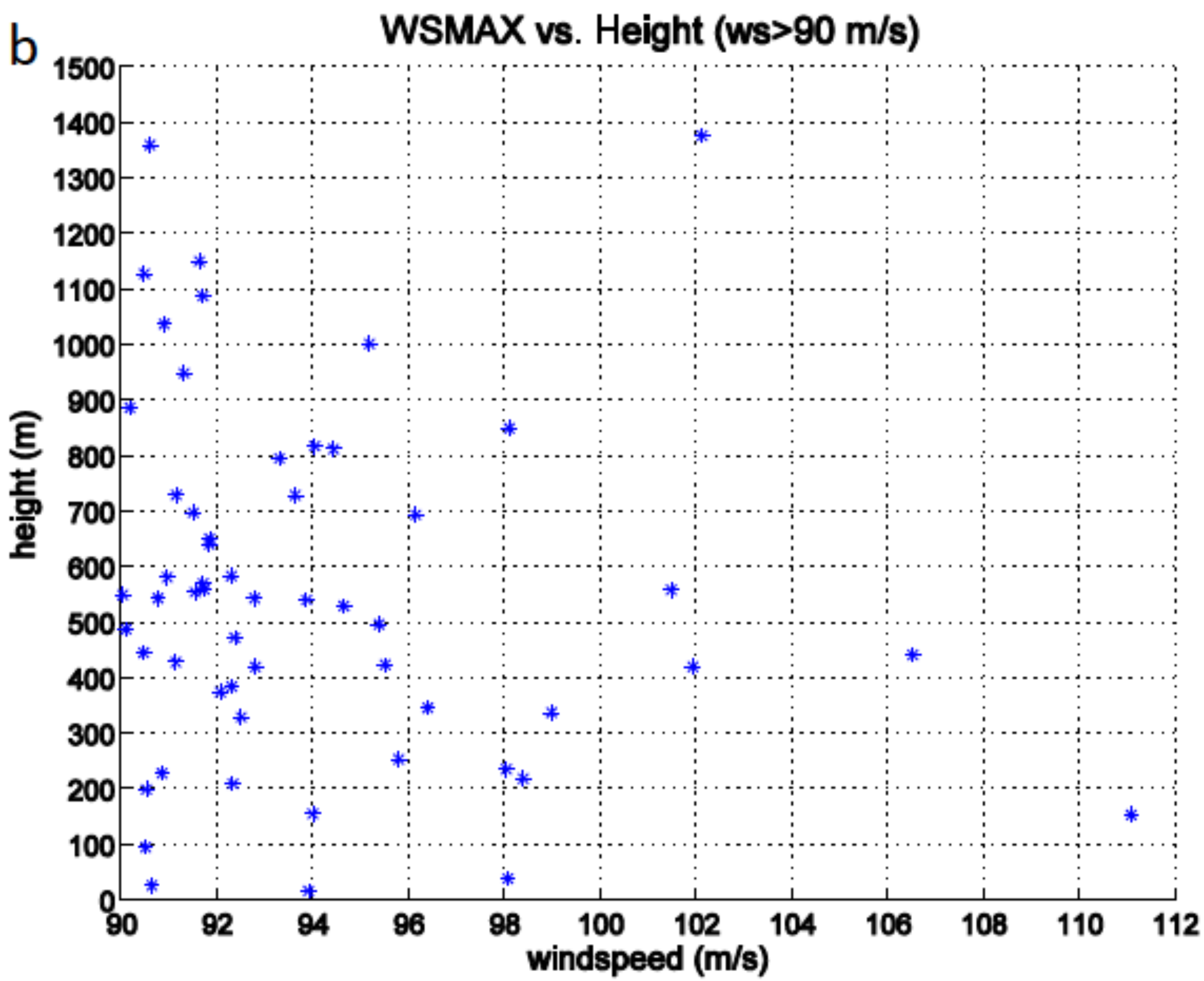


Dropsonde windspeed (m s^{-1})



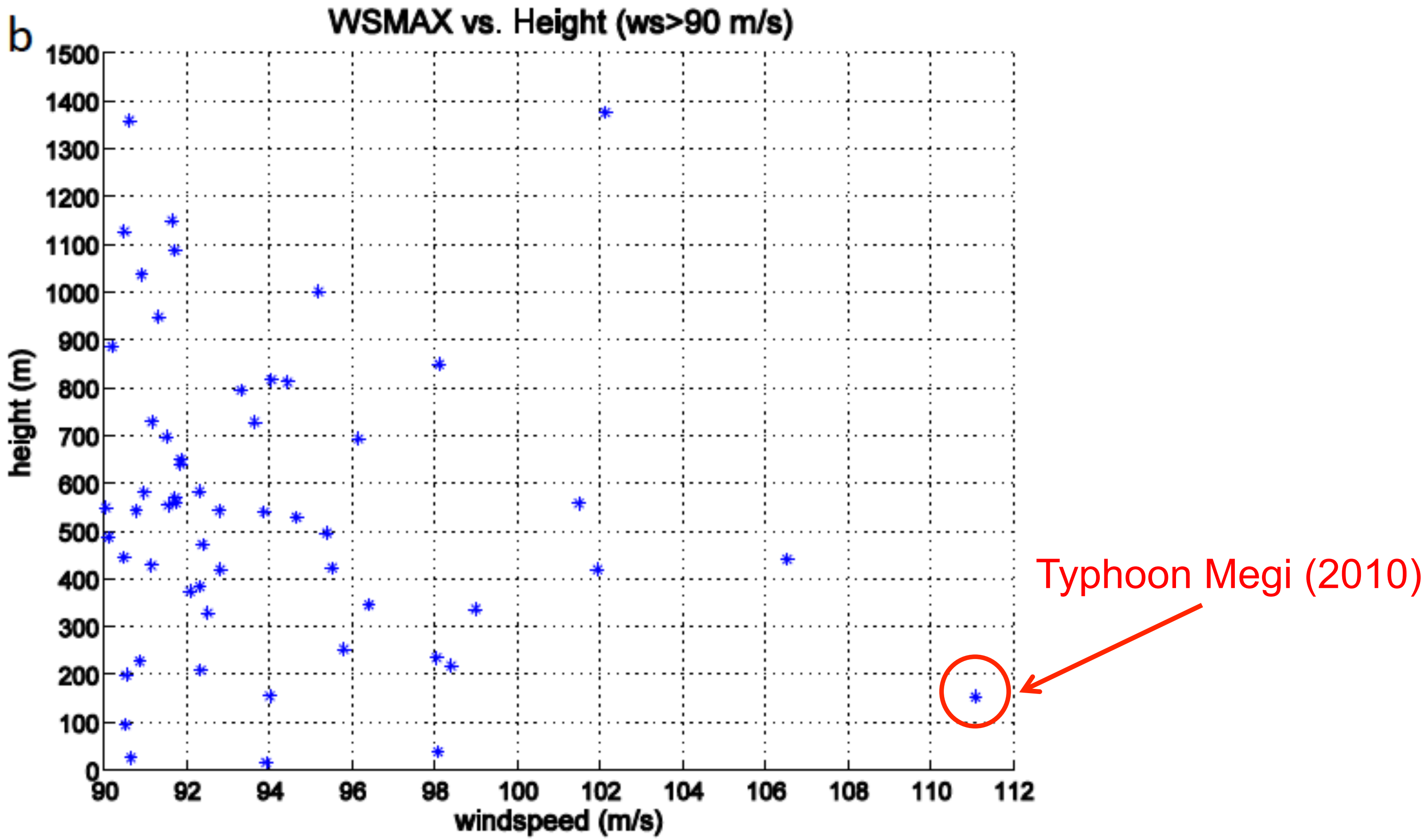
NOAA/Hurricane Research Division

Maximum wind gusts from Dropsondes (1997-2014)



Stern, Bryan, and Aberson (2016)

Maximum wind gusts from Dropsondes (1997-2014)

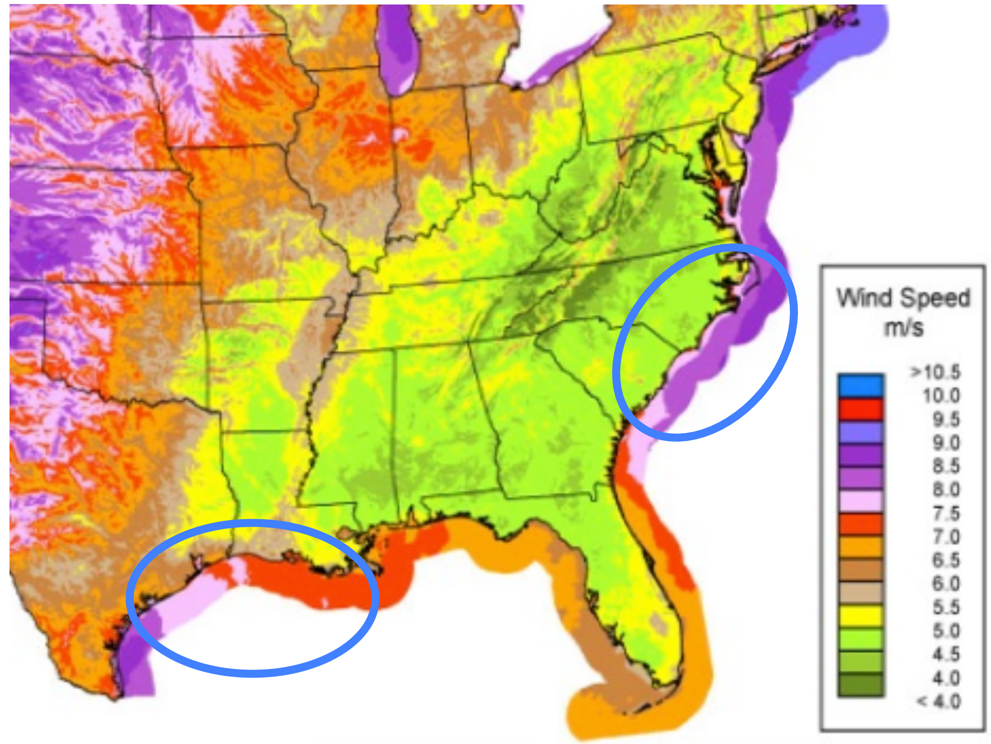


Stern, Bryan, and Aberson (2016)

Offshore wind turbines

Photo by Fotolia/Yauhen Suslo

Annual Average Wind Speed at 80 m



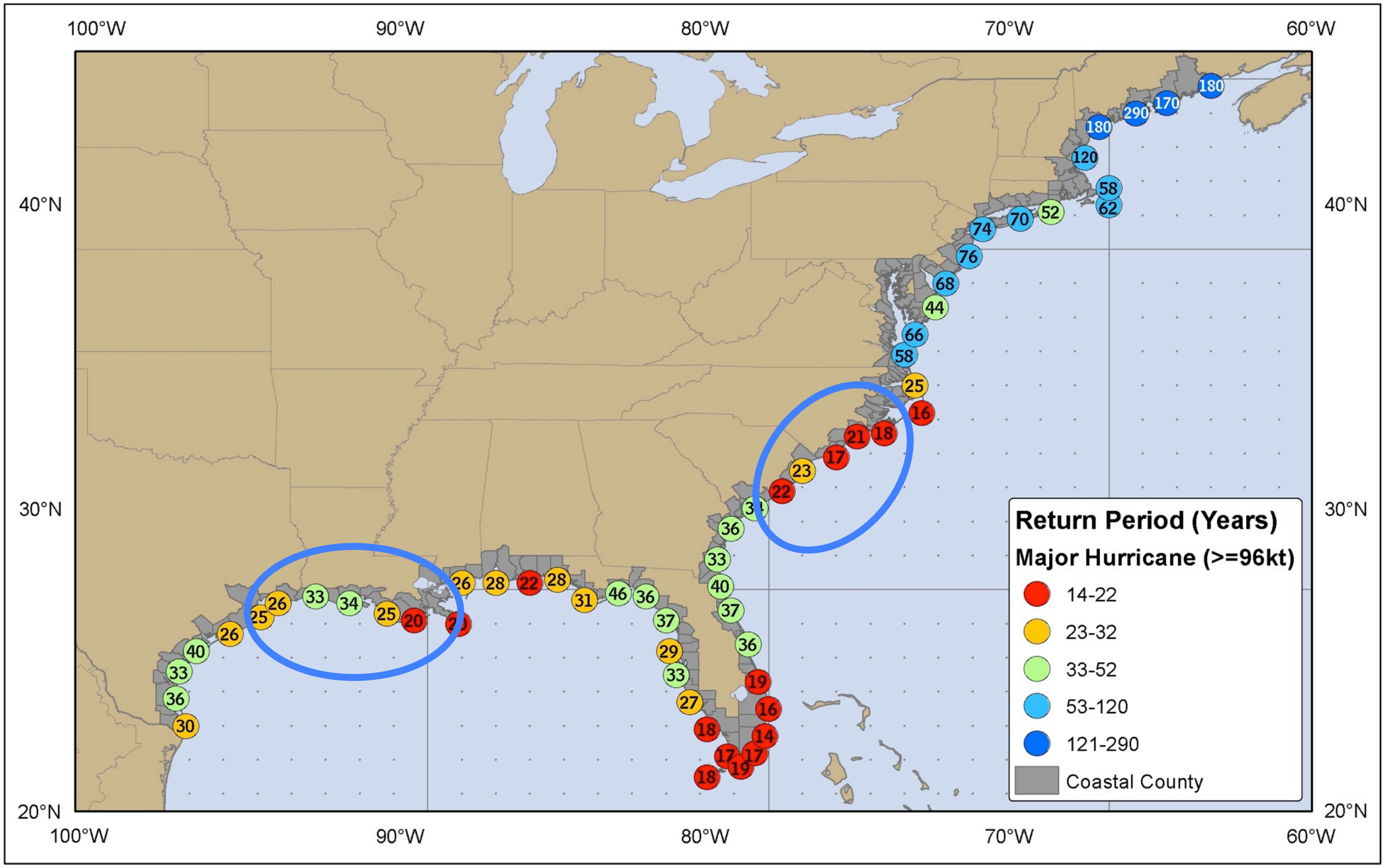
Source: Wind resource estimates developed by AWS Truepower, LLC. Web: http://www.awstruepower.com. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84.

AWS Truepower™ Where science delivers performance.

NREL NATIONAL RENEWABLE ENERGY LABORATORY

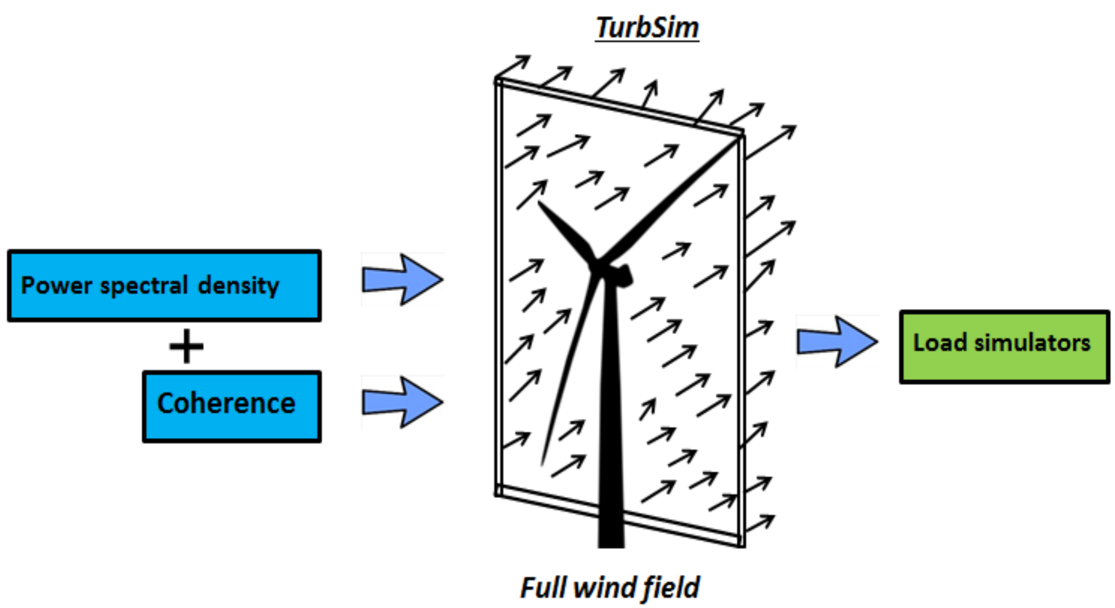
→ Offshore wind turbines need to operate for 20-30 years

→ Thus, wind turbines need to survive hurricanes

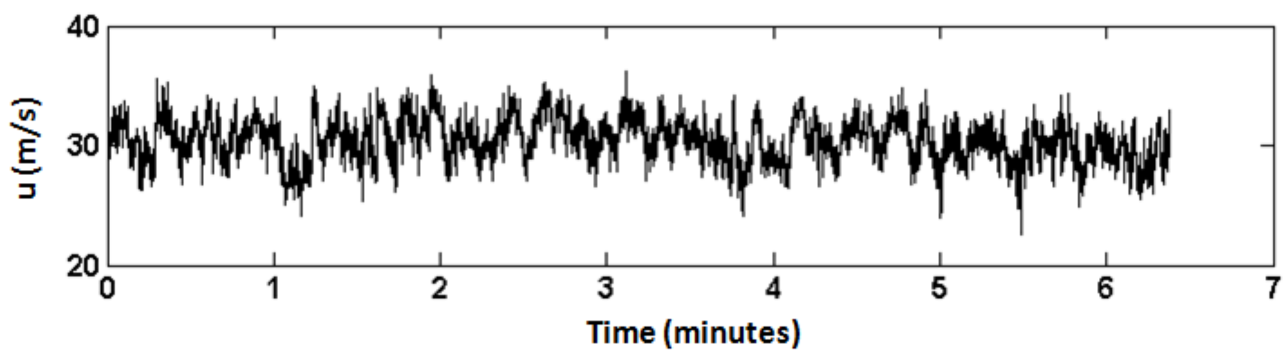


NOAA / National Hurricane Center
(http://www.nhc.noaa.gov)

Tools to evaluate load on wind turbines



Observations: Hurricane Isabel (2003)
r = 130 km, z = 194 m

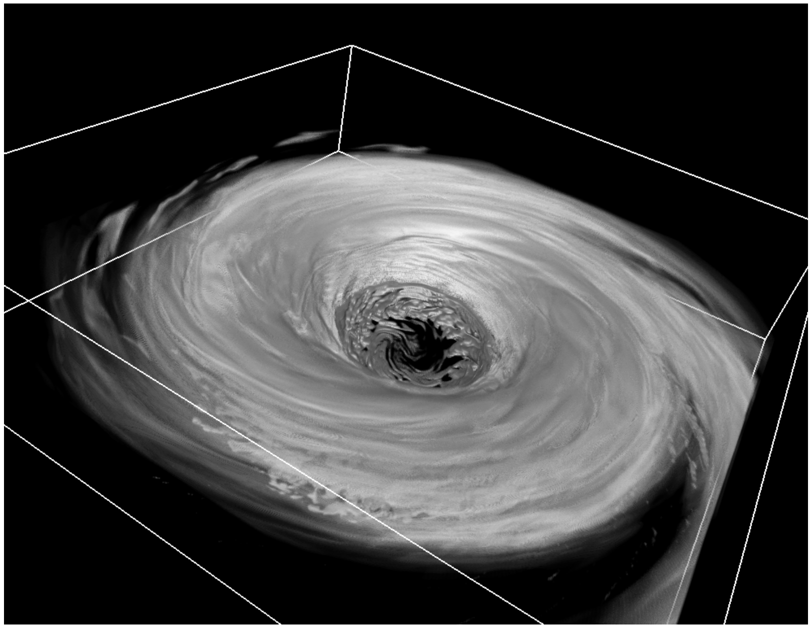


Worsnop (2015)

Need More Data!

