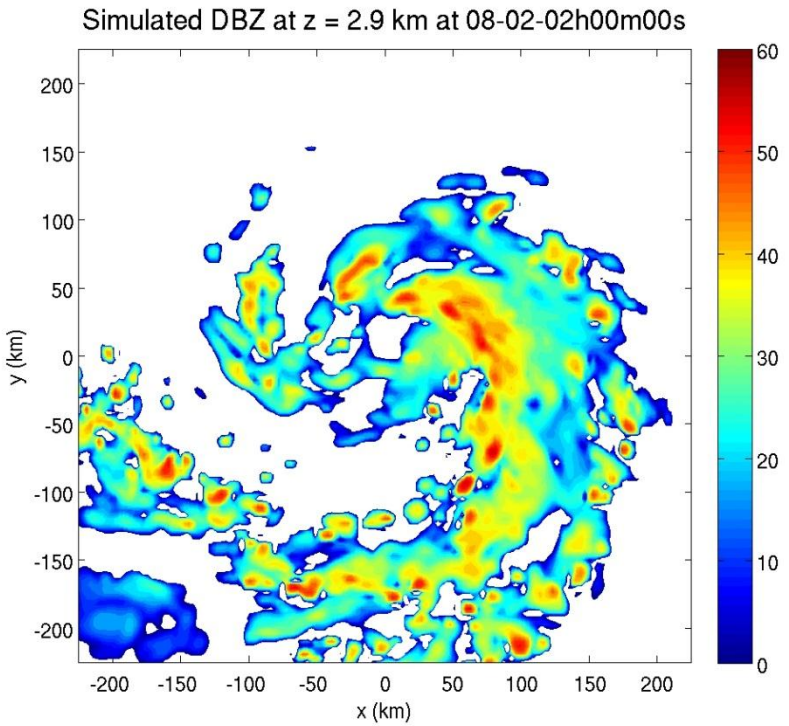
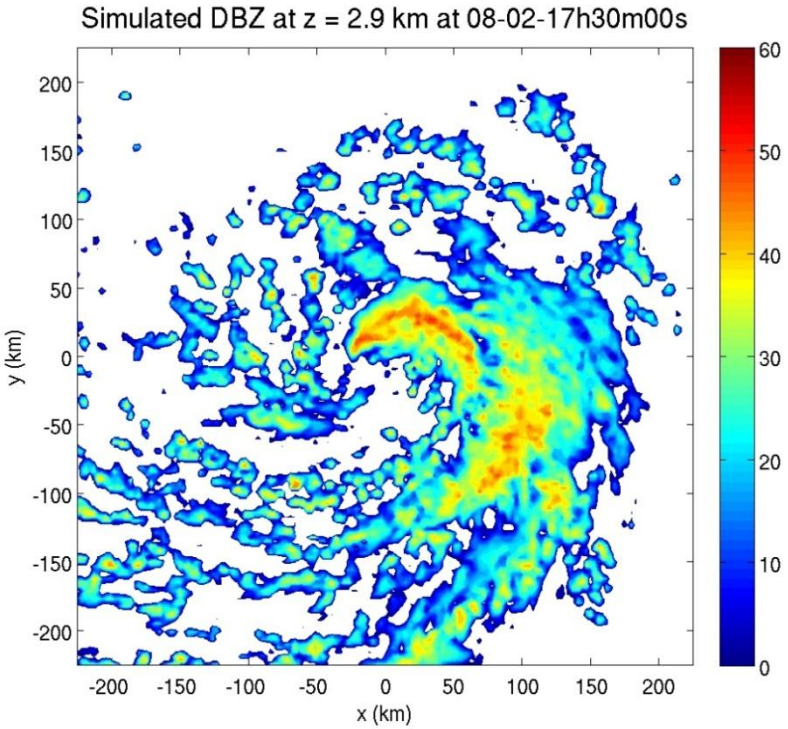
Comparing Hurricane Structure in Research Quality and Forecast Quality Simulations





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I. Research Quality: The ECMWF/WRF Hurricane Nature Run

- The goal of this project is to make a very high quality simulation of an Atlantic hurricane that can be used as a "nature run" for Observing System Simulation Experiments (OSSEs) and other research purposes.

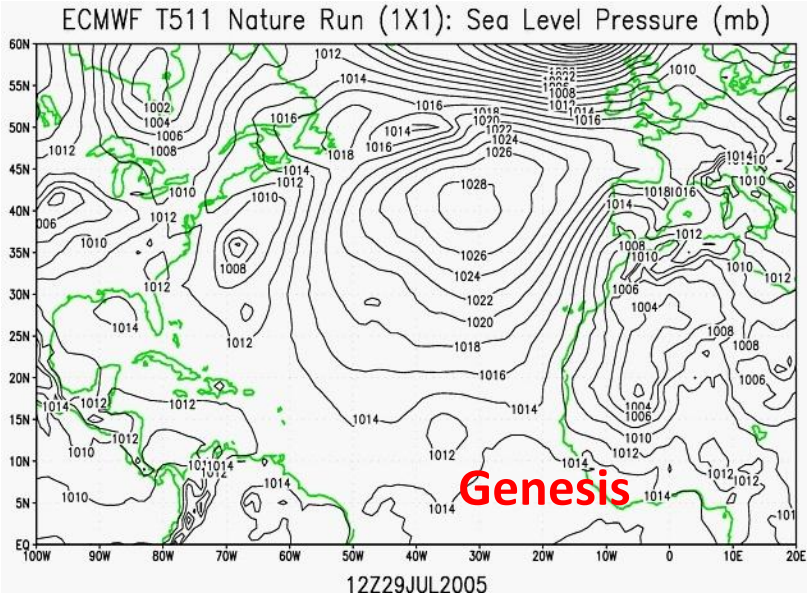
- The model output will be used to generate synthetic observations for forecast models.

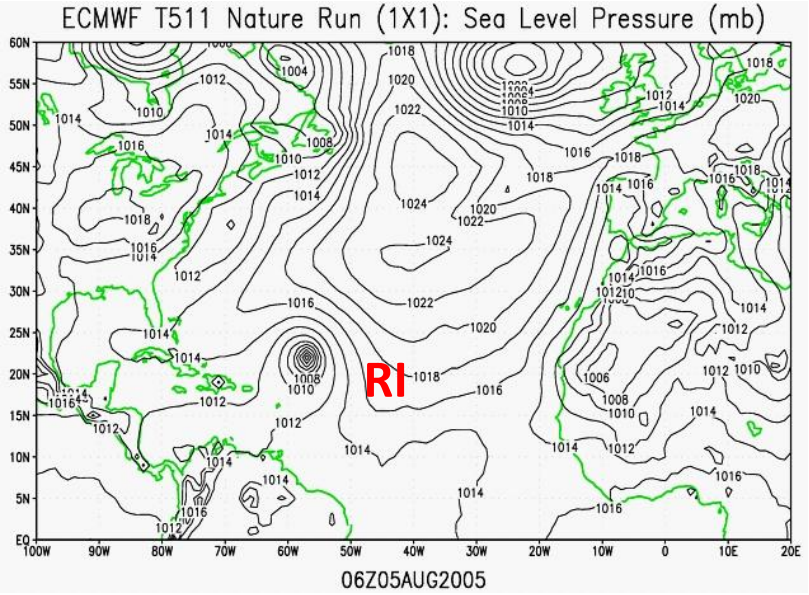
  These observations will be fed into model forecasts of the same event, presumably using HWRF or other regional forecast models.