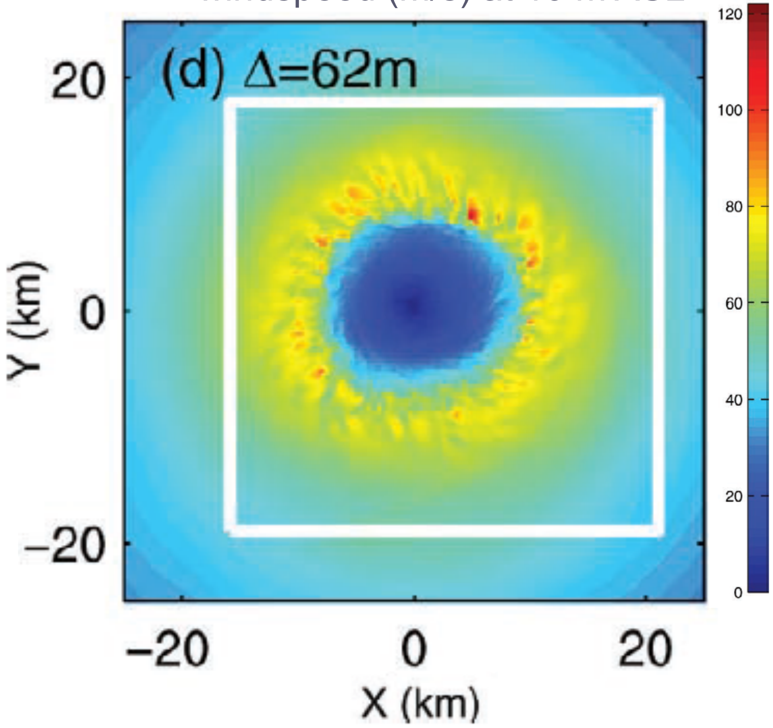
- Observations in strong TCs are rare
- Can we generate accurate data using numerical models?

WRF simulation (Yongsheng Chen)



Rotunno et al. (2009, BAMS)

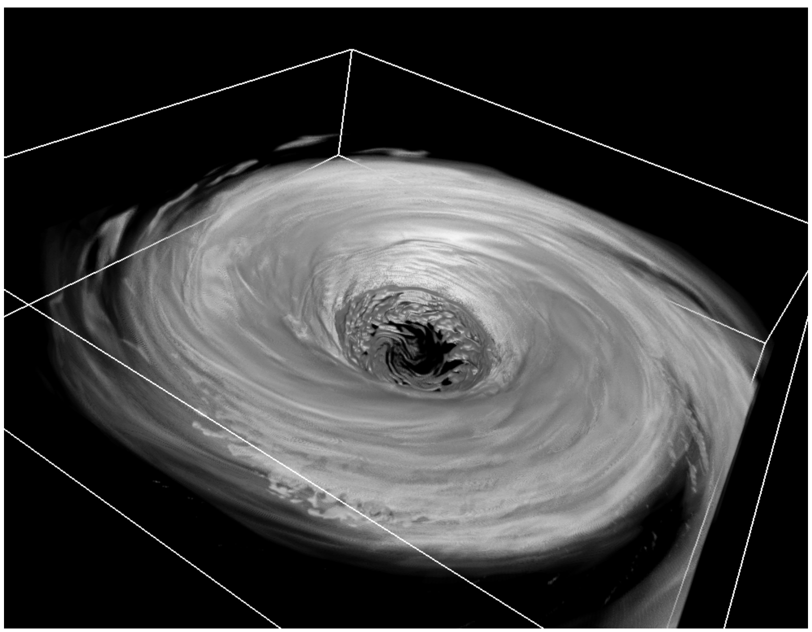
windspeed (m/s) at 10 m ASL



Need More Data!

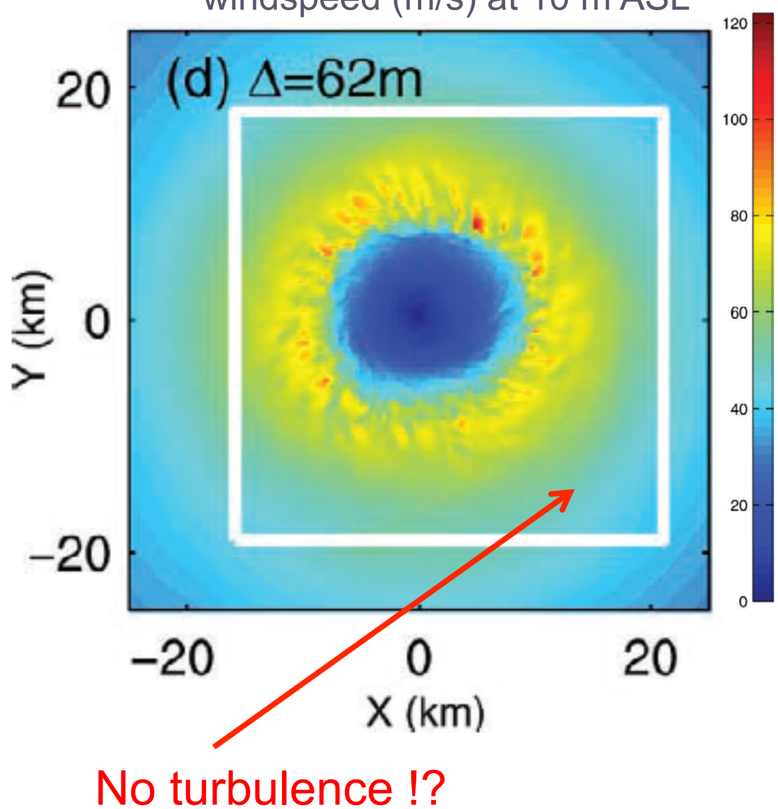
- Observations in strong TCs are rare
- Can we generate accurate data using numerical models?

WRF simulation (Yongsheng Chen)



Rotunno et al. (2009, BAMS)

windspeed (m/s) at 10 m ASL



Numerical Model: CM1 ("Cloud Model version 1")

http://www2.mmm.ucar.edu/people/bryan/cm1

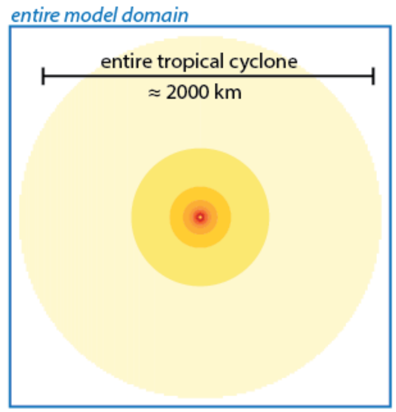
- Developed at Penn State (2000-2002) and NCAR (2003-present)
  - (Bryan and Fritsch, 2002; Bryan and Rotunno, 2009; Bryan and Morrison 2012)

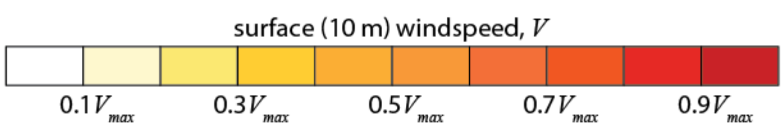
- Similar to WRF (Weather Research and Forecasting) Model
  - Split-explicit RK3 (Wicker and Skamarock 2002)
  - 5th-order WENO advection (Shu 2001, Shan and Zha 2010)
  - Morrison double-moment microphysics

- Some differences from WRF
  - Energy-conserving equations for moist flows
  - Height-based terrain following coordinate
  - Different subgrid turbulence model for LES (Sullivan et al. 1994)

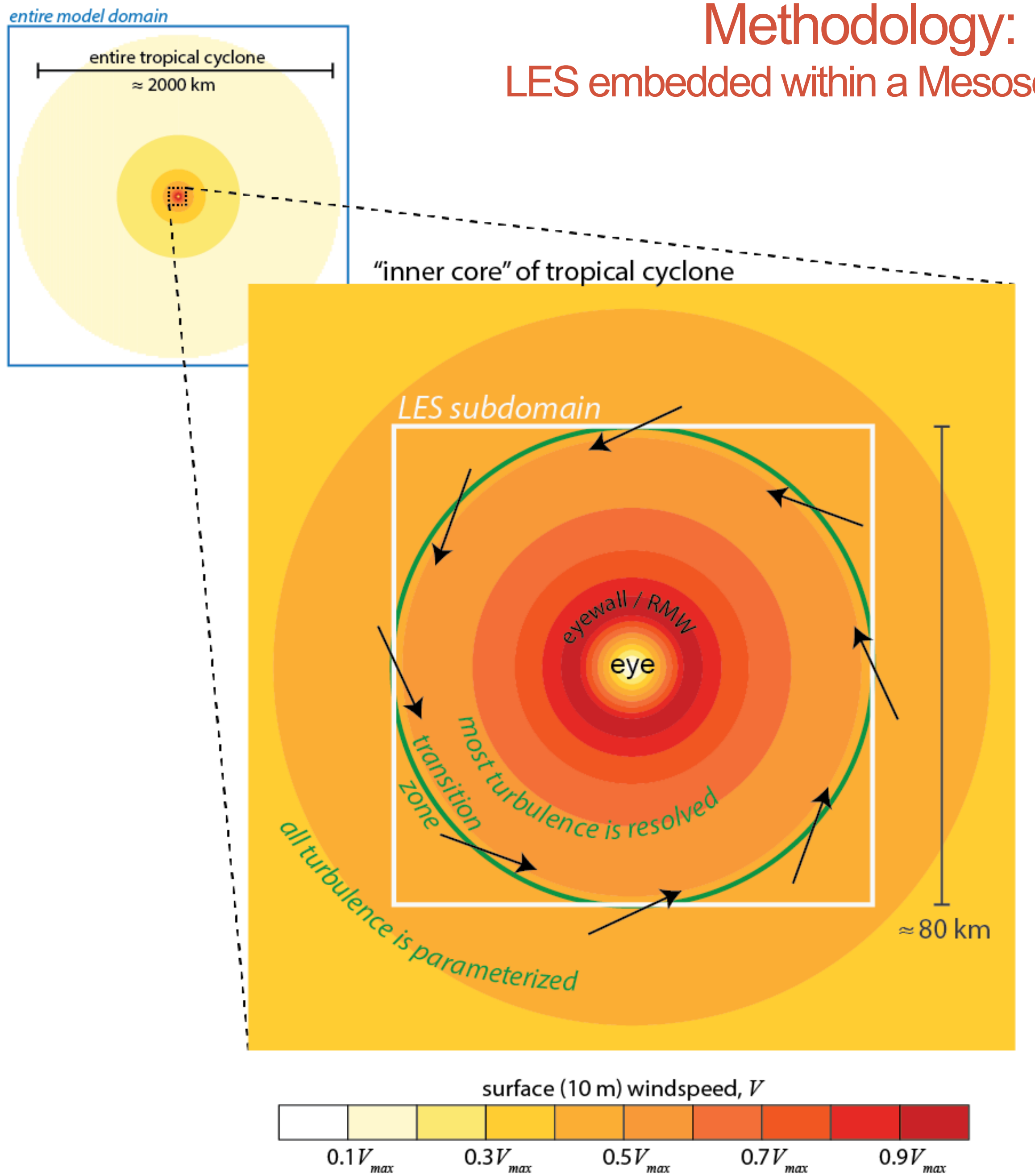
Methodology:

LES embedded within a Mesoscale Model

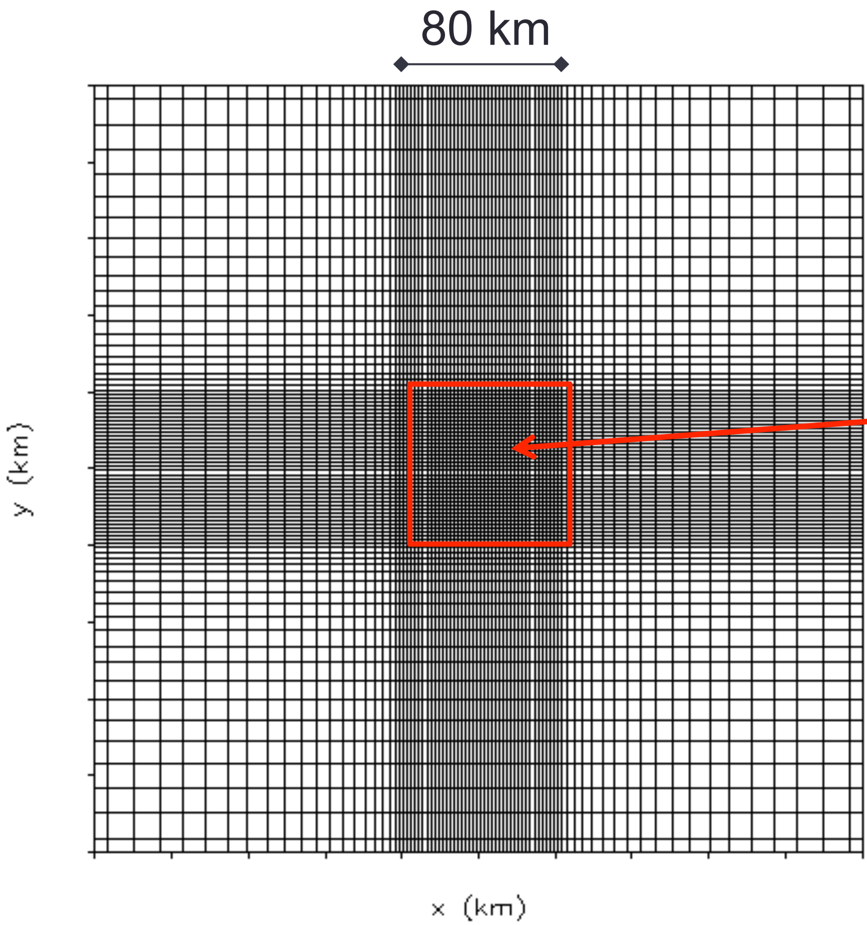




Methodology:
LES embedded within a Mesoscale Model



Setup



- Entire domain:
  - 3,000 km × 3,000 km × 25 km
  - Δx, Δy, Δz increase gradually
- Fine-mesh part of domain:
  - 80 km × 80 km × 3 km
  - $\Delta x = \Delta y =$ constant; $\Delta z = \Delta x/2$
  - (primarily $\Delta x = 31.25$ m)