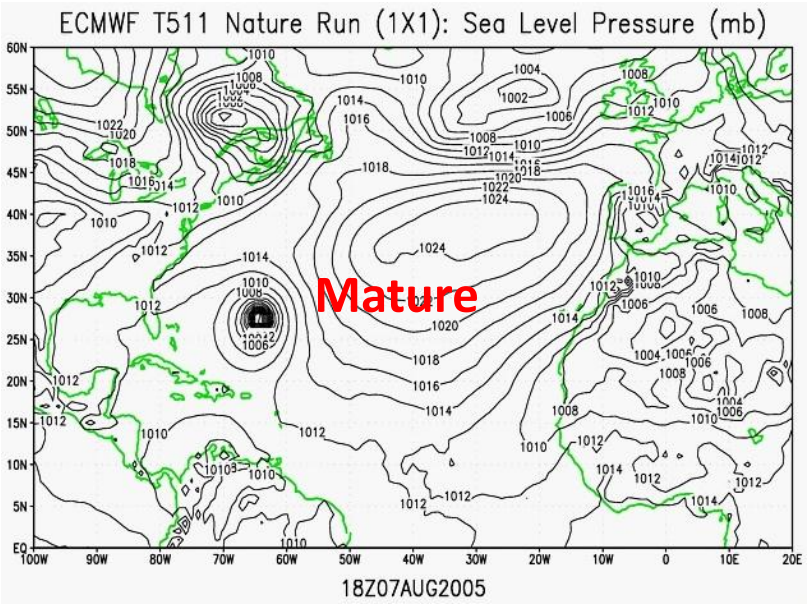
- Since regional forecast models require global forecasts, we also need a global nature run to provide initial conditions for a global forecast model.

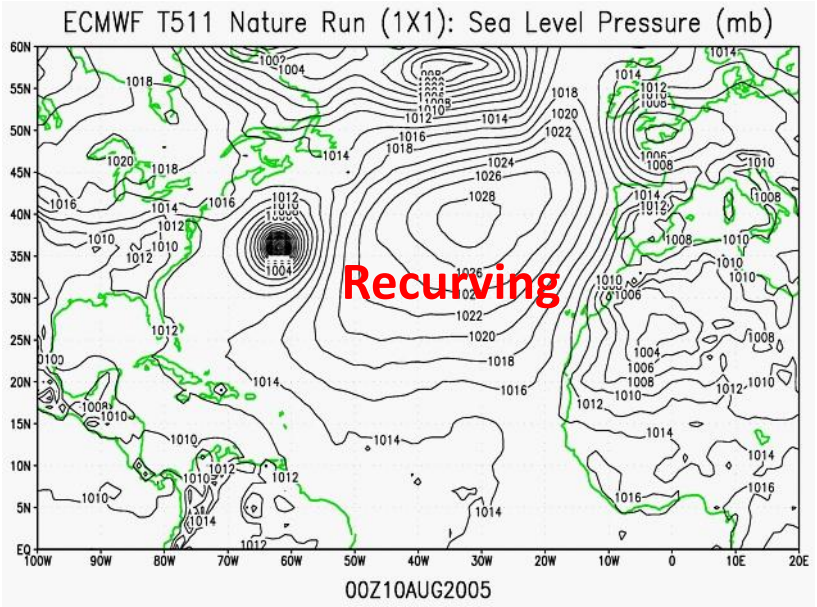
  We use a global nature run that is already completed and validated.

- The ECMWF nature run is a free-running simulation with seasonal forcing and prescribed surface boundary conditions for 13 months from 2005 to 2006.









WRF Model Configurations and Execution

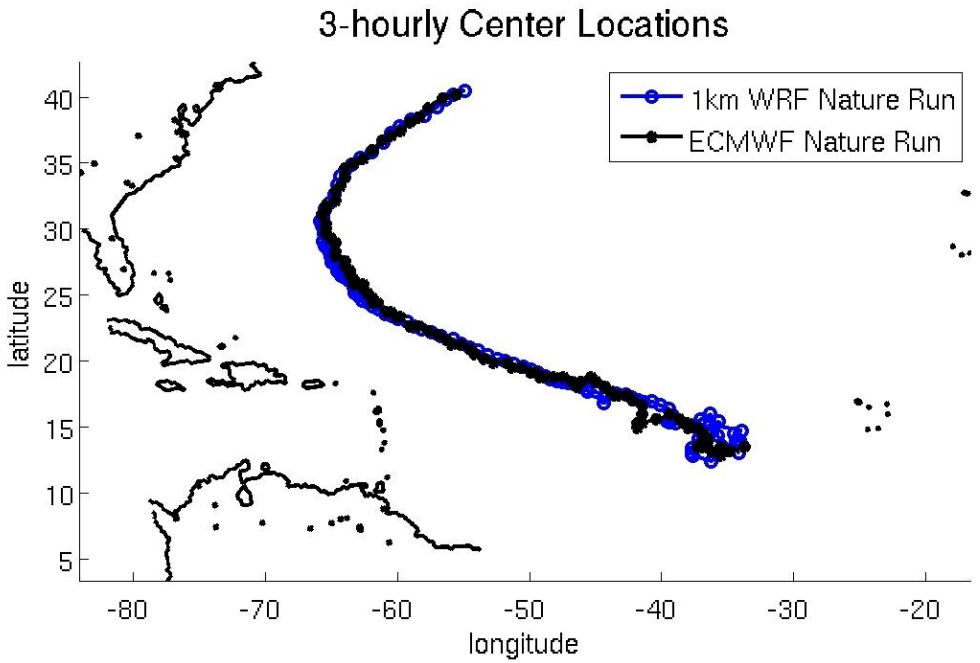
…after extensive testing the following options were implemented in WRF3.2.1…

Domain:

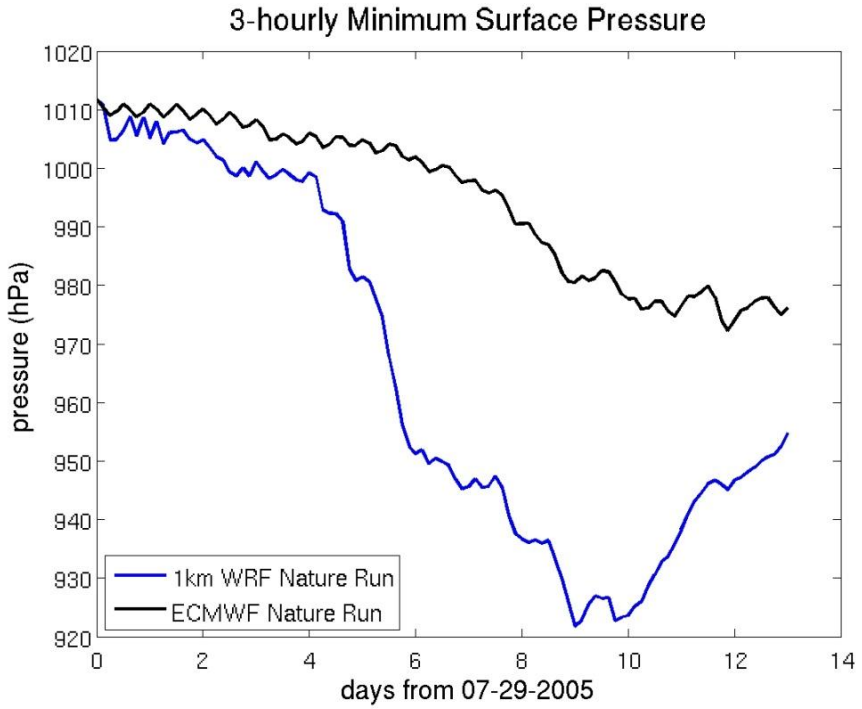
- 27 km resolution grid covering tropical Atlantic.
- Nesting to 9km, 3km, and 1km. Inner grid 480km x 480 km.
- 60 vertical levels

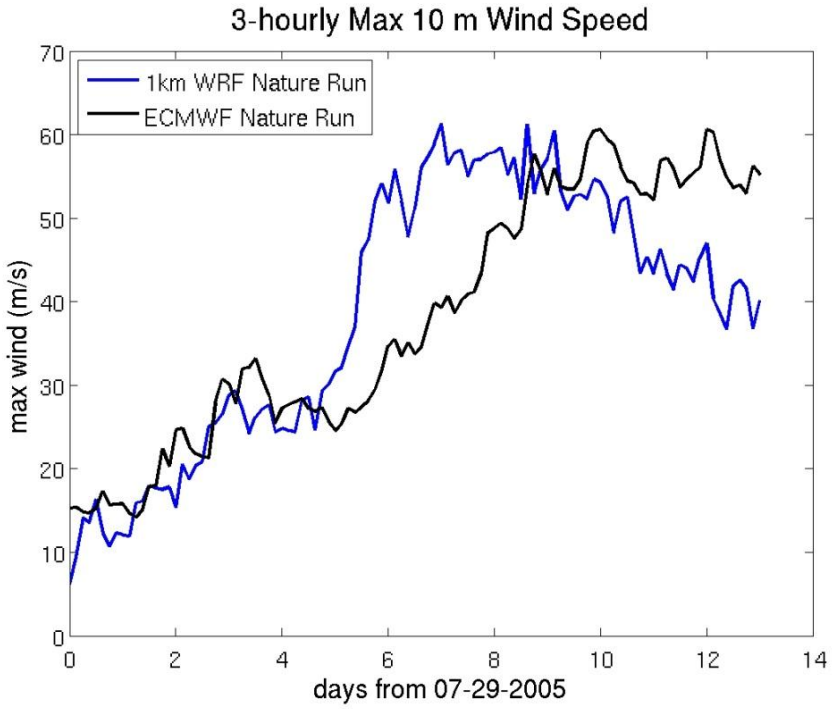
Physics:

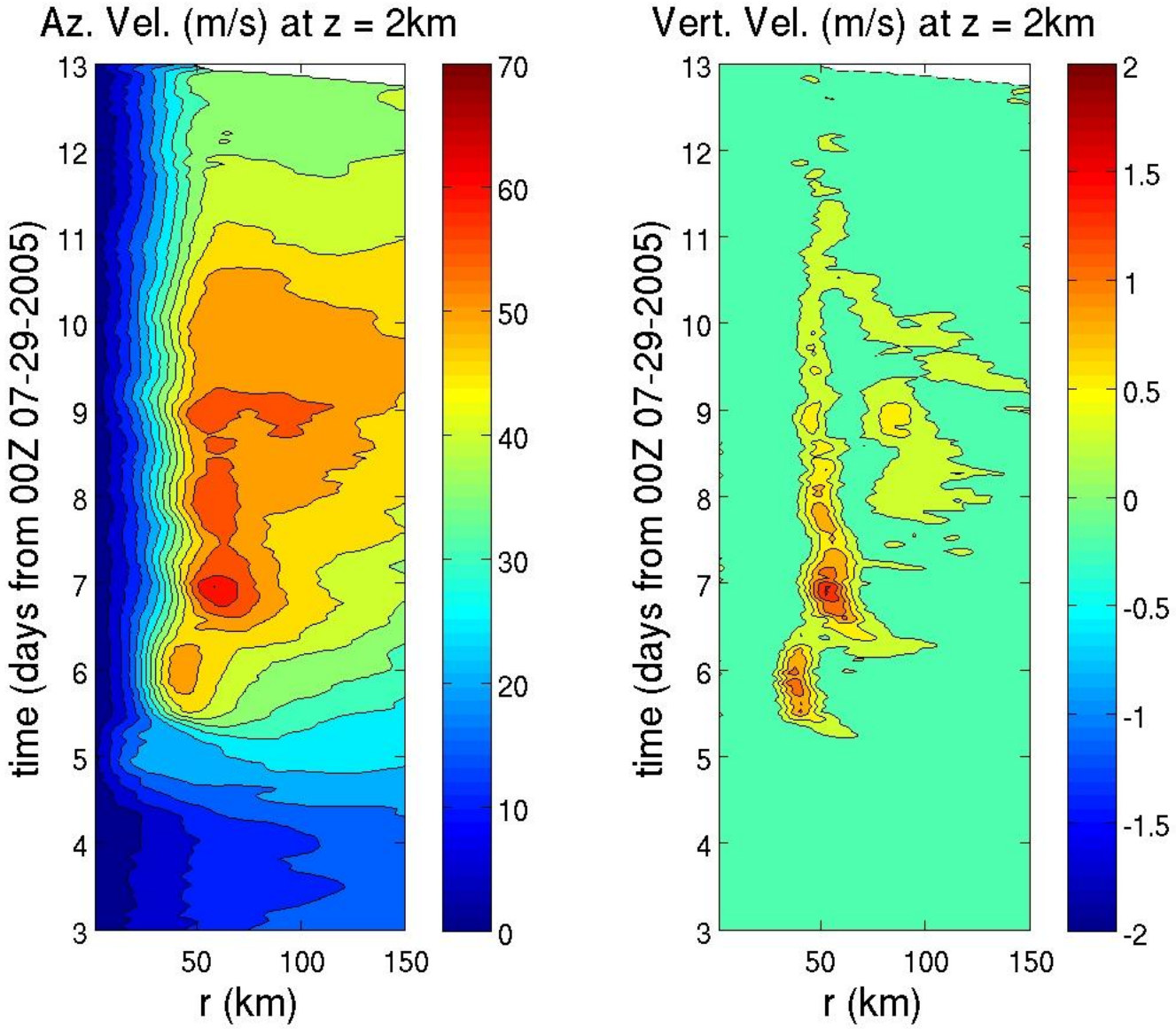
- Kain-Fritsch cumulus parameterization on 27km and 9km grids.
- 6-class, double-moment microphysics (WDM6).
- New RRTM advanced longwave and shortwave radiation schemes (radiation called *every six minutes*).
- YSU PBL scheme with TC-relevant modifications to Ck and Cd.
- Simple mixed layer scheme for ocean cooling under the storm.