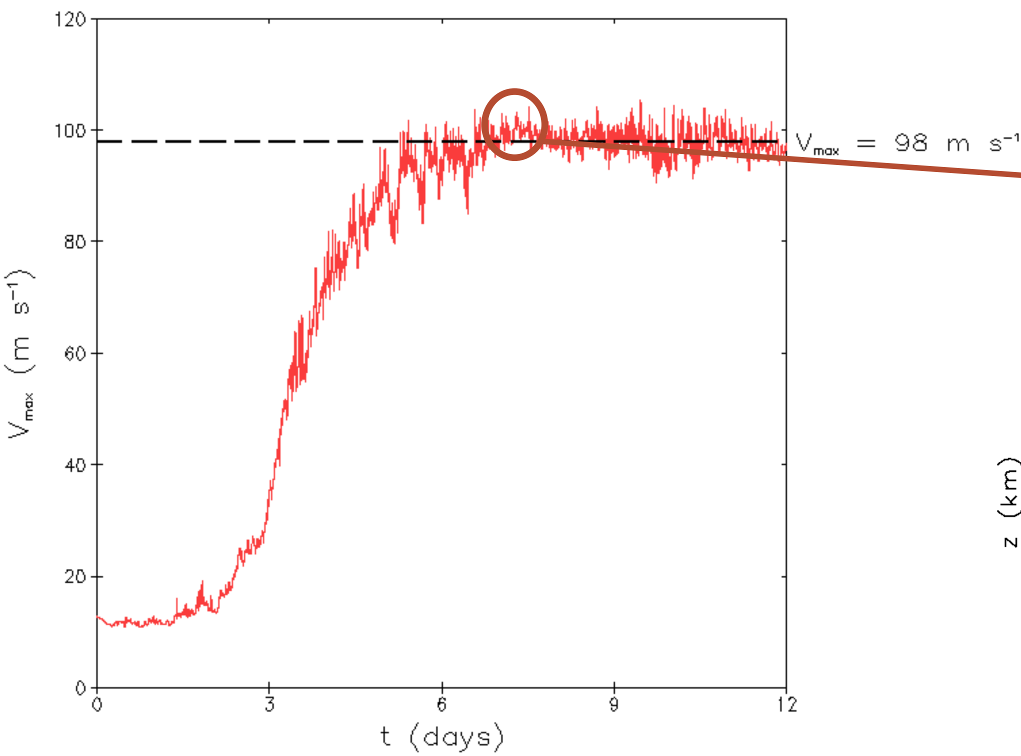
Other settings:

- $T_s = 28$ °C (fixed)
- $f = 5\times10^{-5}\ s^{-1}$
- Periodic lateral boundary conditions (1400 km away from fine mesh)
- Subgrid turbulence: Sullivan et al. (1994, BLM), "two-part" eddy-viscosity model

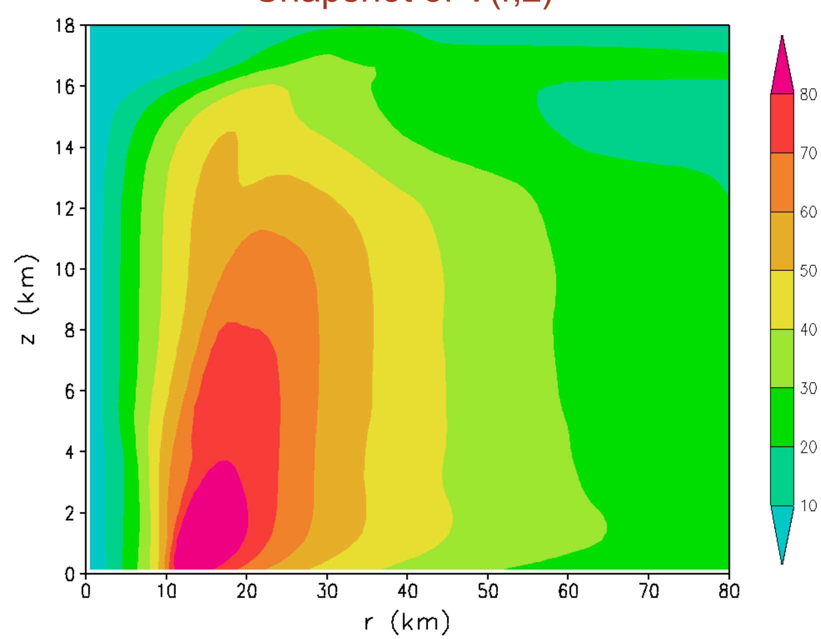
“Precursor Simulation” 1

- Initial conditions from an axisymmetric simulation:
  - Δr = 1 km, 123 vertical levels
  - Same physical parameterization (including PBL scheme)

Time series of maximum windspeed (Vmax)



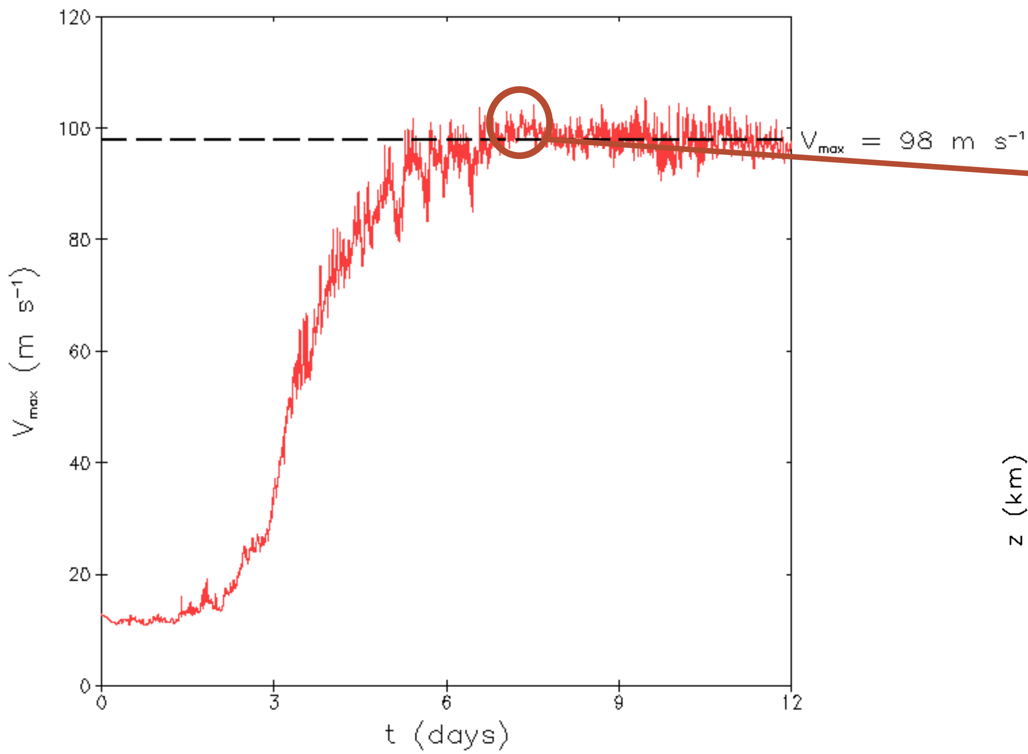
Snapshot of V(r,z)



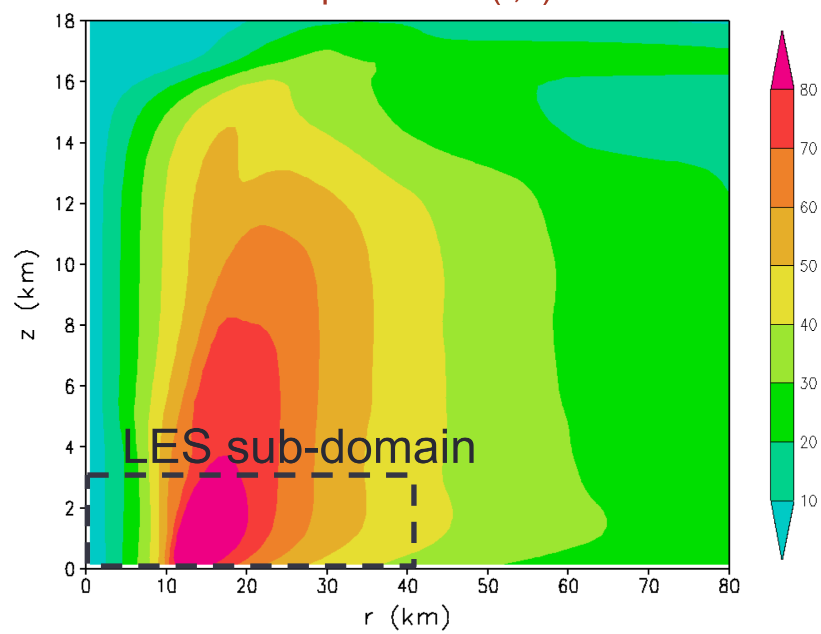
"Precursor Simulation" 1

- Initial conditions from an axisymmetric simulation:
  - Δr = 1 km, 123 vertical levels
  - Same physical parameterization (including PBL scheme)

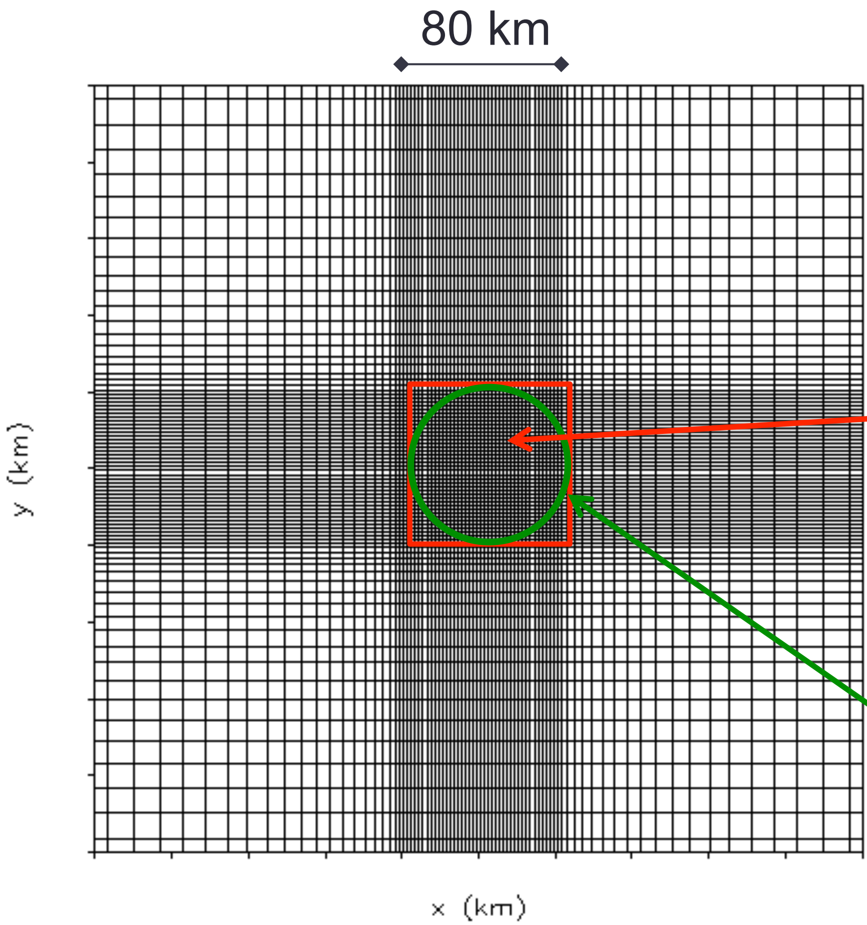
Time series of maximum windspeed (Vmax)



Snapshot of V(r,z)



Setup



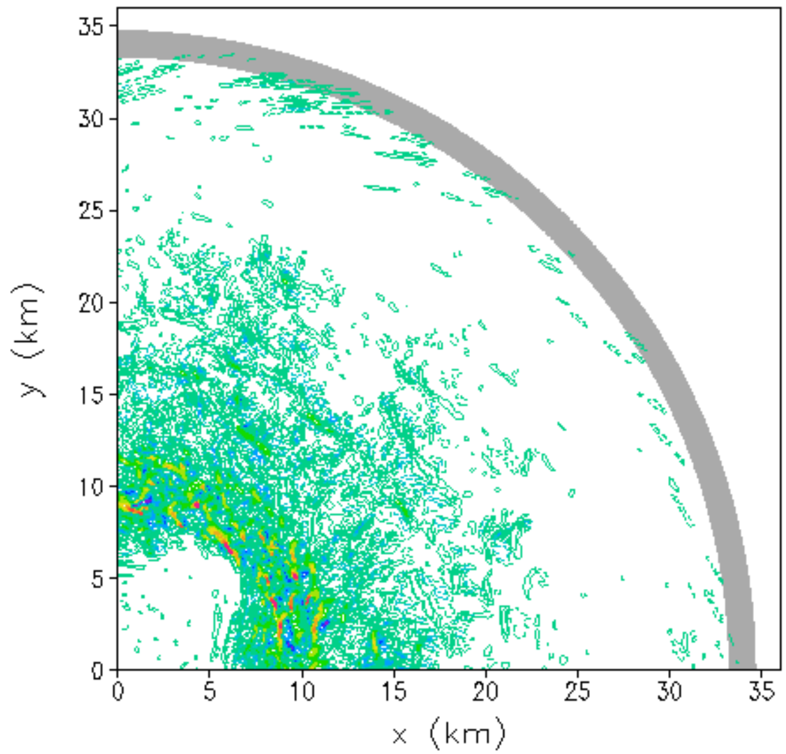
- Entire domain:
  - 3,000 km × 3,000 km × 25 km
  - Δx, Δy, Δz increase gradually
- Fine-mesh part of domain:
  - 80 km × 80 km × 3 km
  - Δx = Δy = constant; Δz = Δx/2
  - (primarily Δx = 31.25 m)
- Transition zone
  - 2-km-wide ring, r = 40 km
  - Add random perturbations to θ, q_v

Other settings:

- T_s = 28 °C (fixed)
- f = 5×10^{-5} s^{-1}
- Periodic lateral boundary conditions (1400 km away from fine mesh)
- Subgrid turbulence: Sullivan et al. (1994, BLM), “two-part” eddy-viscosity model

Turbulence at the LES/MM interface

w at z=100 m (c.i. = 1 m s^{-1})

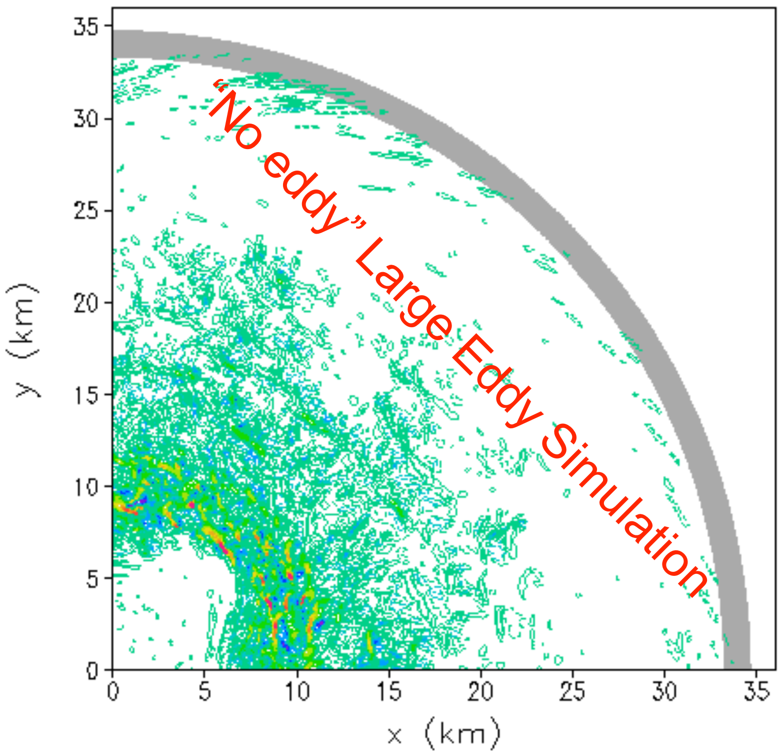


Δx=62m; Δz=31m

Note: turbulence exists primarily at eye/eyewall interface (as in Rotunno et al. 2009)

Turbulence at the LES/MM interface

w at *z*=100 m (c.i. = 1 m s^{-1})



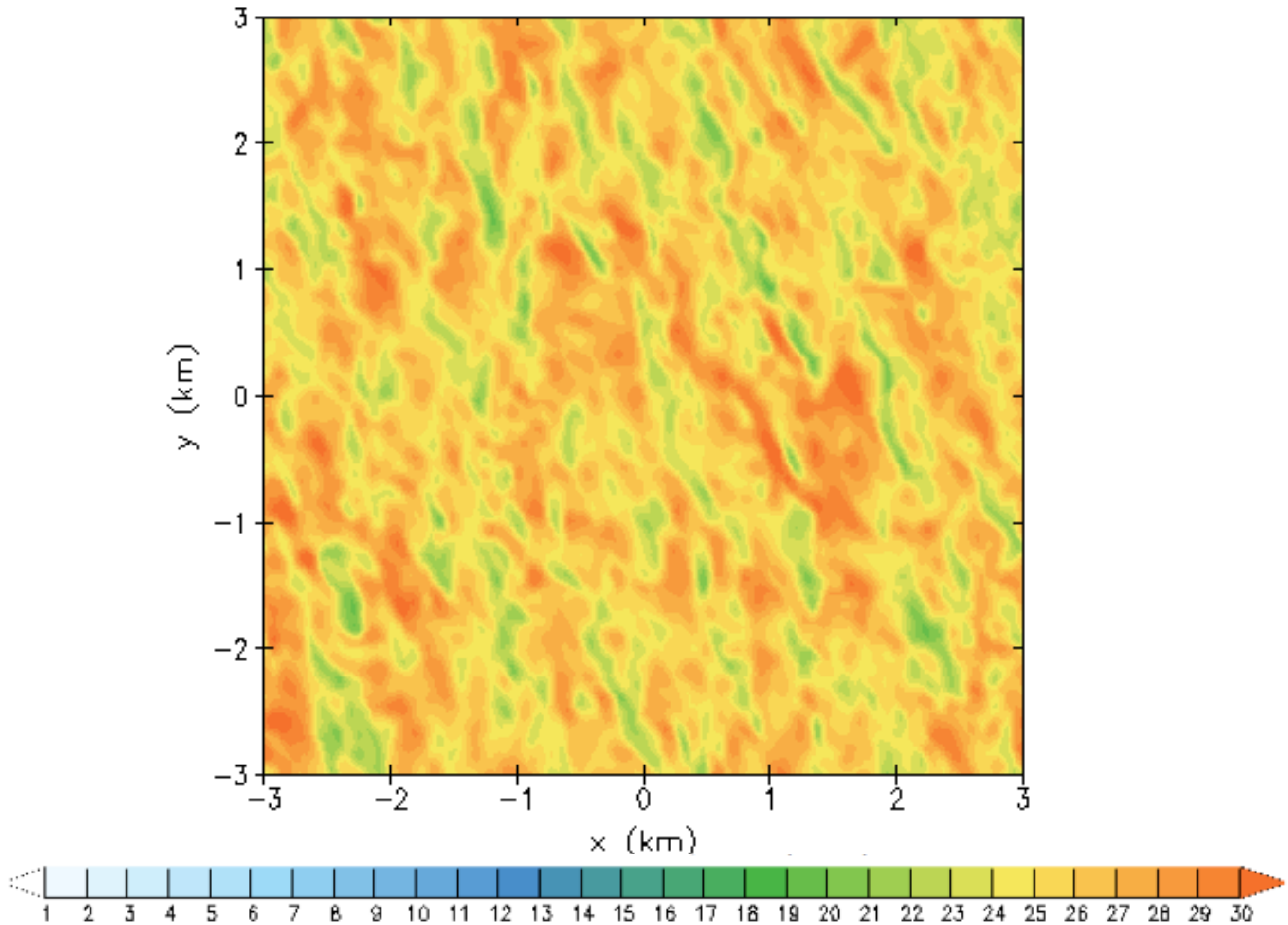
Δx=62m; Δz=31m

Note: turbulence exists primarily at eye/eyewall interface (as in Rotunno et al. 2009)

“Precursor Simulation” 2

- Run a “traditional” doubly-periodic LES, at same resolution
- Output u’, v’, w’ every-other timestep (lowest 1 km ASL)
- Then, apply these perturbations within the “transition zone” in the “complex” simulation

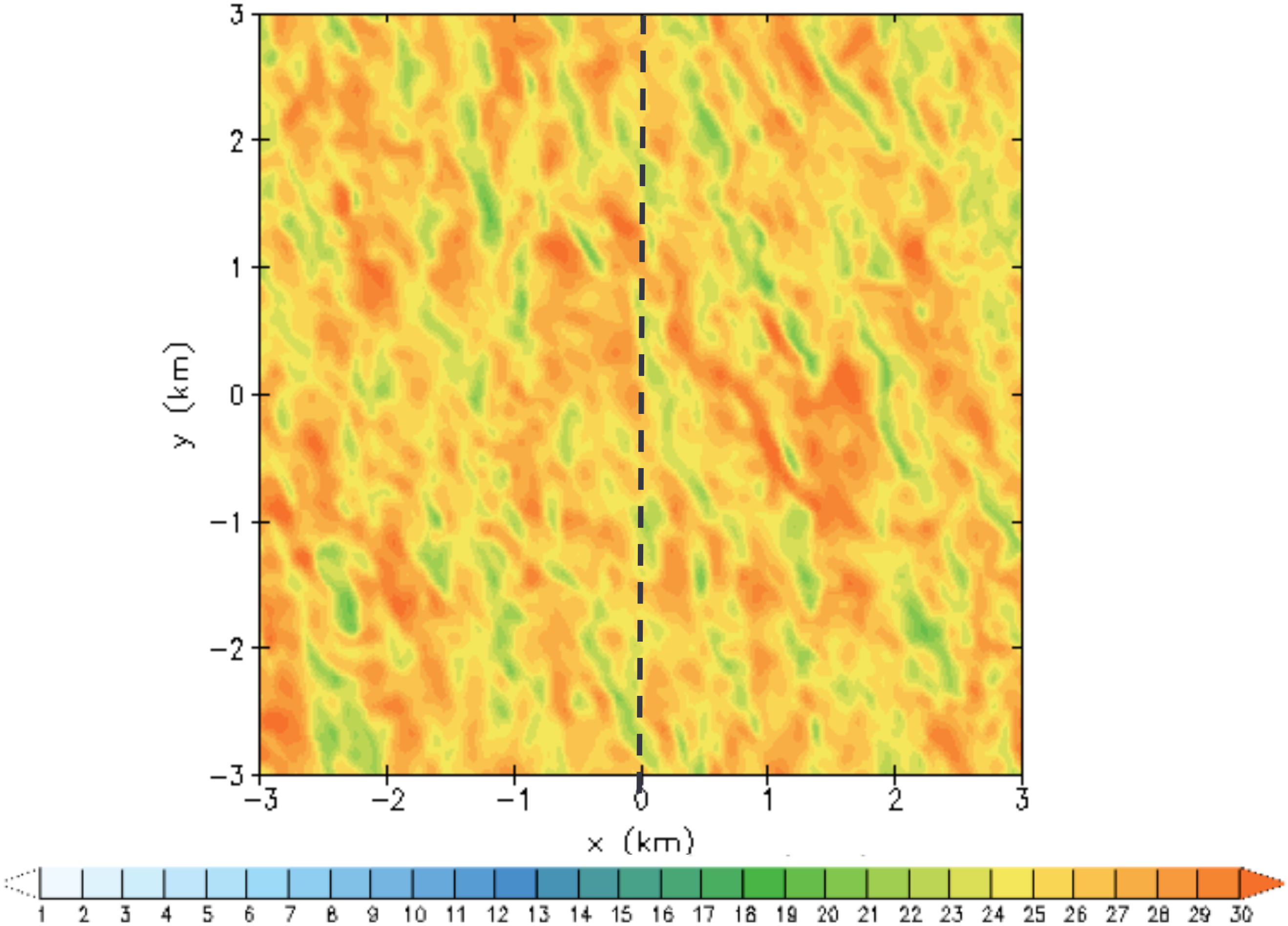
Horizontal windspeed (nondimensional) at 100 m ASL



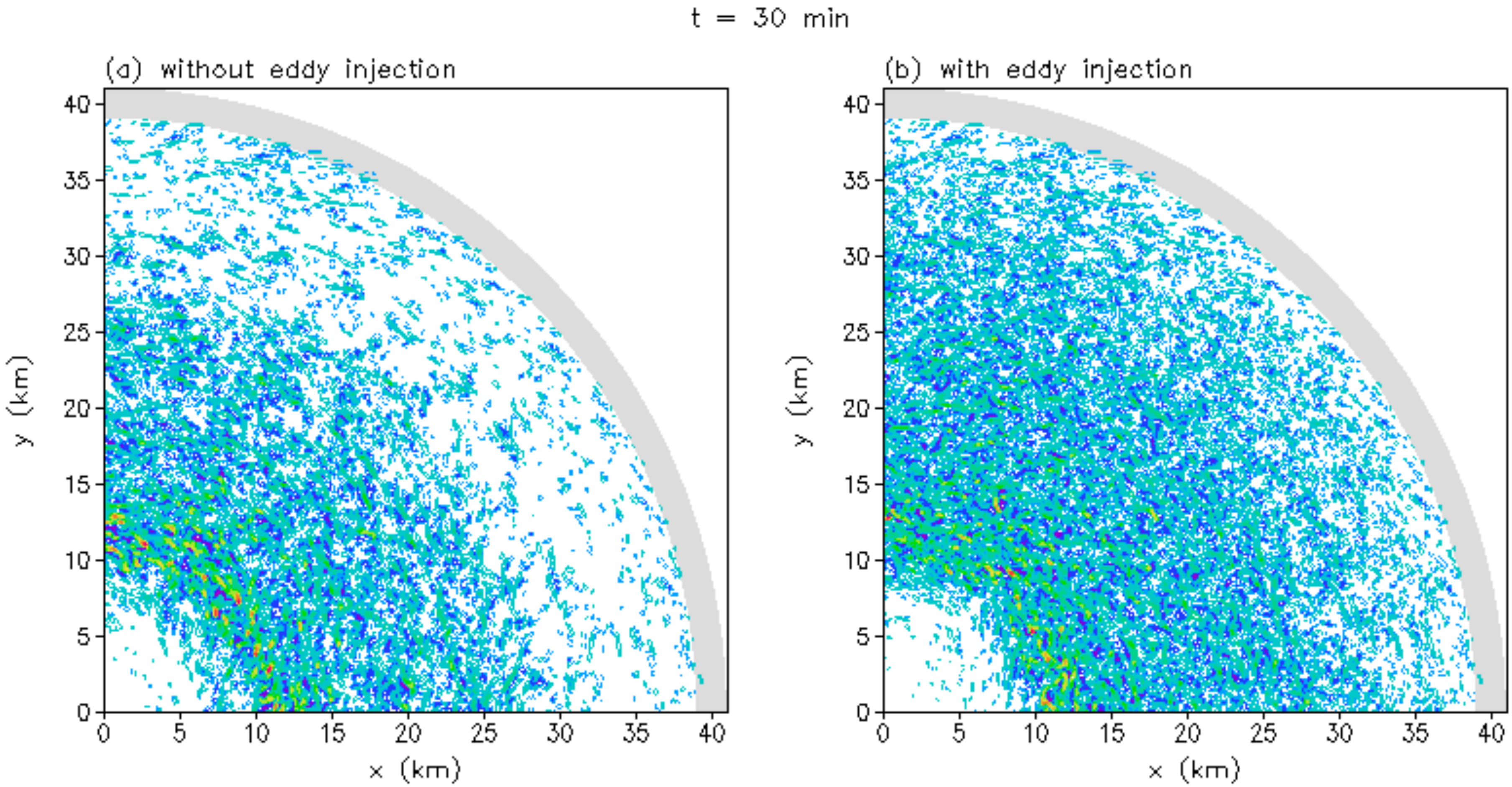
“Precursor Simulation” 2

- Run a “traditional” doubly-periodic LES, at same resolution
- Output u’, v’, w’ every-other timestep (lowest 1 km ASL)
- Then, apply these perturbations within the “transition zone” in the “complex” simulation

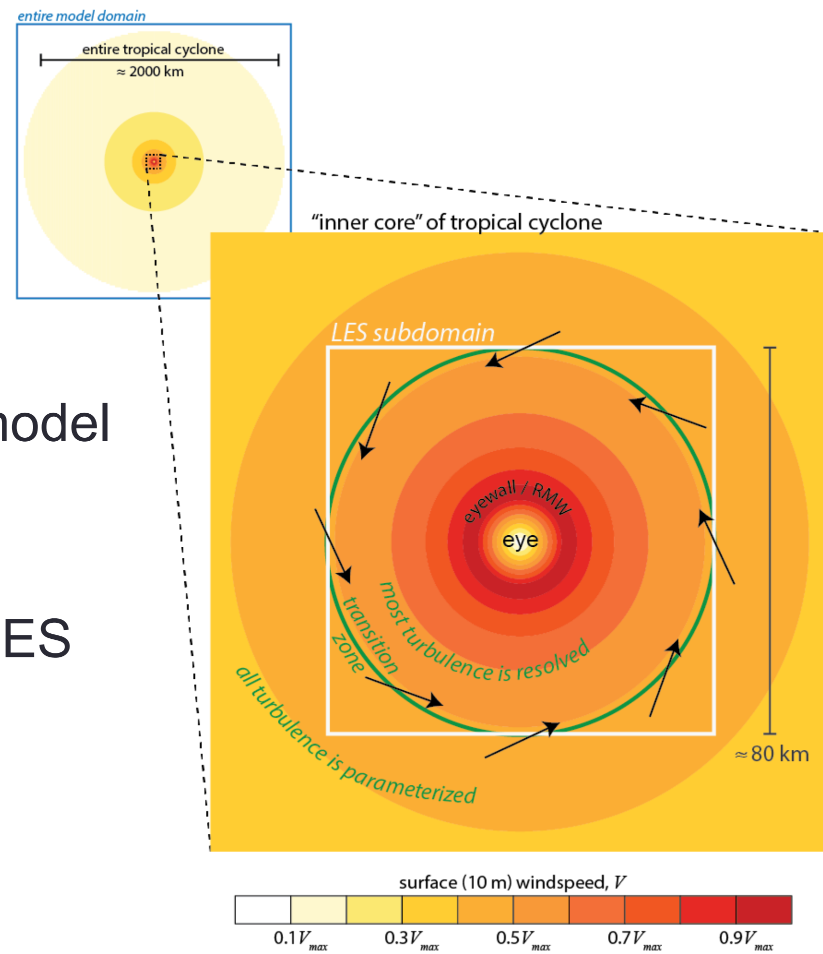
Horizontal windspeed (nondimensional) at 100 m ASL



w at z =100 m   (c.i. = 1 m s^{-1})



Methodology

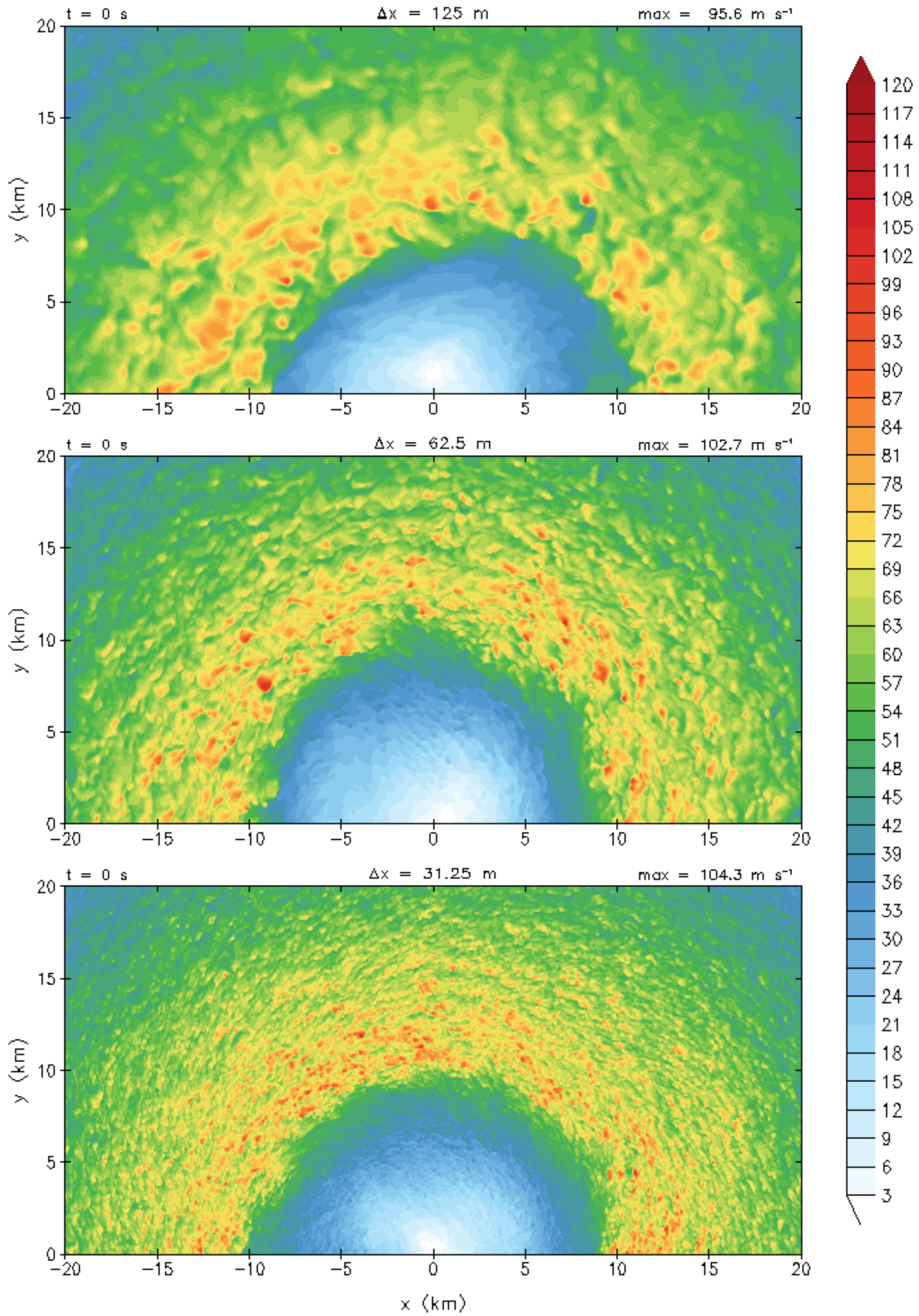


- Precursor Simulation 1: axisymmetric model
  - For initial conditions
- Precursor Simulation 2: small-domain LES
  - Generates perturbations for transition-zone
- Hurricane LES
  - LES within Mesoscale Model
- Highest resolution: $\Delta x = \Delta y = 32$ m, $\Delta z = 16$ m

(2,944 × 2,944 × 264 grid points) (0.2 s time step)

≈ 750,000 CPU hours on *Yellowstone* for a 4-hour integration
(7.5 days using 4,096 processors)

Windspeed at 10 m ASL
(9-minute animation; every 2 s)