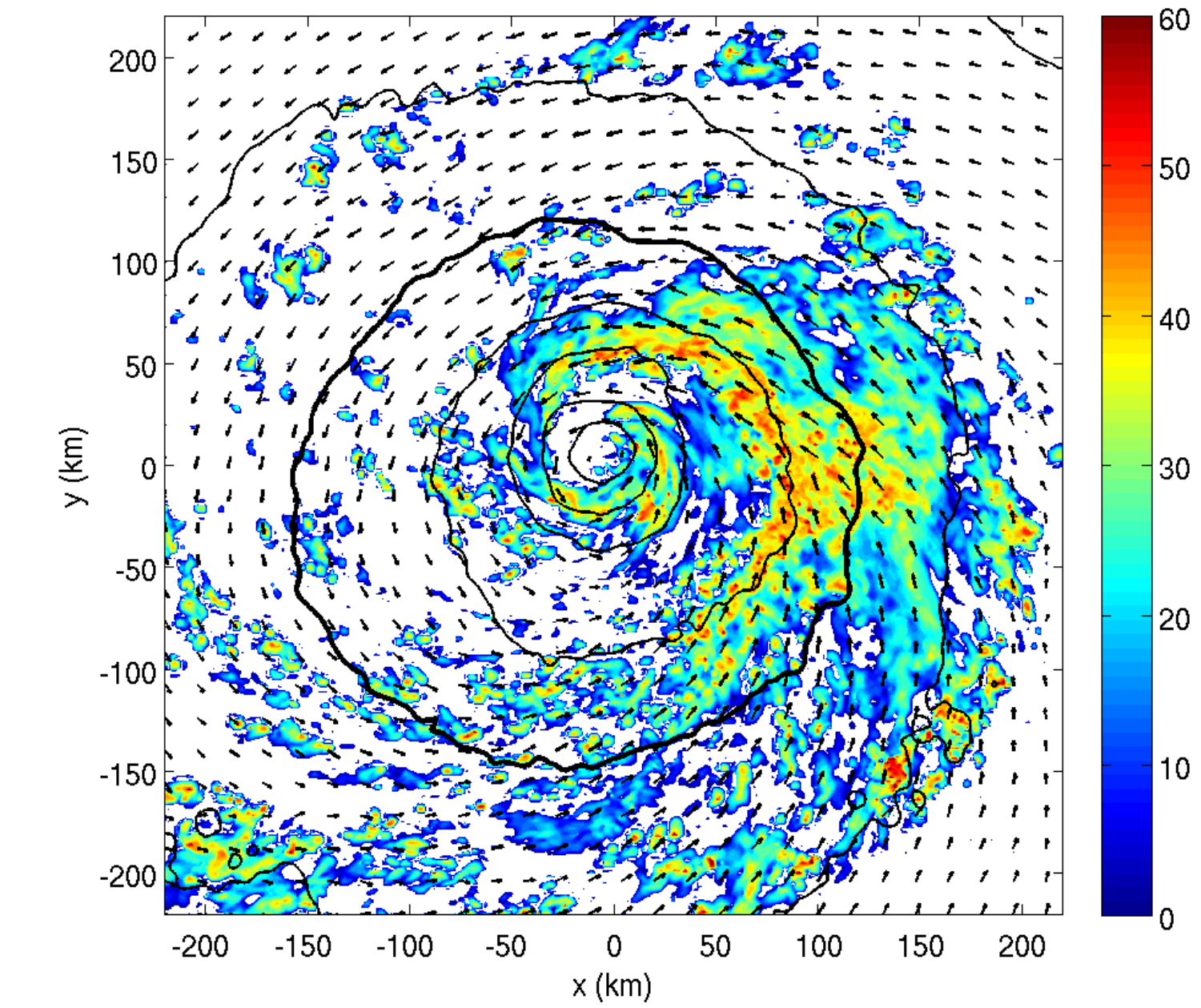
- 1km nature run data from 3km nest







Smaller RMW, then eyewall replacement cycle, then RMW remains steady.


Flight Level DBZ, Surf. Pres., and Surf. Wind Vecs. at 08-02-20h00m
y (km)
x (km)
200
150
100
50
0
-50
-100
-150
-200
-200
-150
-100
-50
0
50
100
150
200
60
50
40
30
20
10
0

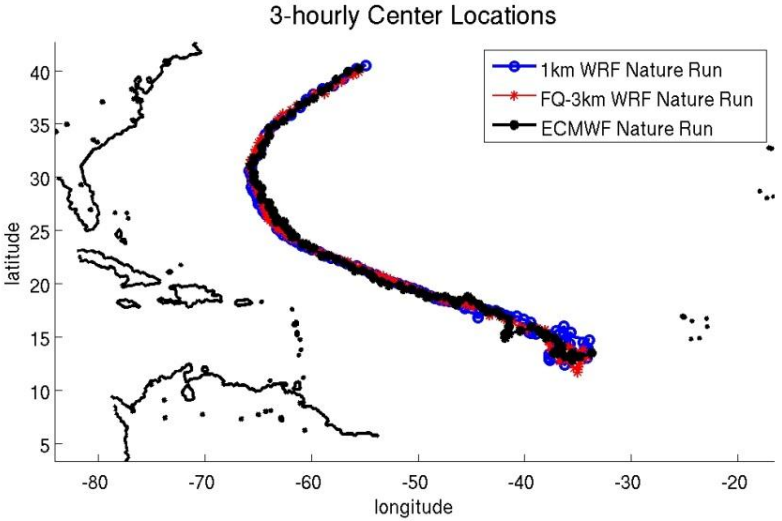
II. The Forecast-Quality Nature Run

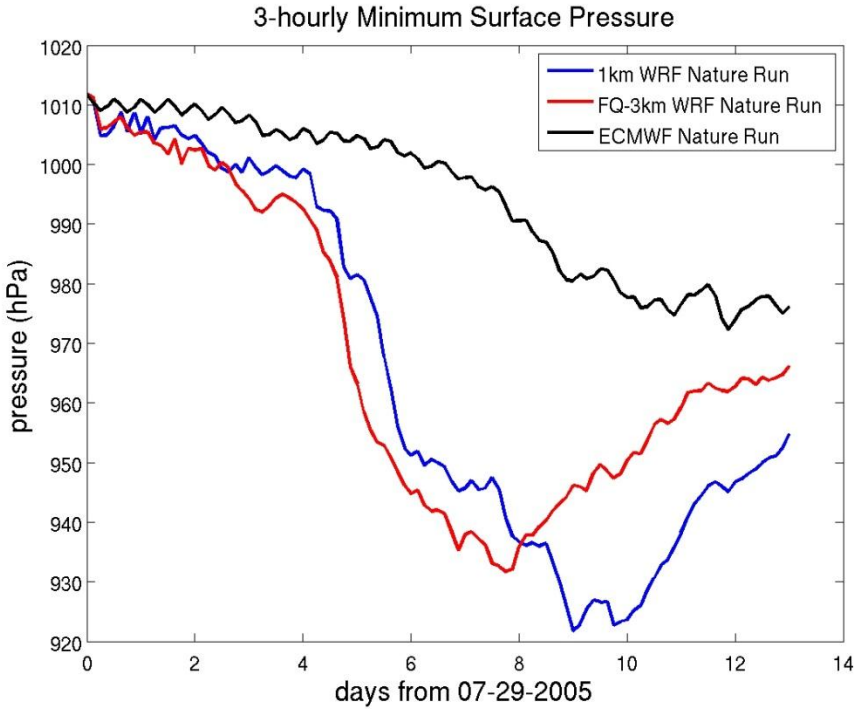
What did we gain by going to 1 km resolution, 60 vertical levels, etc…?

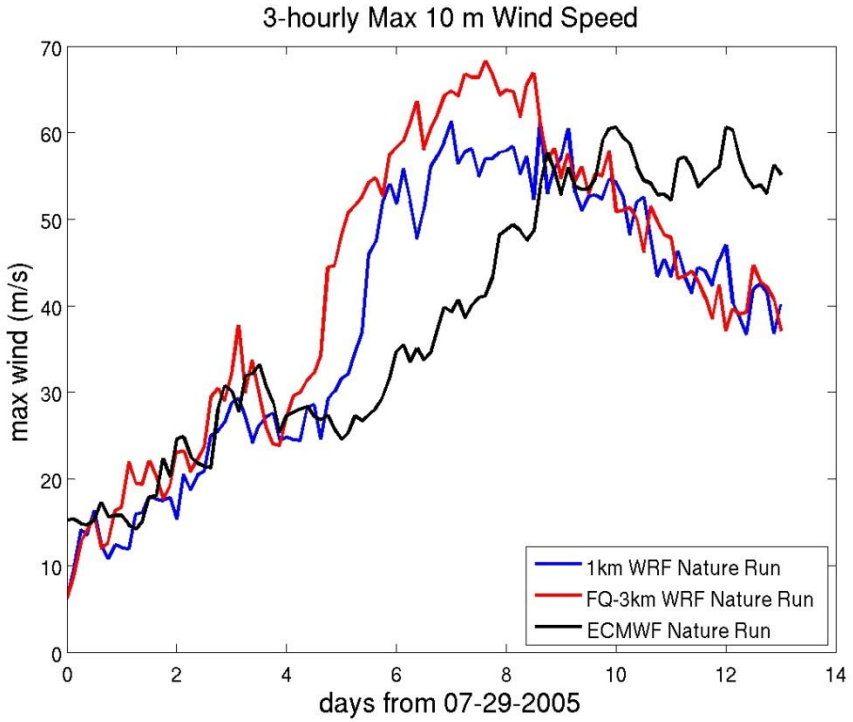
For comparison, we have created a "forecast quality" version of the hurricane nature run, with:

- 42 vertical levels
- Nesting to 3km resolution
- 5-class, single-moment microphysics (WSM5)
- Radiation calls every 30 minutes
- PBL scheme, C_d and C_k formulas, all other physics and options the same.