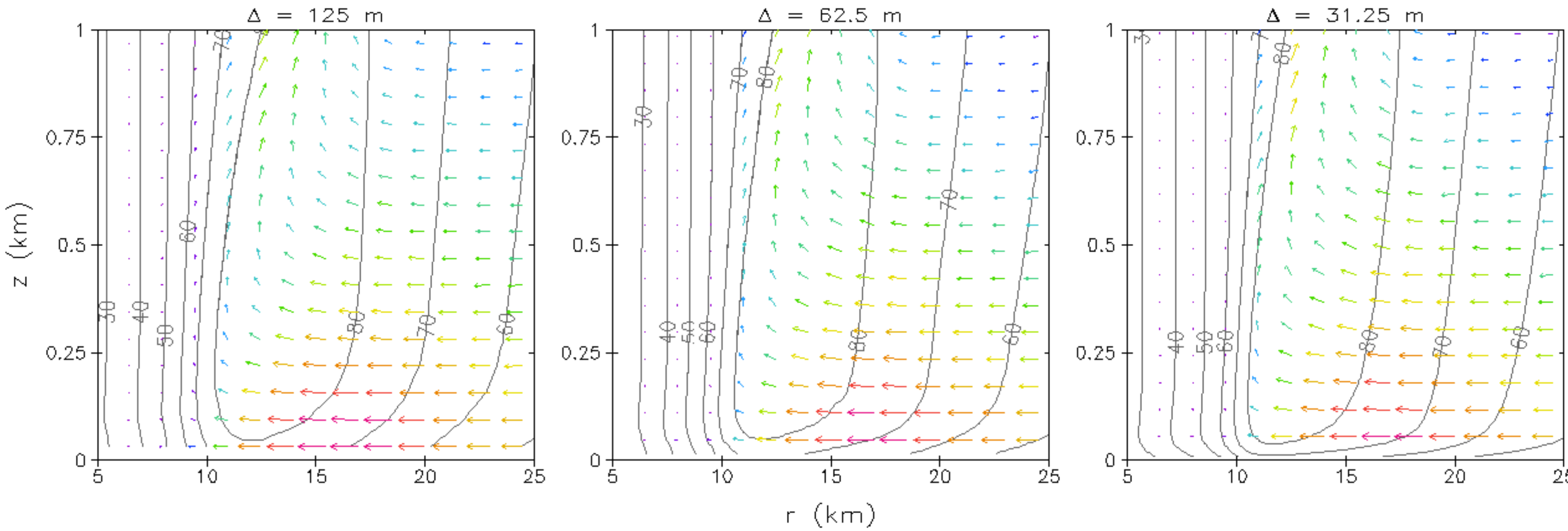


Δx = 125 m

Δx = 62.5 m

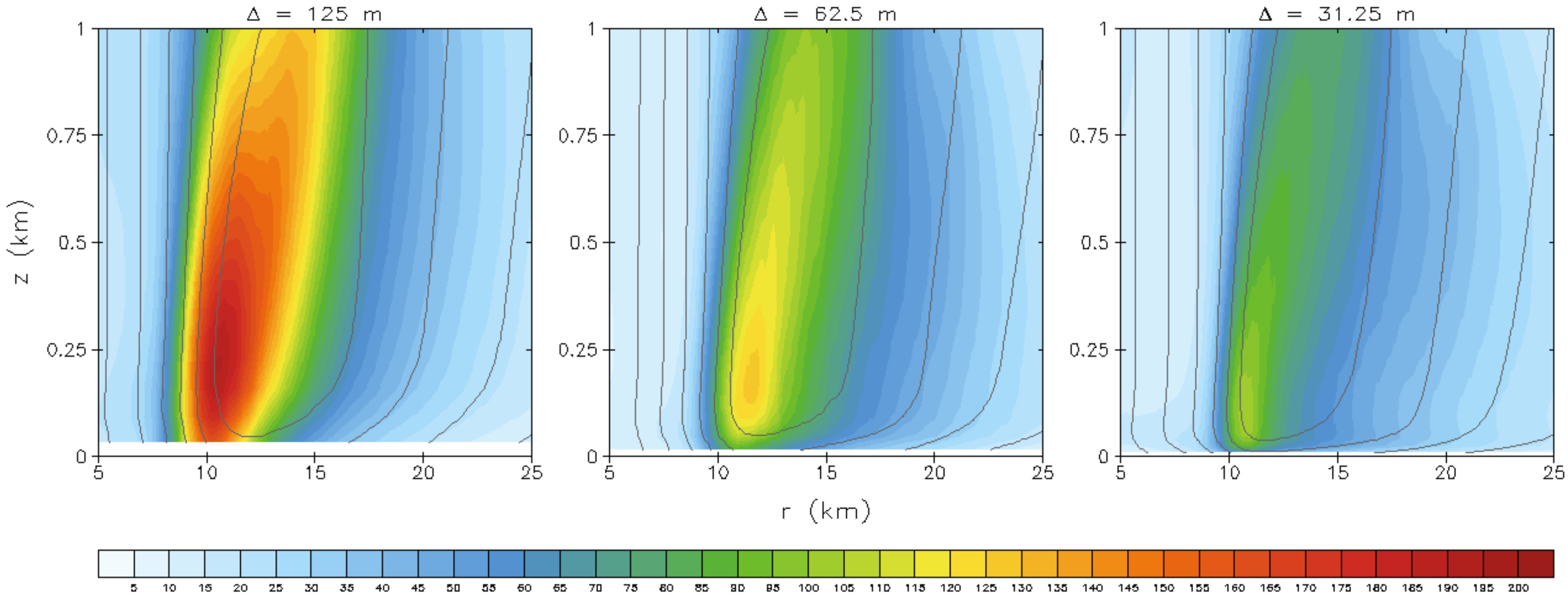
Δx = 31.25 m

Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})



Vectors: <u> and <w> (azimuthally averaged radial-vertical flow)

Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})



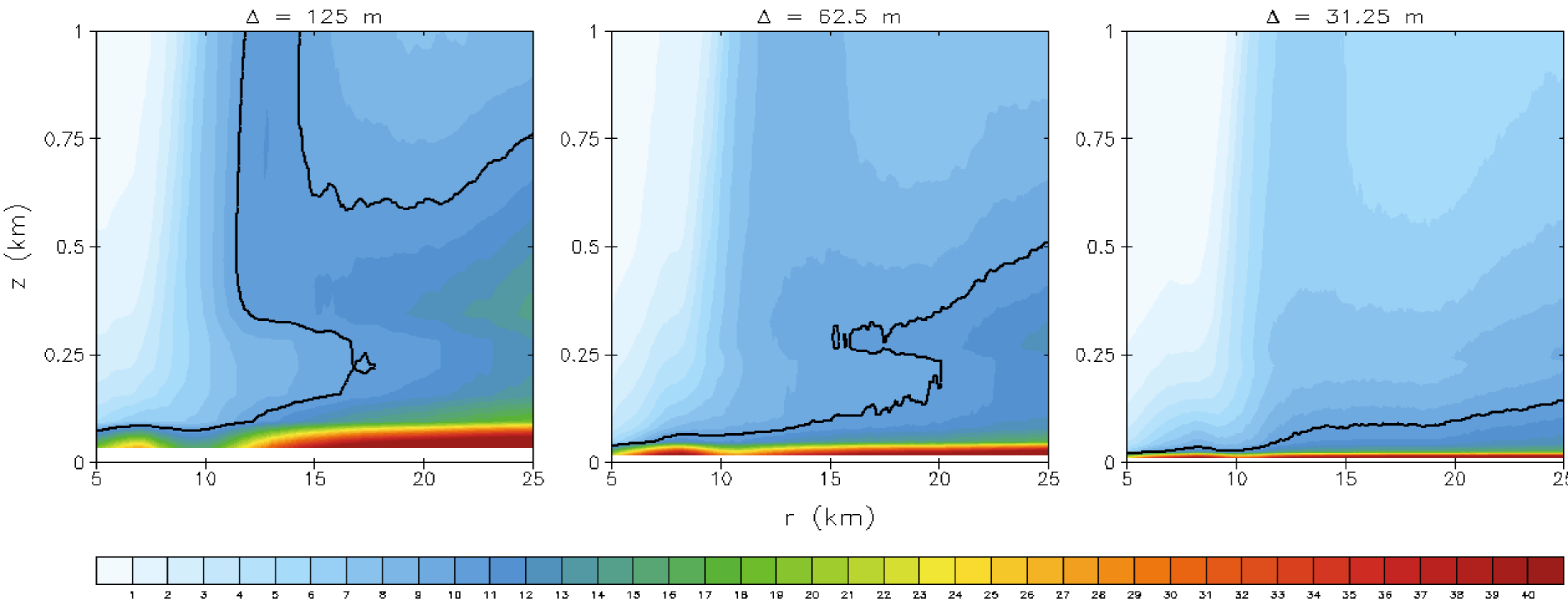
Color shading: turbulence kinetic energy, TKE (resolved + subgrid)

resolved TKE:

$$e_r = \frac{1}{2}(< u'u' > + < v'v' > + < w'w' >)$$

subgrid TKE: (Deardorff subgrid TKE model)

total TKE = resolved TKE + subgrid TKE



Color shading: ratio of subgrid TKE to total TKE

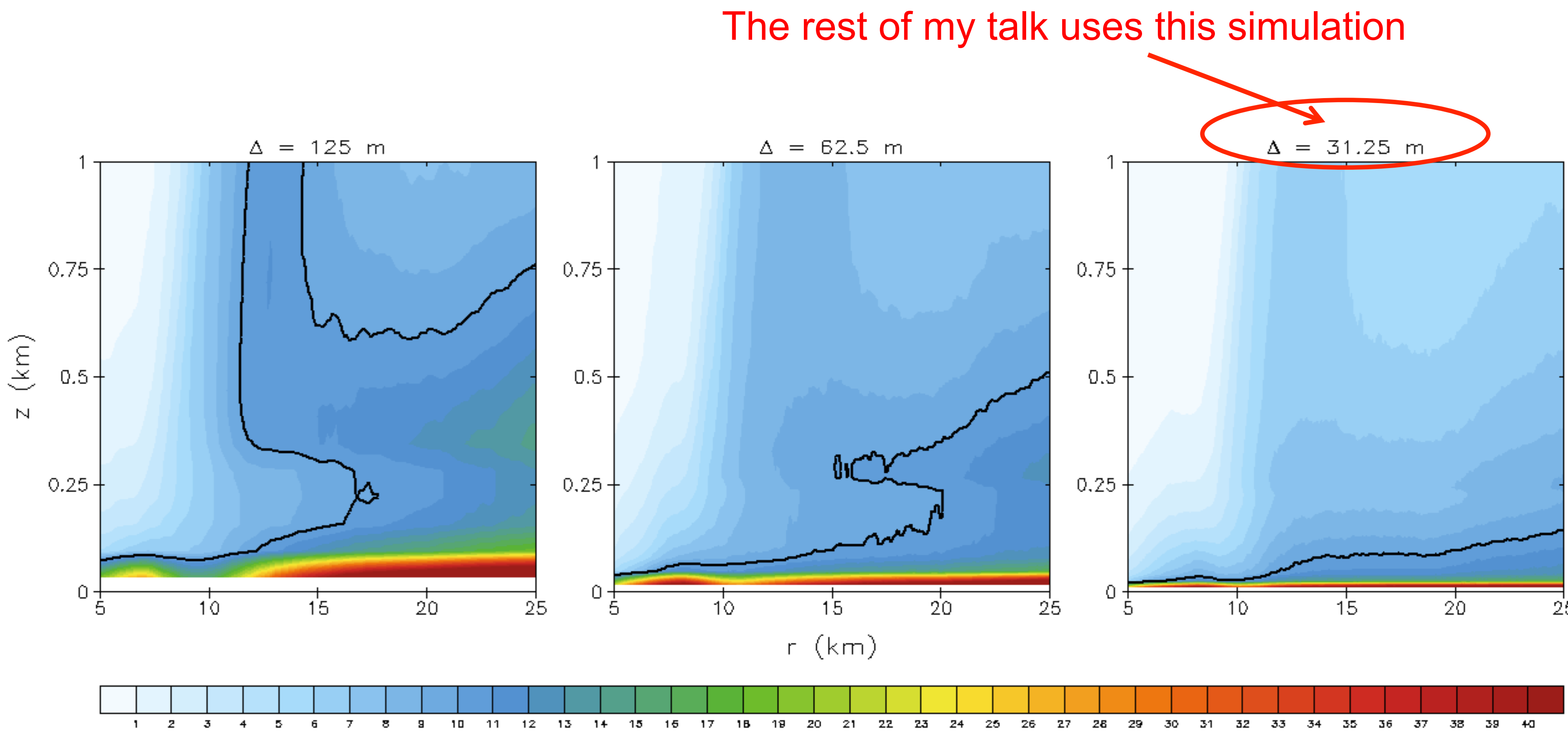
Contour: 10%

resolved TKE:

$$e_r = \frac{1}{2}(< u'u' > + < v'v' > + < w'w' >)$$

subgrid TKE: (Deardorff subgrid TKE model)

total TKE = resolved TKE + subgrid TKE



Color shading: ratio of subgrid TKE to total TKE

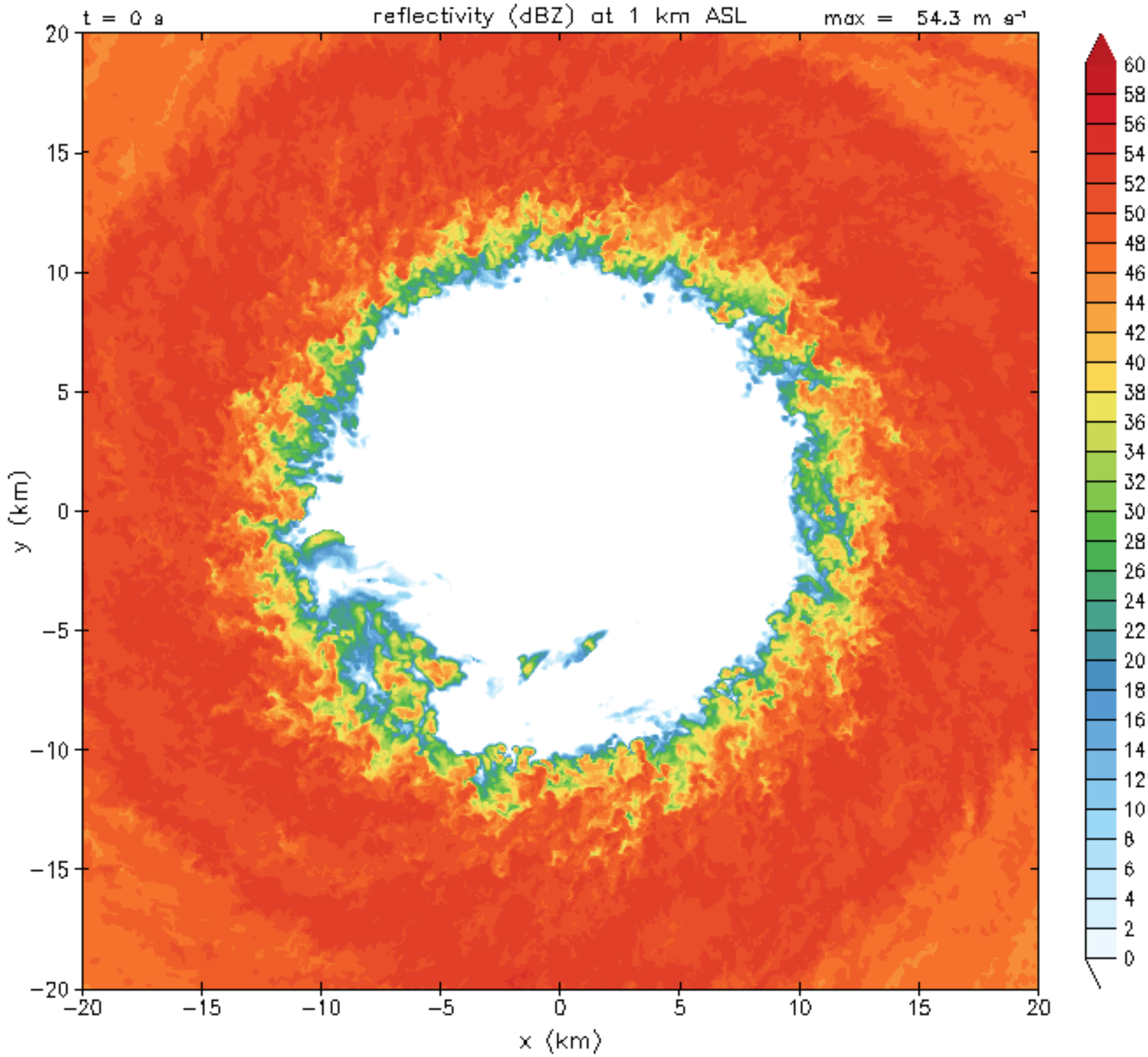
Contour: 10%

resolved TKE:

$$e_r = \frac{1}{2}(< u'u' > + < v'v' > + < w'w' >)$$

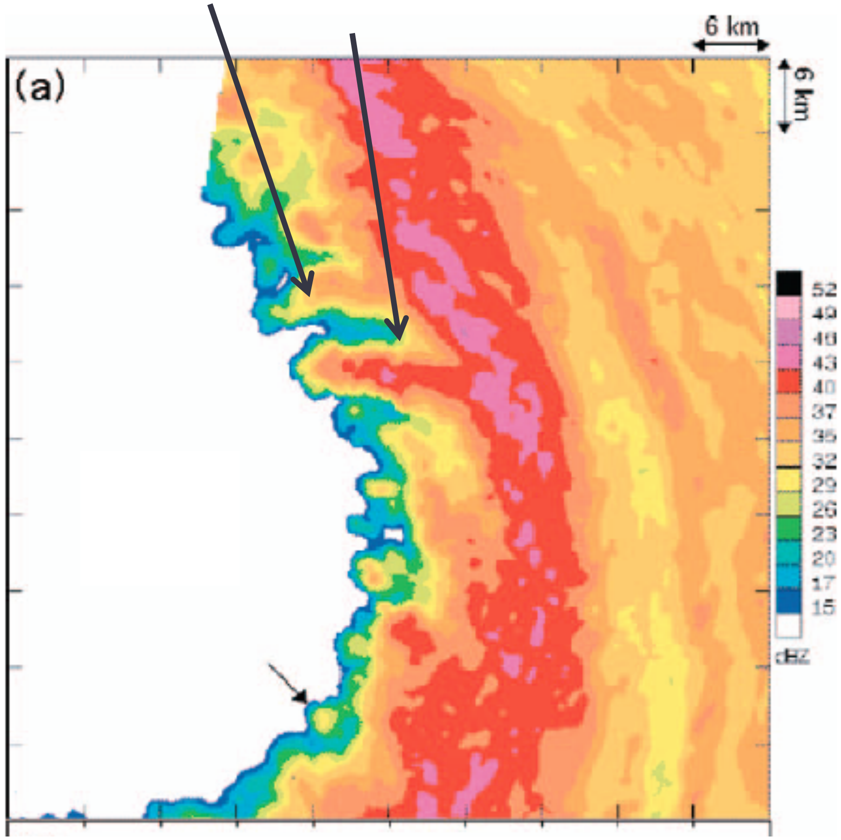
subgrid TKE: (Deardorff subgrid TKE model)

total TKE = resolved TKE + subgrid TKE



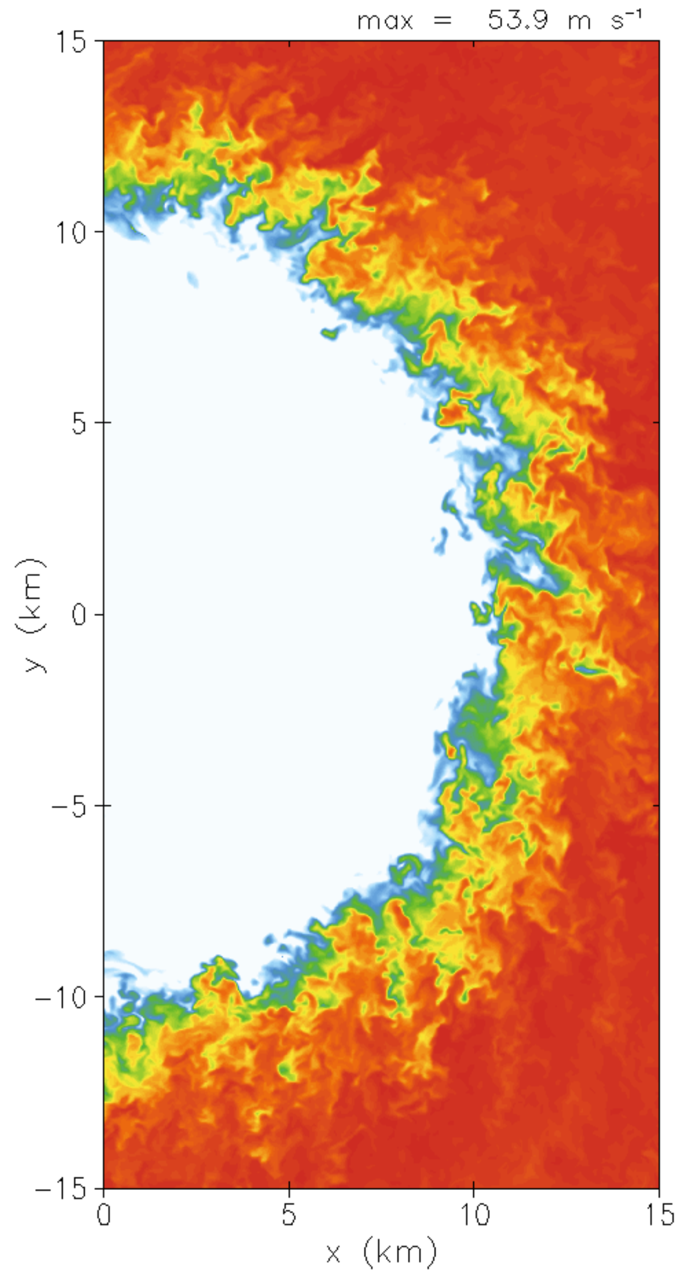
t = 0 s
reflectivity (dBZ) at 1 km ASL
max = 54.3 m s⁻¹
y (km)
x (km)
20
15
10
5
0
−5
−10
−15
−20
−20
−15
−10
−5
0
5
10
15
20
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

Reflectivity (dBZ)

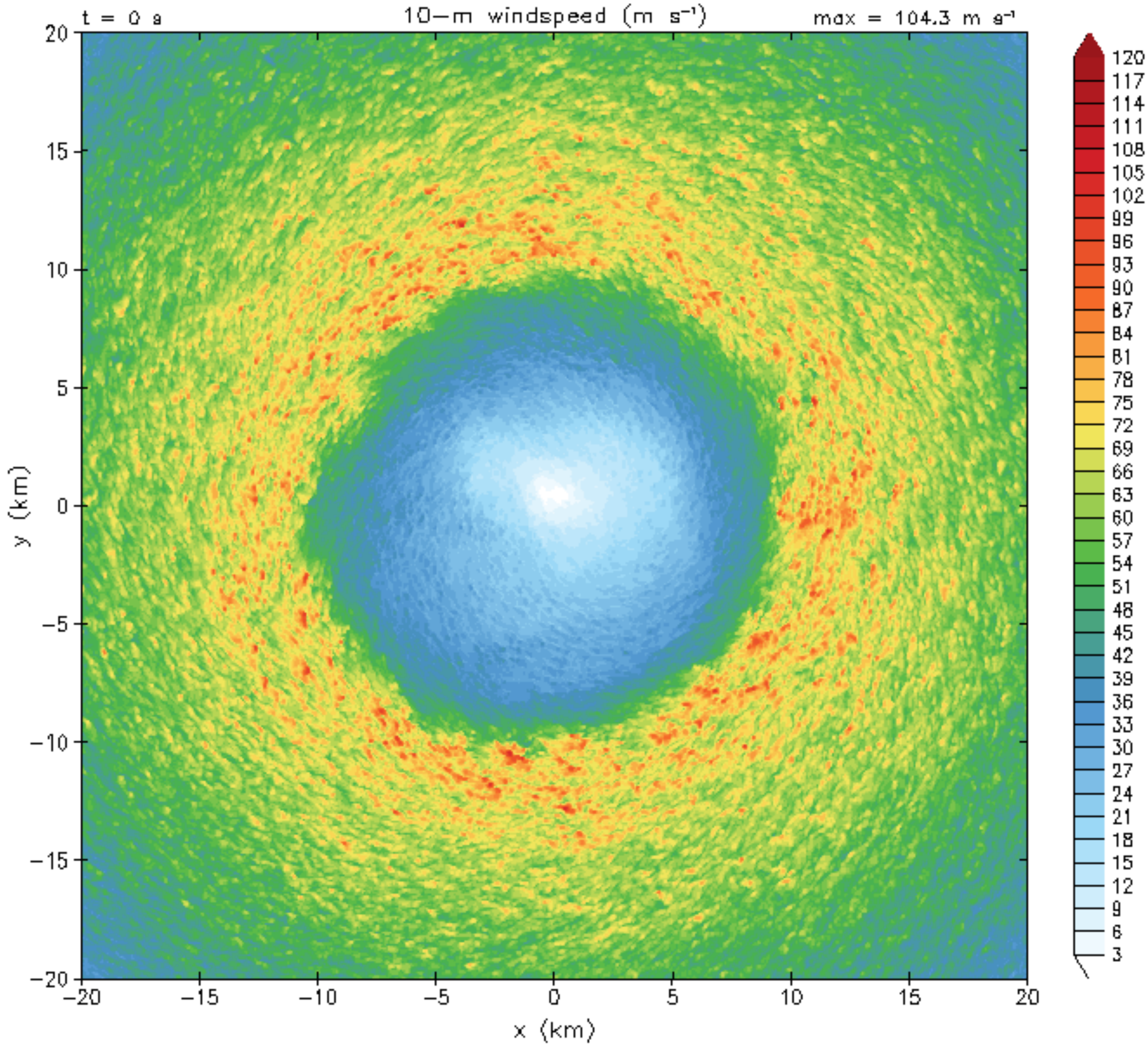


Aberson et al. (2006, BAMS)

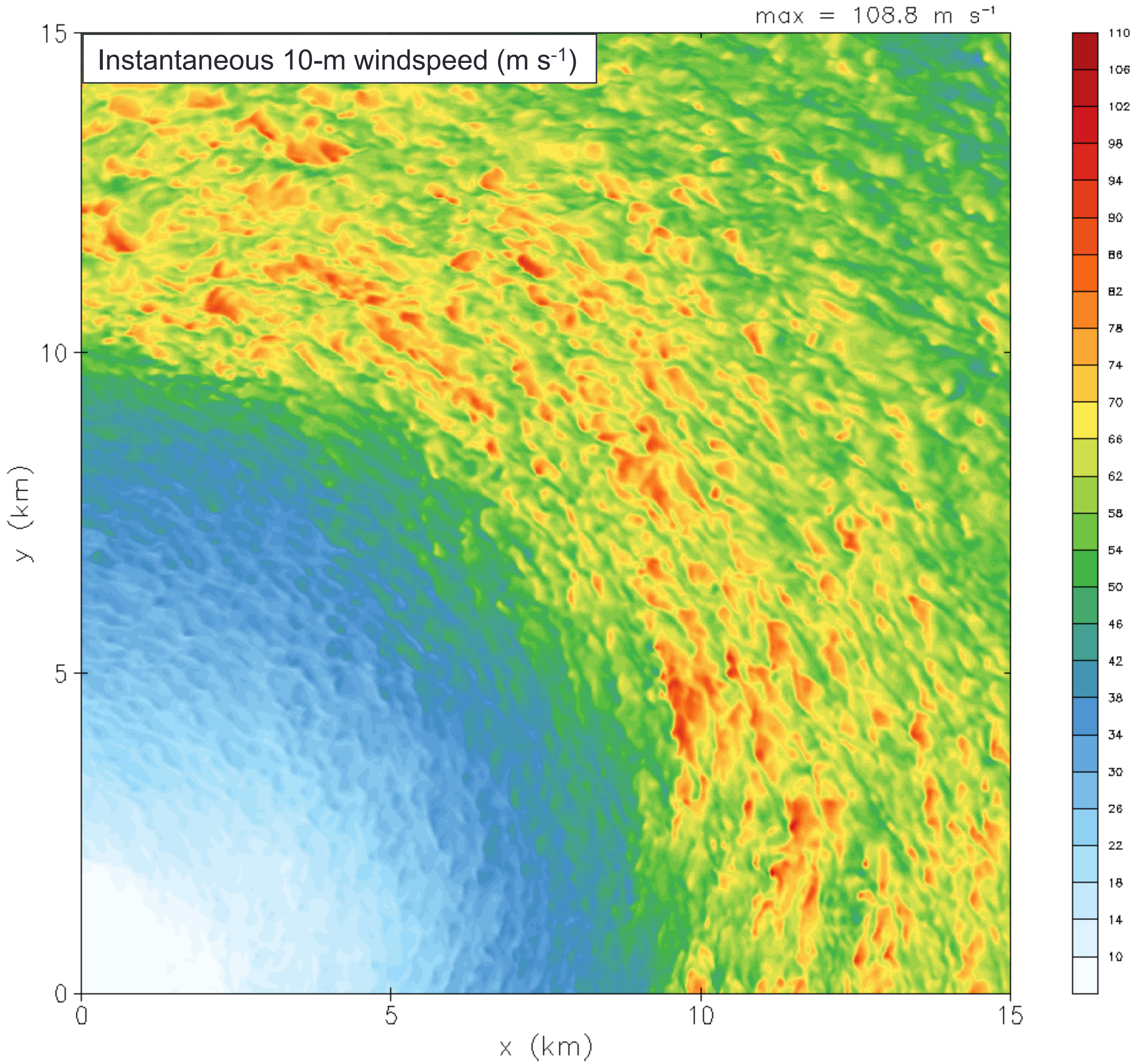
Reflectivity from NOAA P3
lower-fuselage radar (C band, 5 cm),
≈2 km ASL



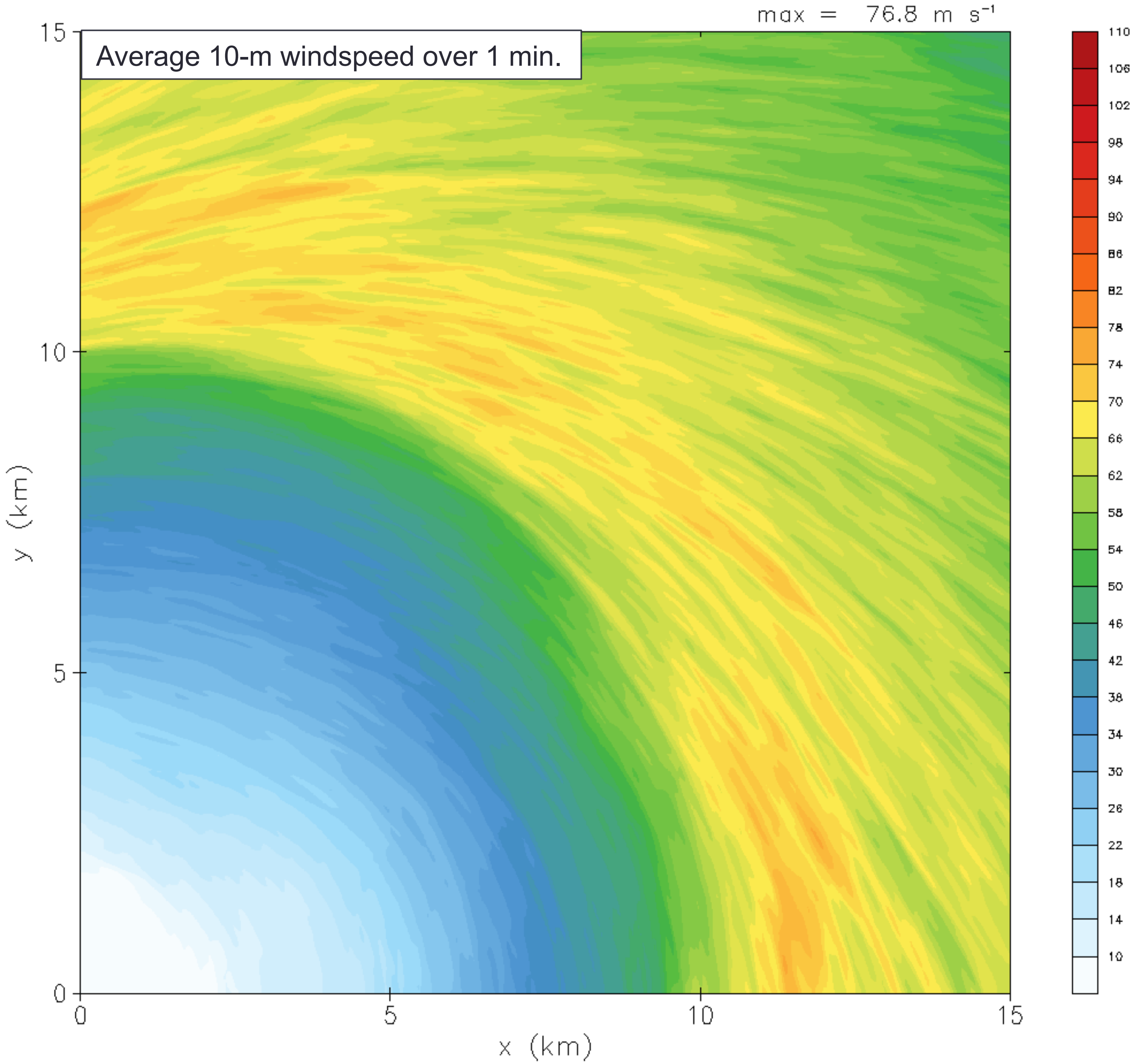
LES, z = 1 km
(assuming 10-cm radar)



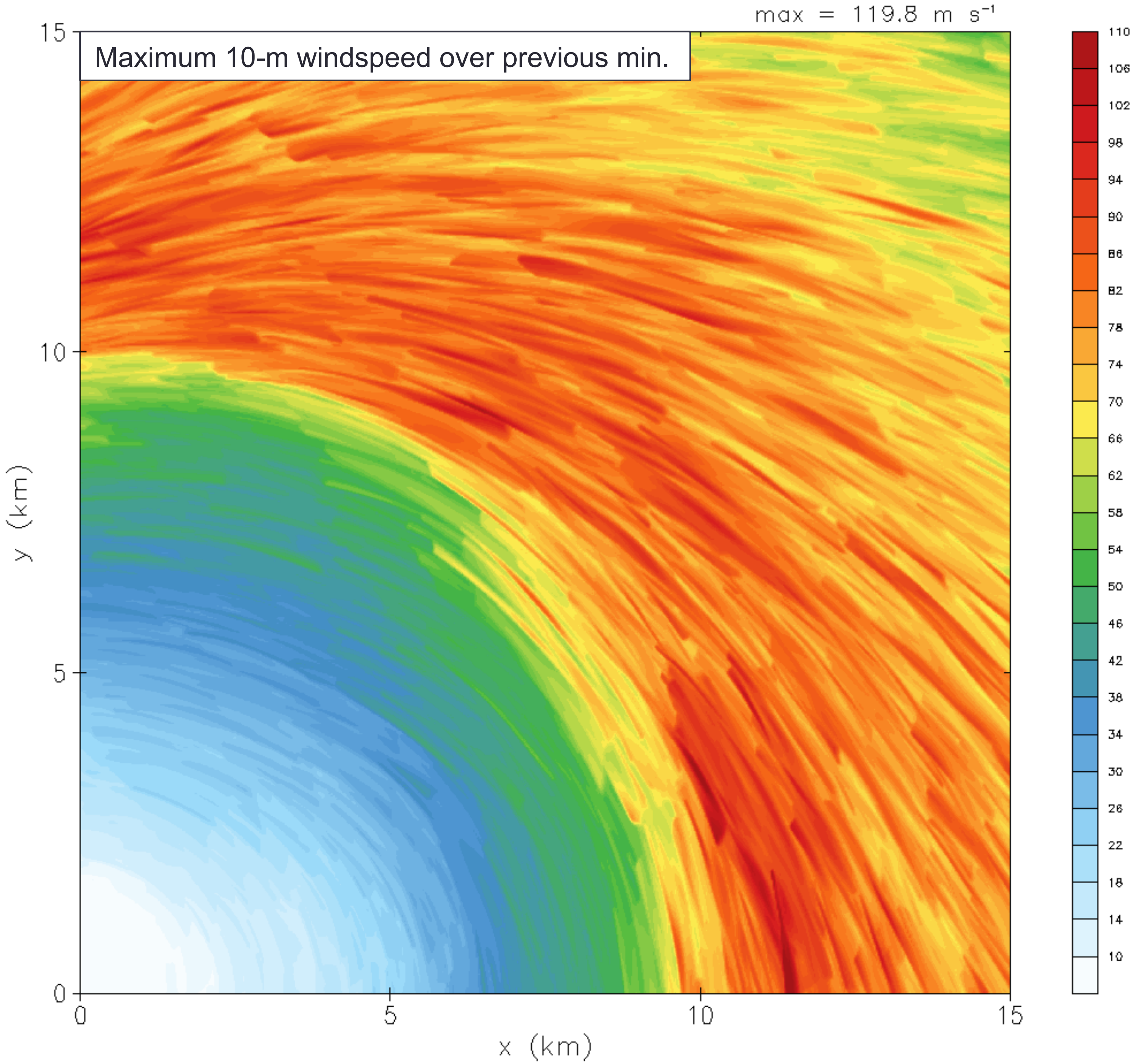
t = 0 s
10–m windspeed (m s⁻¹)
max = 104.3 m s⁻¹
y (km)
x (km)
20
15
10
5
0
−5
−10
−15
−20
120
117
114
111
108
105
102
99
96
93
90
87
84
81
78
75
72
69
66
63
60
57
54
51
48
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3



max = 108.8 m s⁻¹
Instantaneous 10-m windspeed (m s⁻¹)
y (km)
x (km)
0
5
10
15
110
106
102
98
94
90
86
82
78
74
70
66
62
58
54
50
46
42
38
34
30
26
22
18
14
10

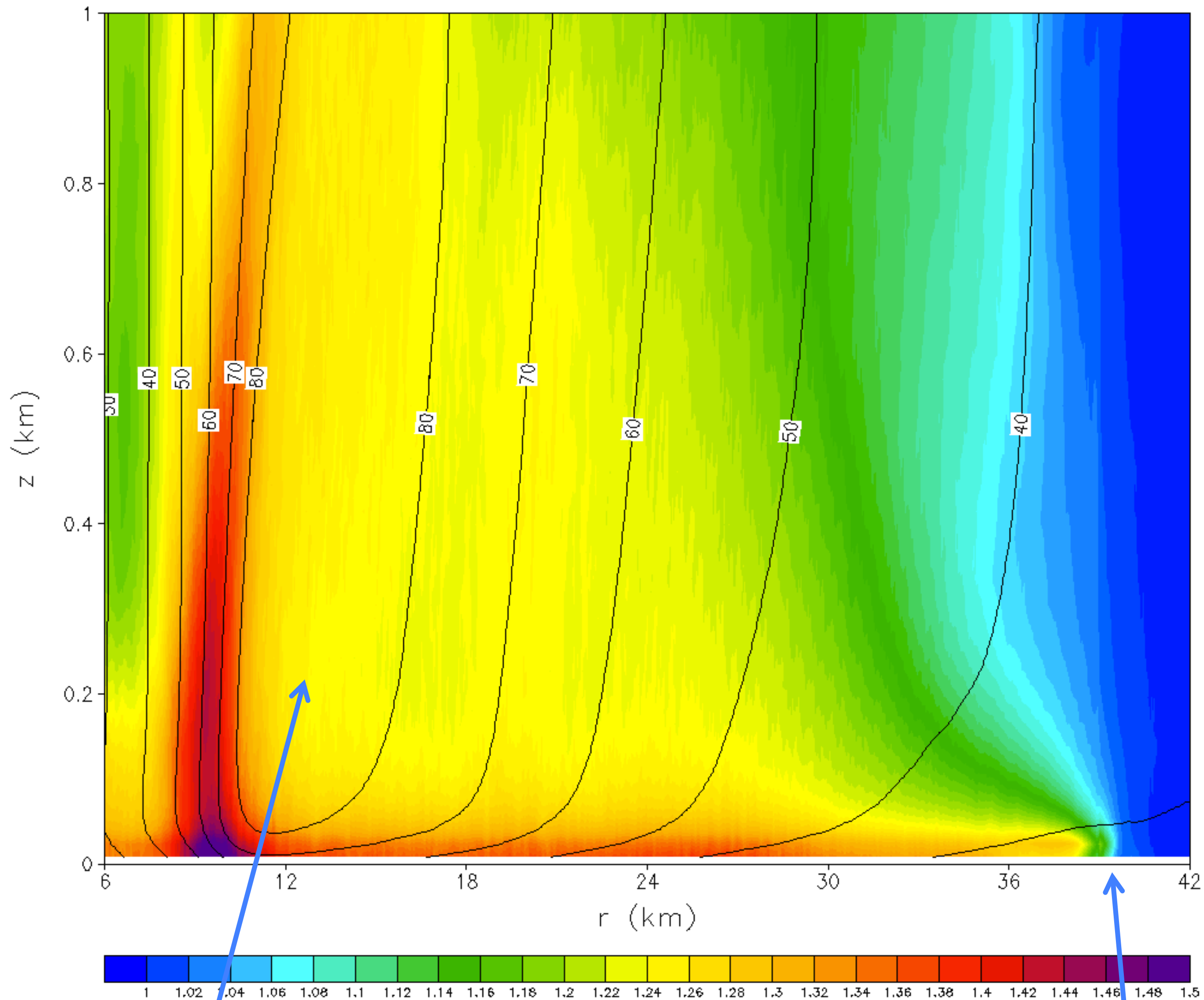


Average 10-m windspeed over 1 min.
max = 76.8 m s^{-1}
y (km)
x (km)
0
5
10
15
110
106
102
98
94
90
86
82
78
74
70
66
62
58
54
50
46
42
38
34
30
26
22
18
14
10



Maximum 10-m windspeed over previous min.
max = 119.8 m s⁻¹
y (km)
x (km)
0
5
10
15
110
106
102
98
94
90
86
82
78
74
70
66
62
58
54
50
46
42
38
34
30
26
22
18
14
10

Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})

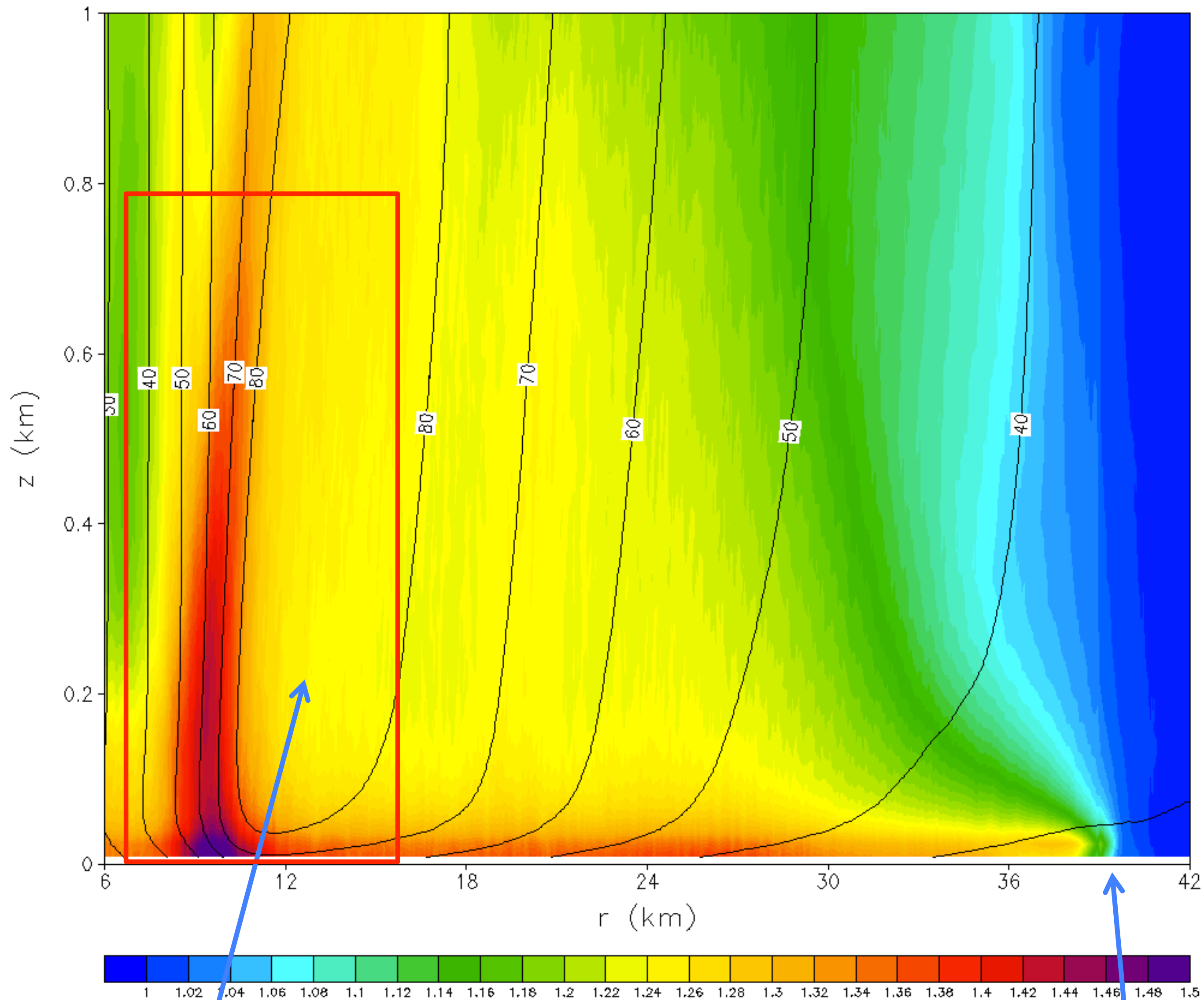


color shading: Gust factor, U_{max} / <U>

Location of Max. windspeed

Boundary of fine-mesh domain

Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})

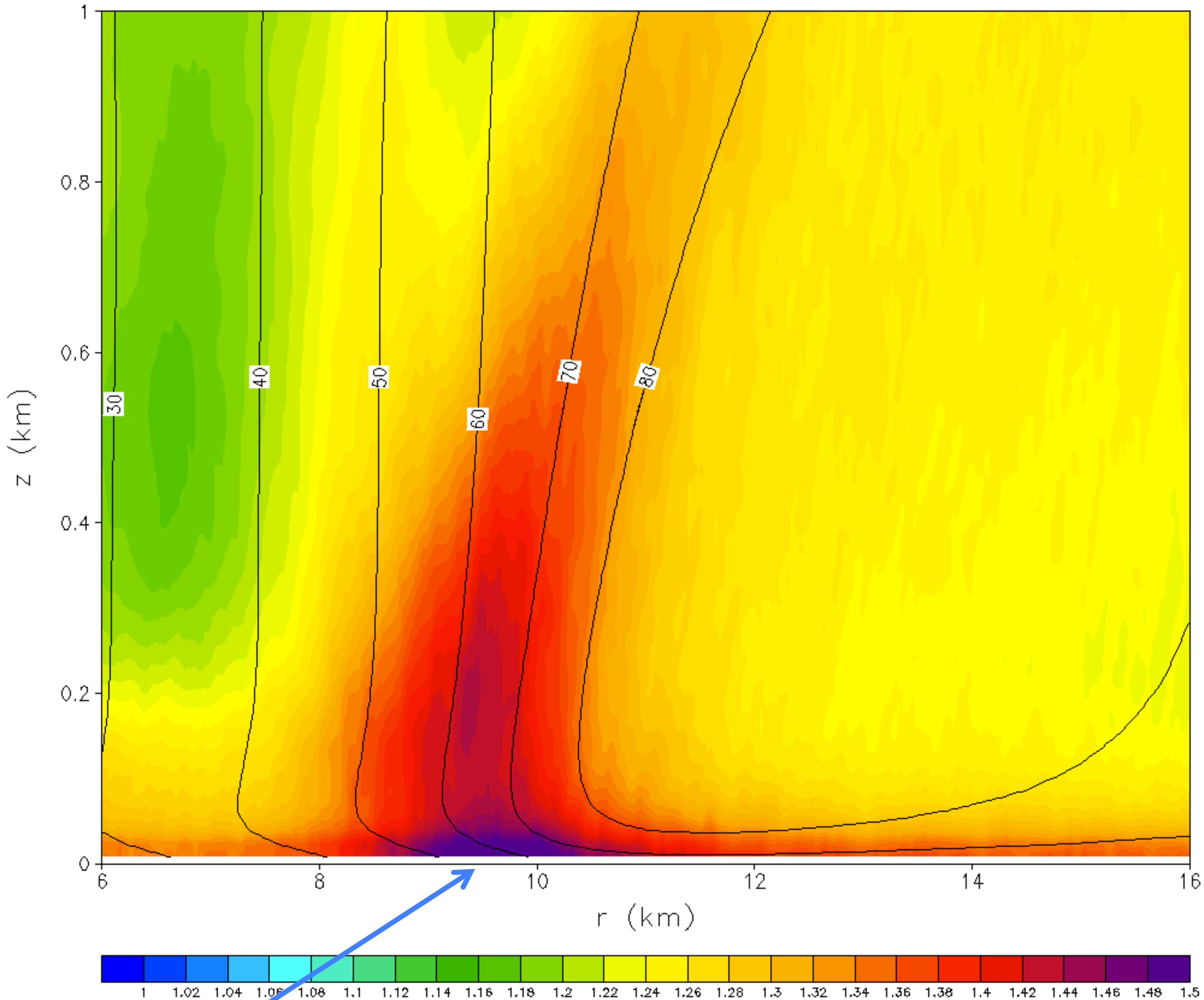


color shading: Gust factor, U_{max} / <U>

Location of Max. windspeed

Boundary of fine-mesh domain

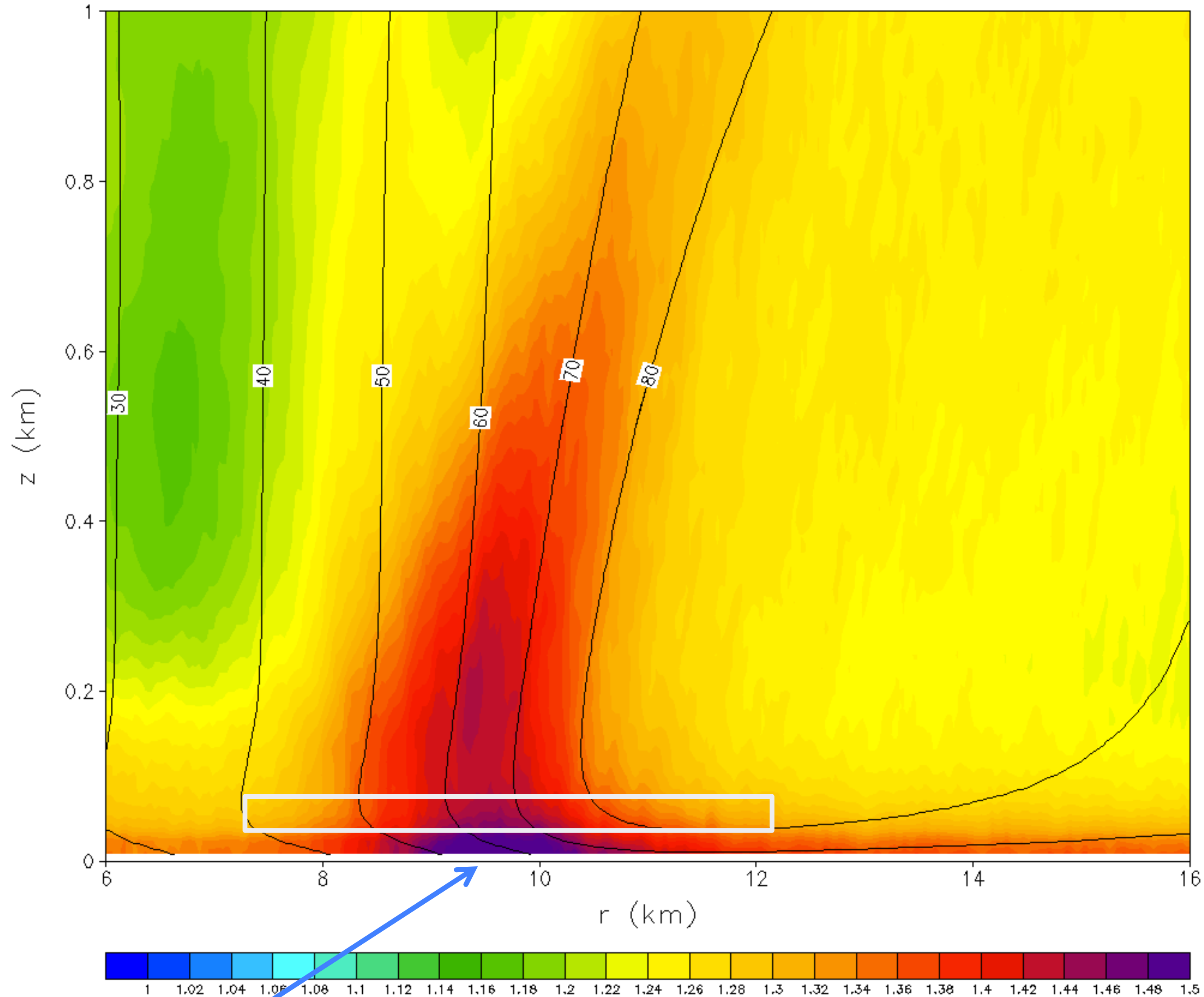
Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})