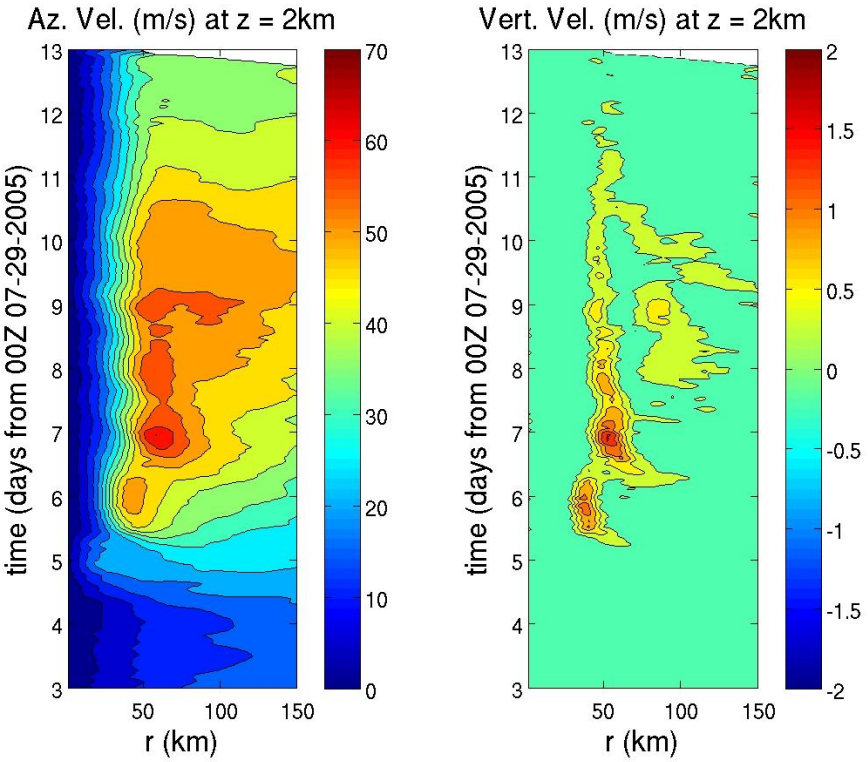
Forecast Quality
vs.
Research Quality







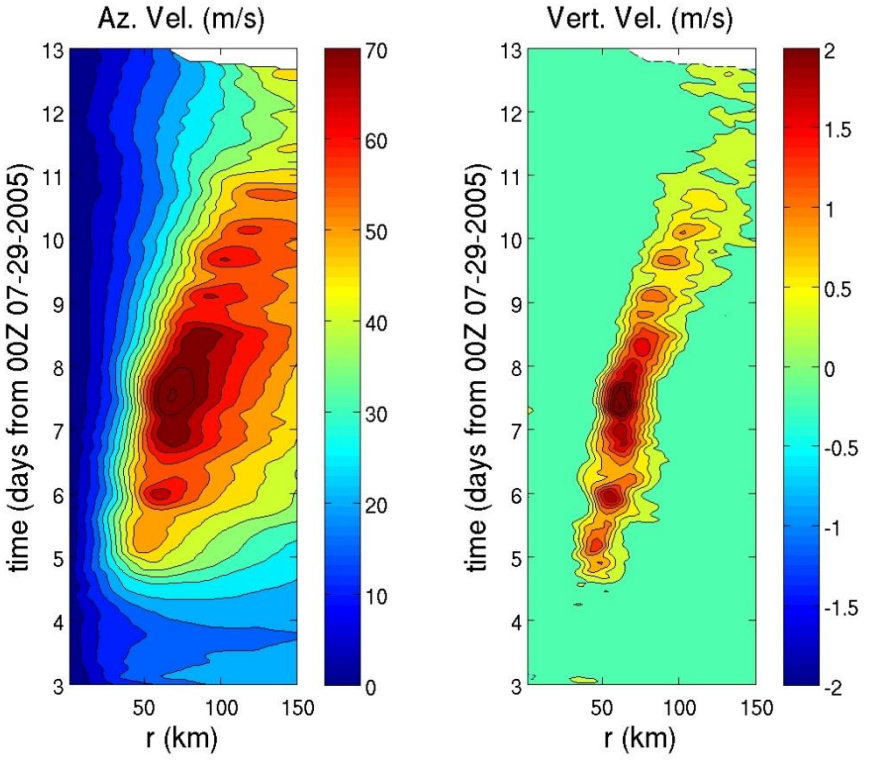
1 km Nature Run



smaller RMW

eyewall replacement cycles

Forecast Quality Nature Run



broader wind maximum

steadily increasing RMW

III. Comparisons to Data

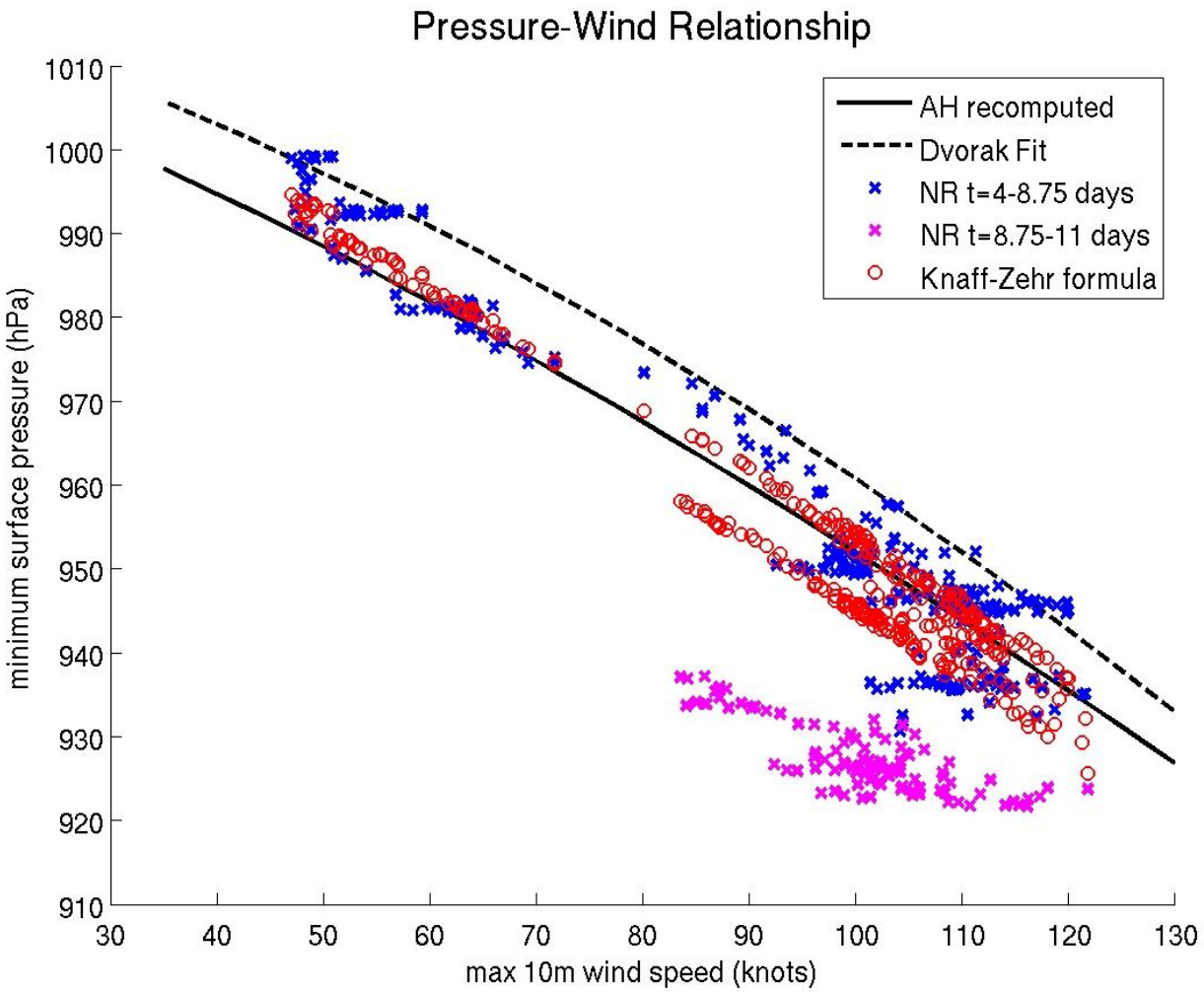
How similar to real hurricanes is the 1km nature run?

And how does the forecast-quality nature run compare?

We have been working to validate these simulations against composites from data sets:

- Pressure-wind relationships
- Boundary layer structure
- Size and outward slope of the eyewall
- CFADs of vertical velocity, vorticity, DBZ, etc.
- Other metrics?

1km Nature Run:

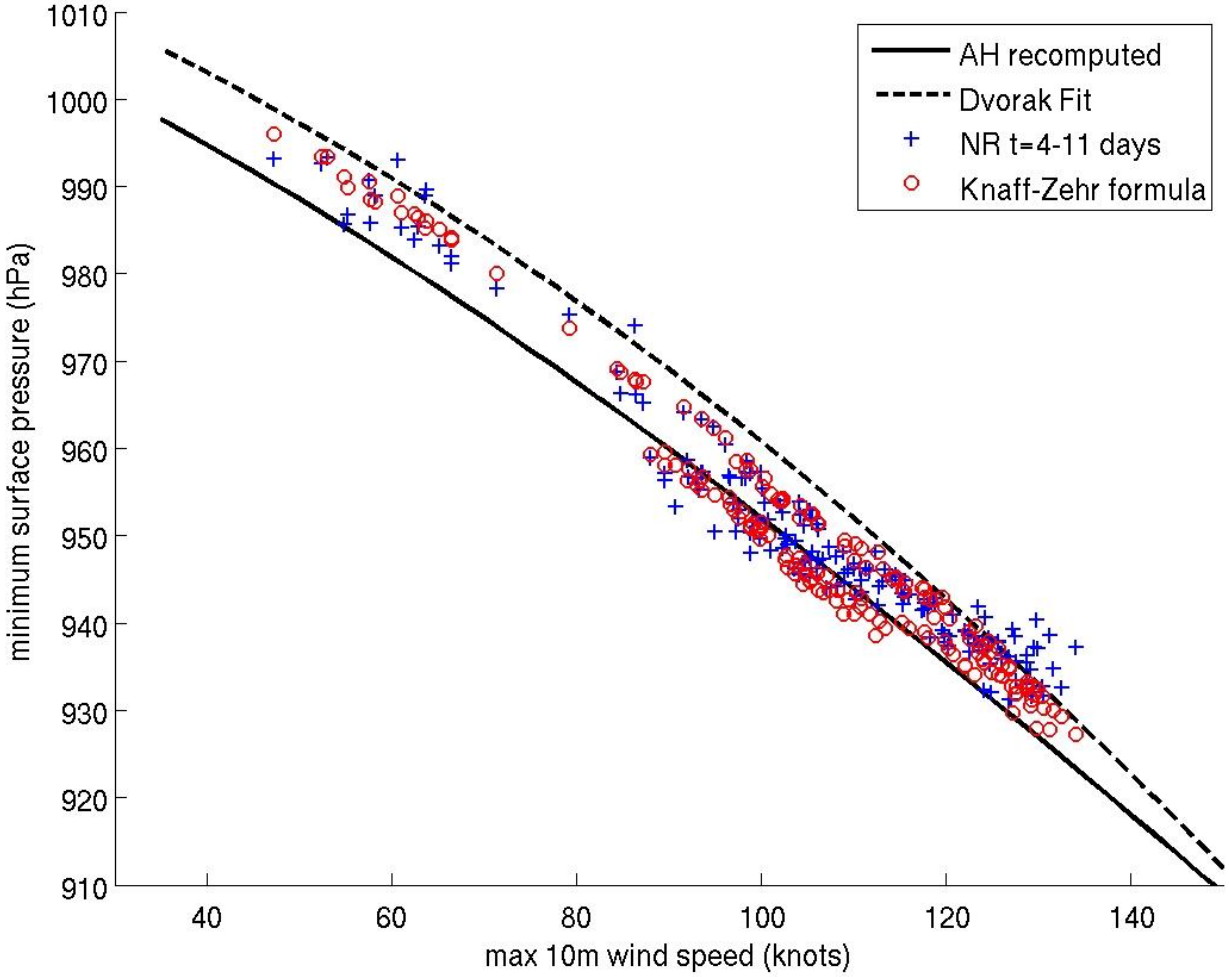


NR vs. KZ, days 4.0 to 8.75: RMSE = 4.5 hPa, bias = 0.8 hPa

KZ vs. Best Track: RMSE = 5.8 hPa, bias = -0.5 hPa

FQ Nature Run:

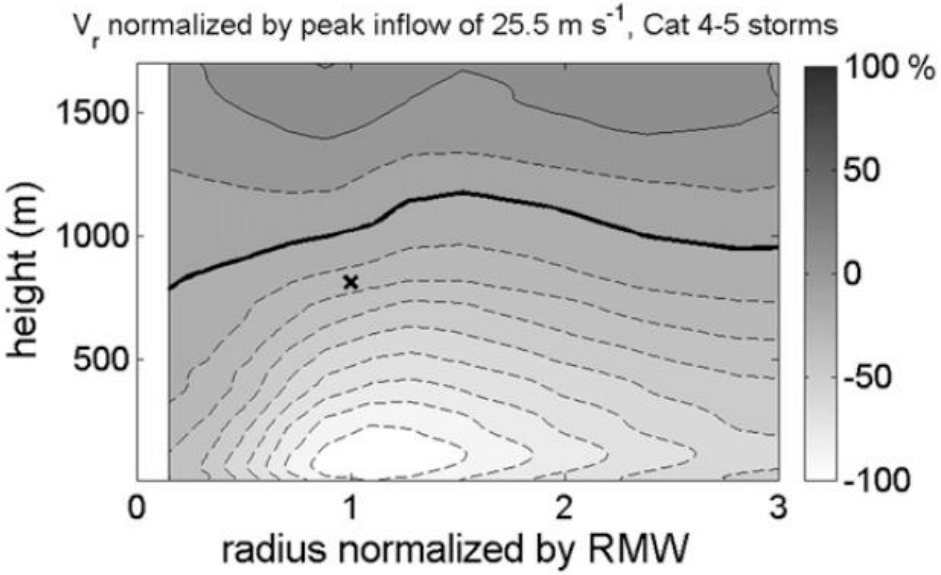
Pressure-Wind Relationship

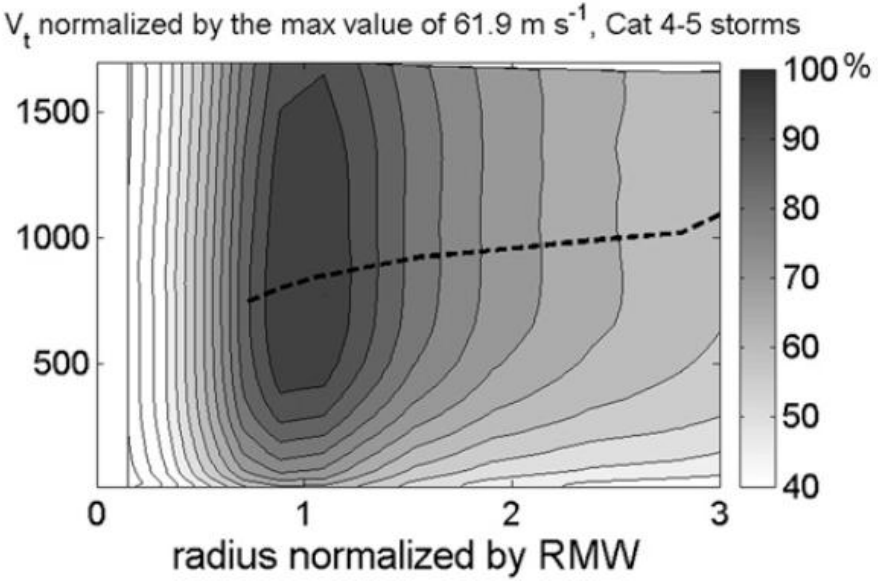


FQ vs. KZ, days 4.0 to 11.0: RMSE = 3.4 hPa, bias = 0.7 hPa

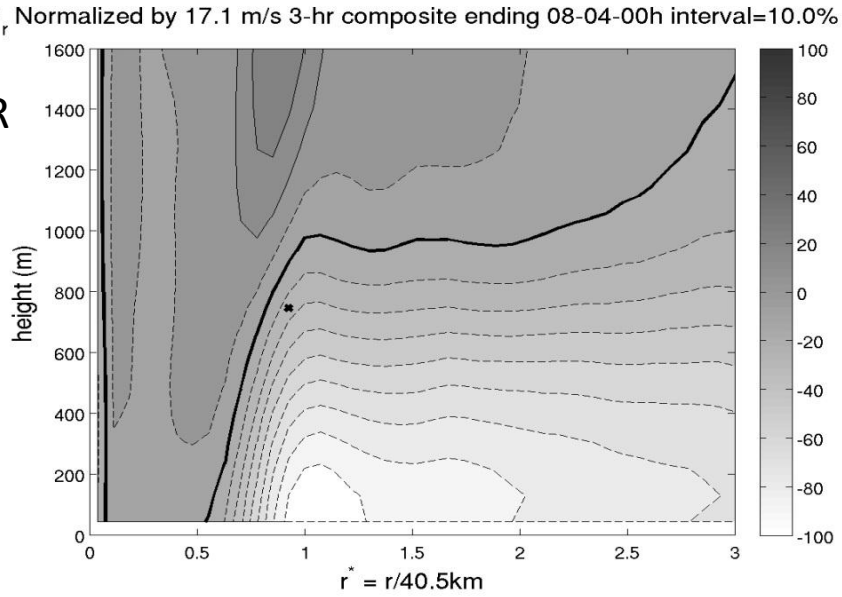
KZ vs. Best Track: RMSE = 5.8 hPa, bias = -0.5 hPa

Composite boundary layer wind fields from thousands of dropsondes: Jun Zhang et al. (2011, MWR)