1.53

color shading: Gust factor, U_{max} / <U>

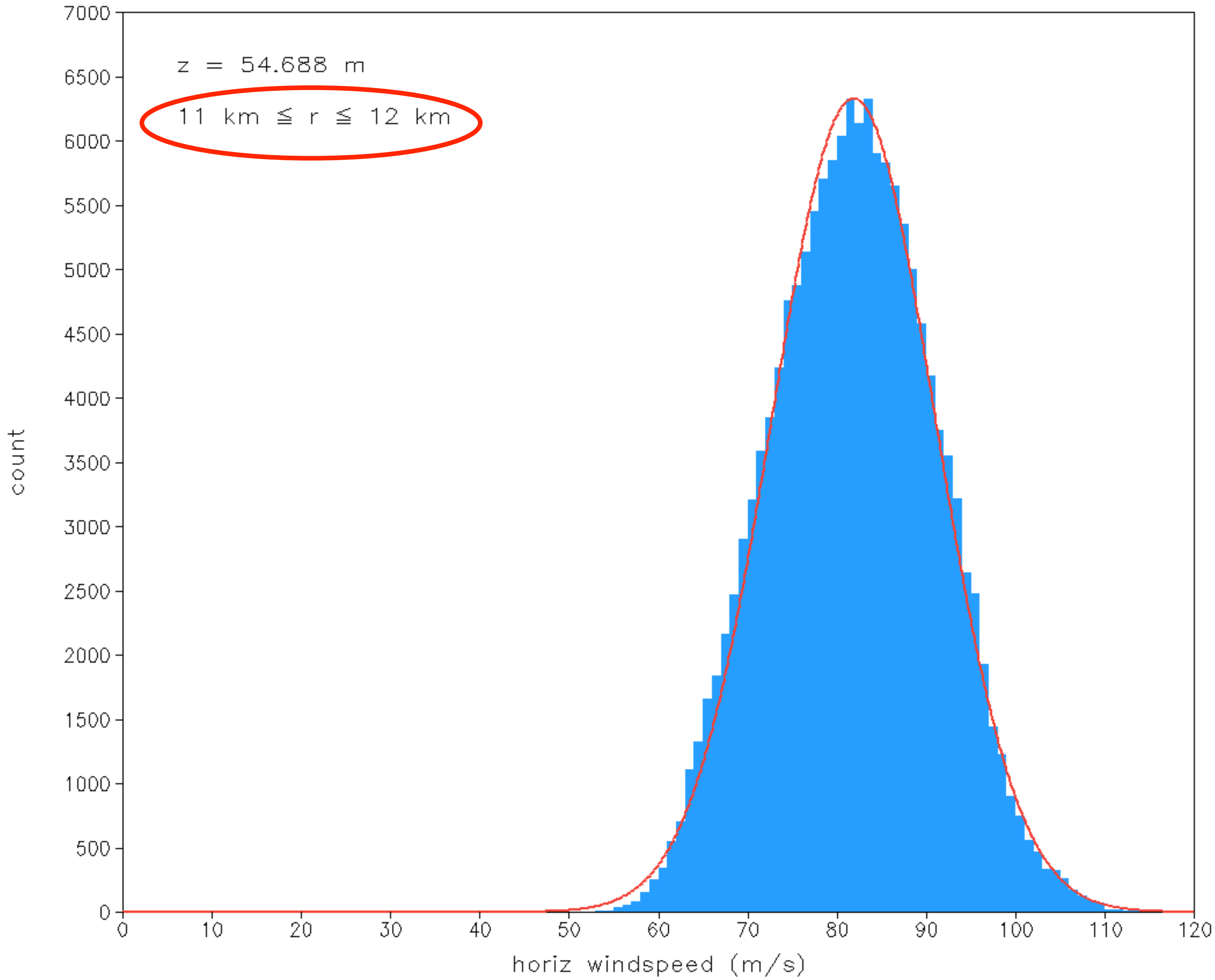
Contours: azimuthally averaged horizontal windspeed, <U> (c.i. = 10 m s^{-1})



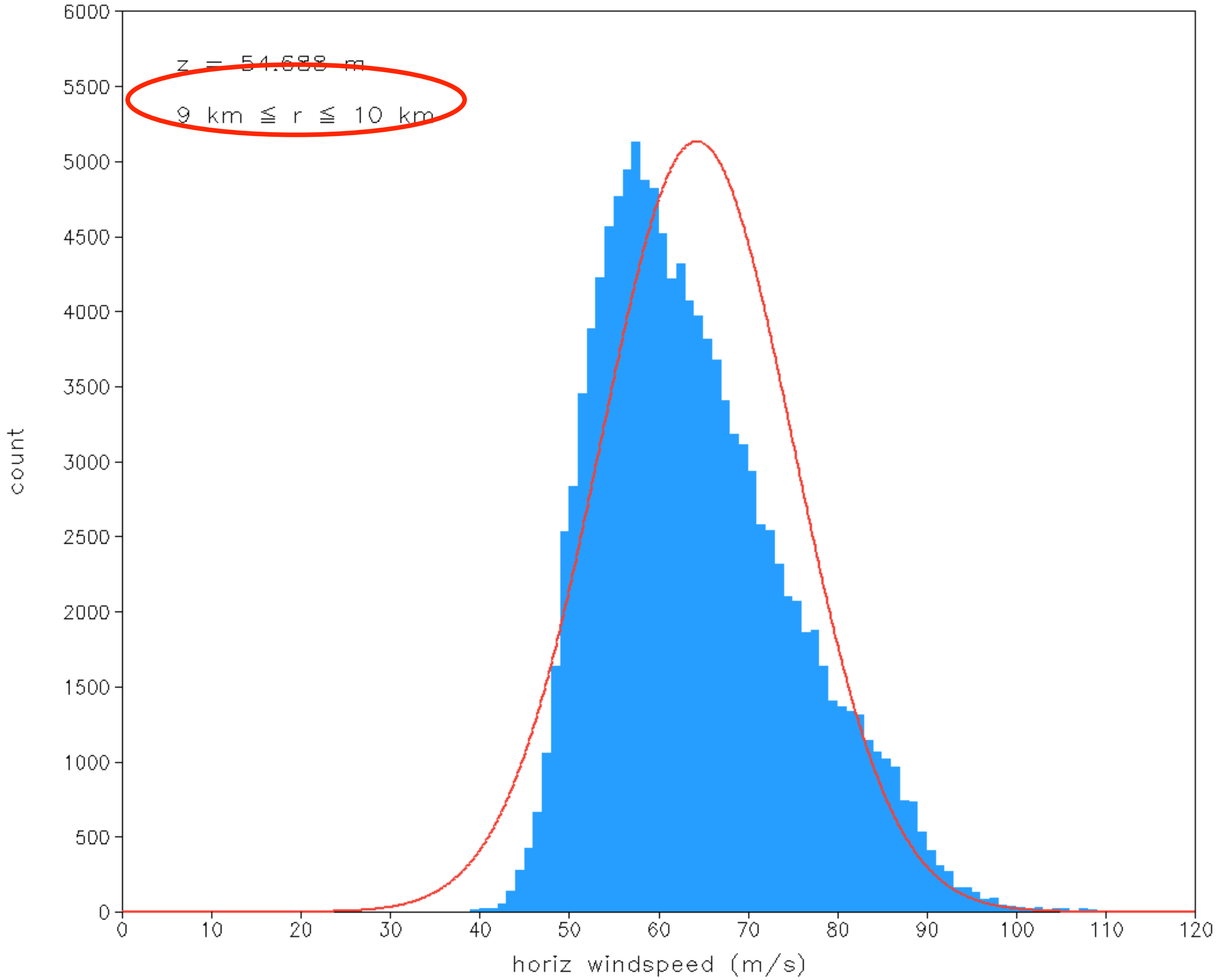
1.53

color shading: Gust factor, U_{max} / <U>

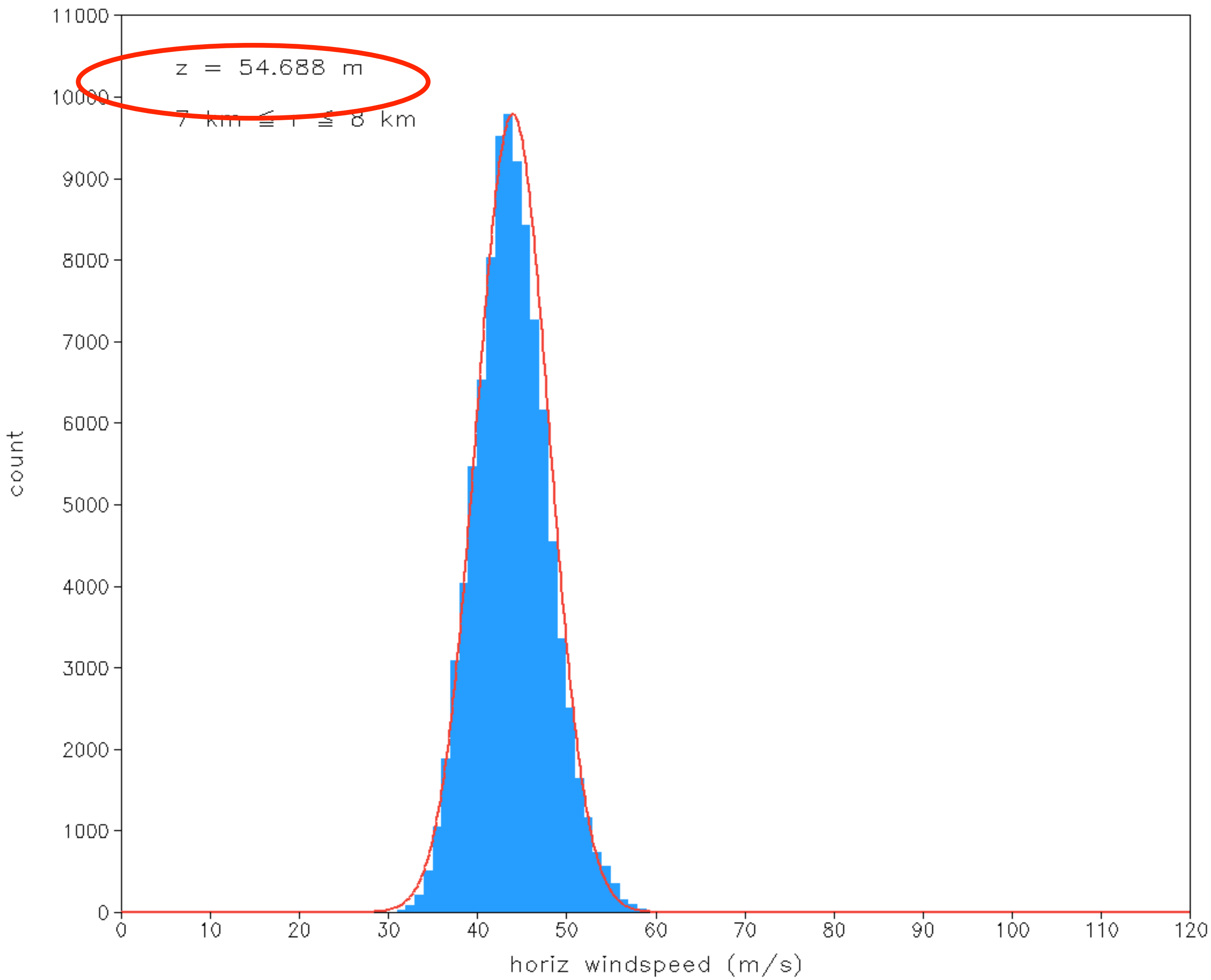
Histogram of Windspeed



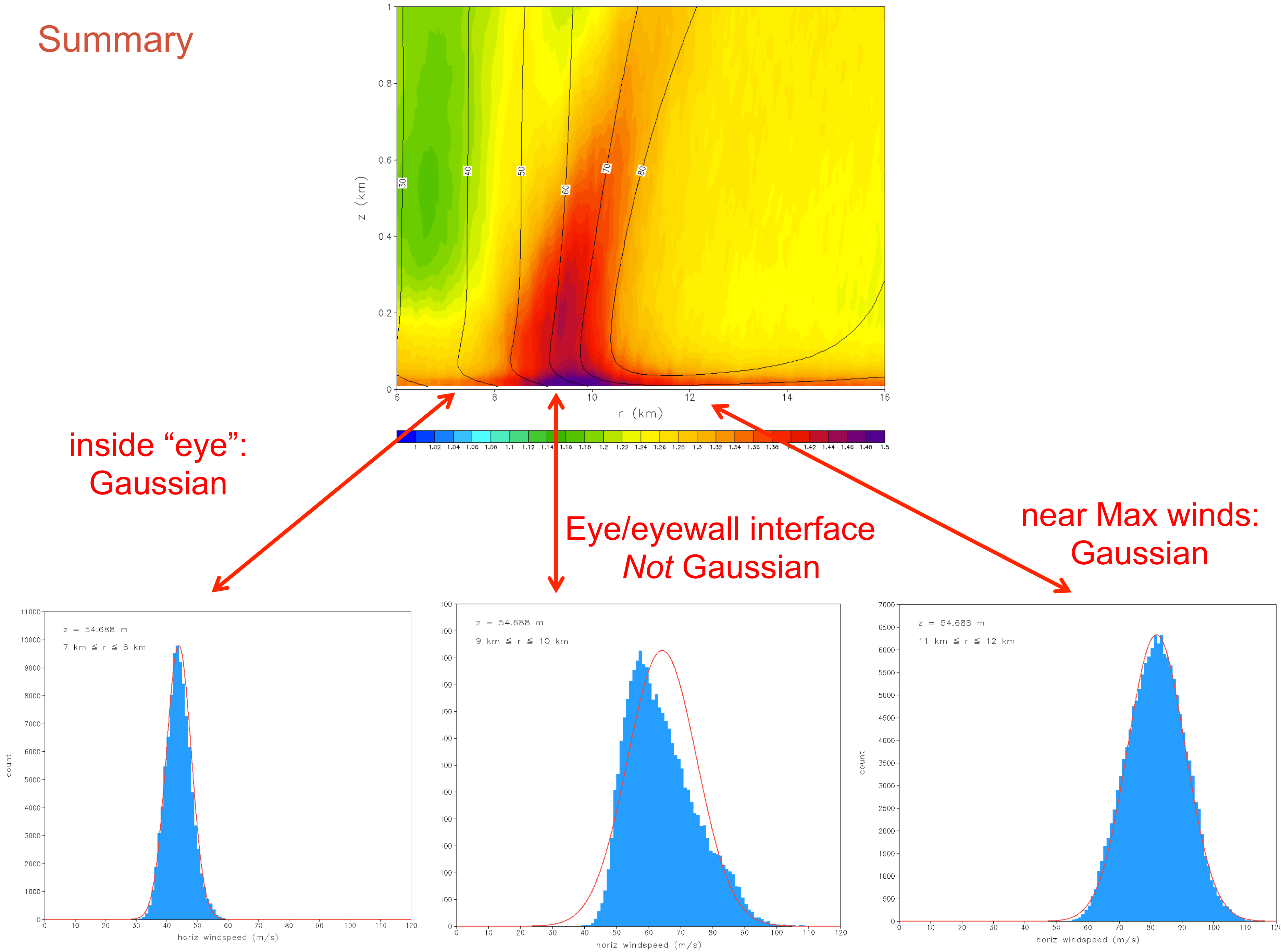
Histogram of Windspeed



Histogram of Windspeed



Summary



z (km)
r (km)
30
40
50
60
70
80
inside “eye”:
Gaussian
Eye/eyewall interface
Not Gaussian
near Max winds:
Gaussian
z = 54.688 m
7 km ≦ r ≦ 8 km
count
horiz windspeed (m/s)
z = 54.688 m
9 km ≦ r ≦ 10 km
horiz windspeed (m/s)
z = 54.688 m
11 km ≦ r ≦ 12 km
count
horiz windspeed (m/s)

Summary

- A framework for Large-Eddy Simulation (LES) with a mesoscale model
  - Key step: insert perturbations in "transition zone"
- Gusts exceed 100 m s^{-1}
  - Eye/eyewall interface: "mesovortices"
  - Not Gaussian
- Future Work:
  - Dynamics of extreme gusts
    - (presentation at AMS Hurricanes Conf.)
  - Statistical convergence
    - ($\Delta x \approx 5$ m?)