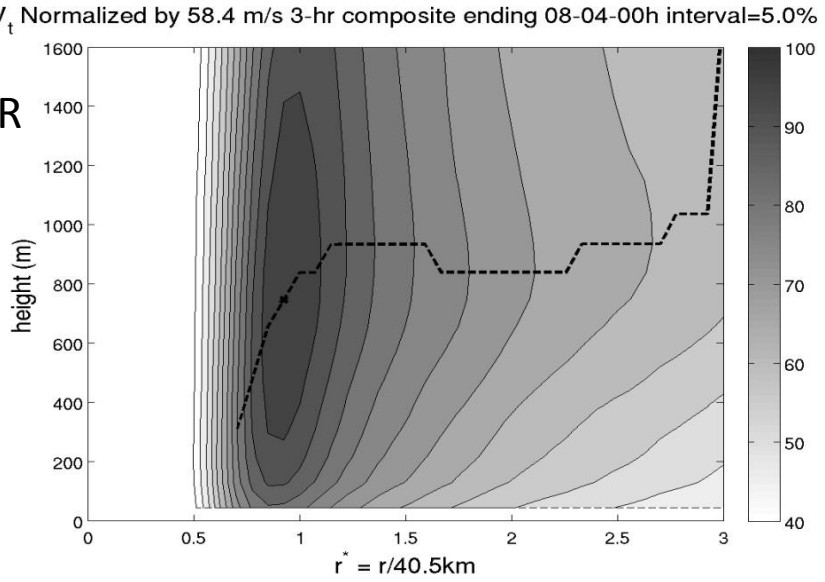




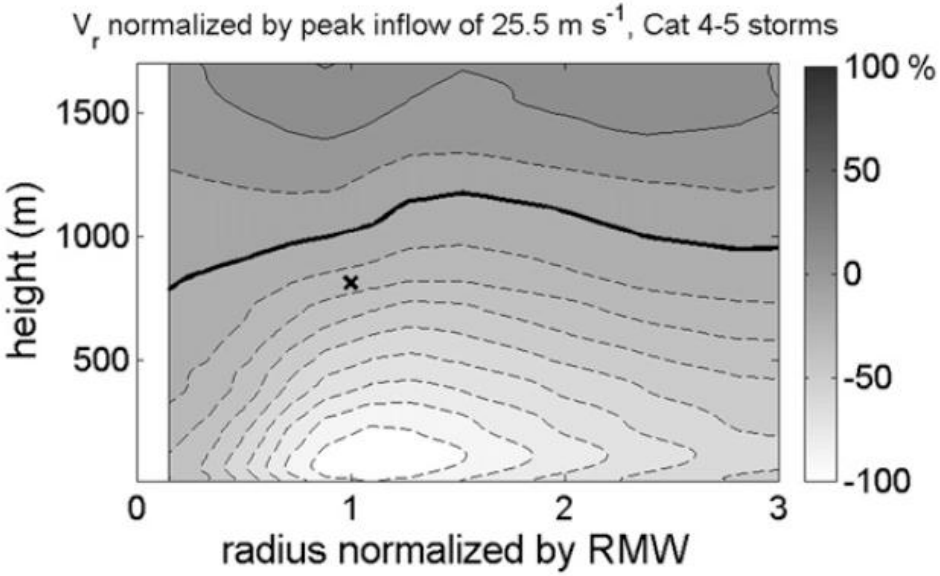
NR

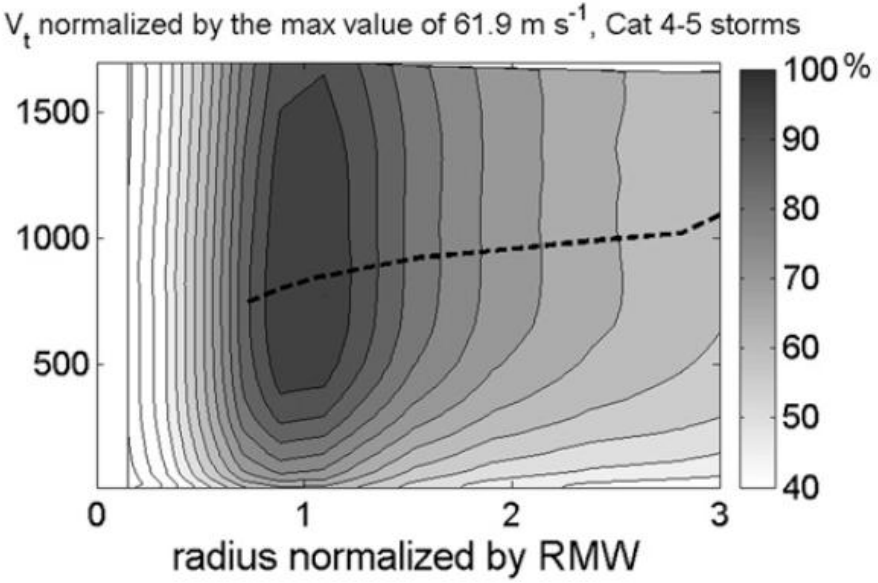


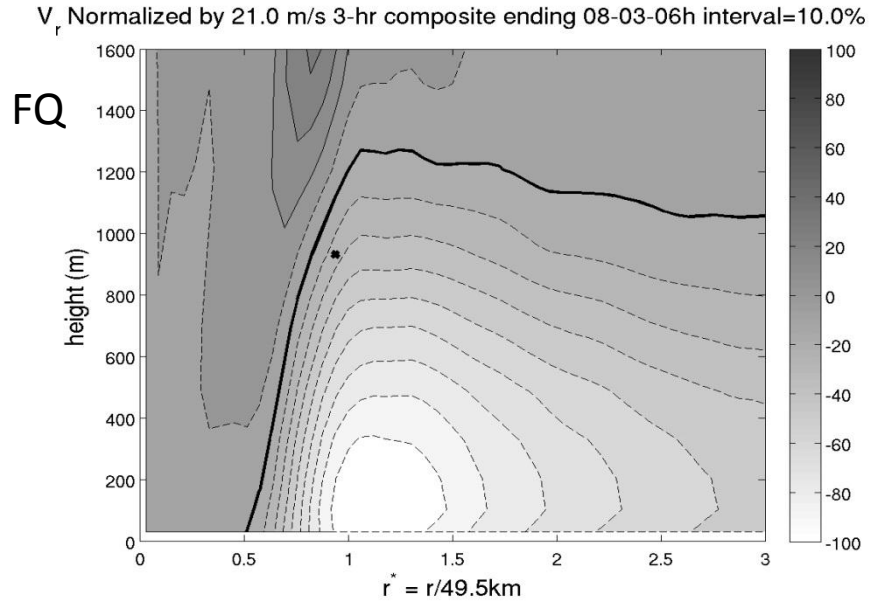
NR

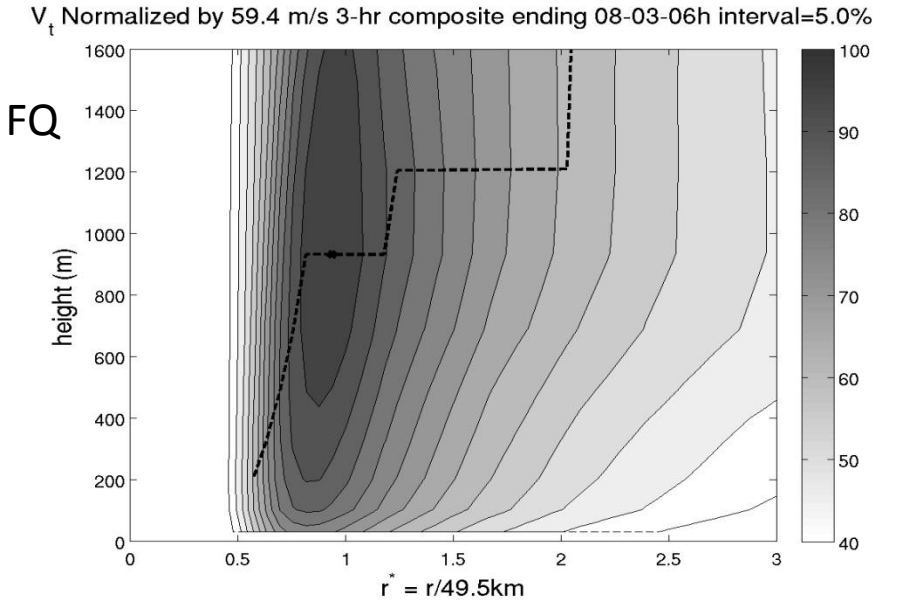


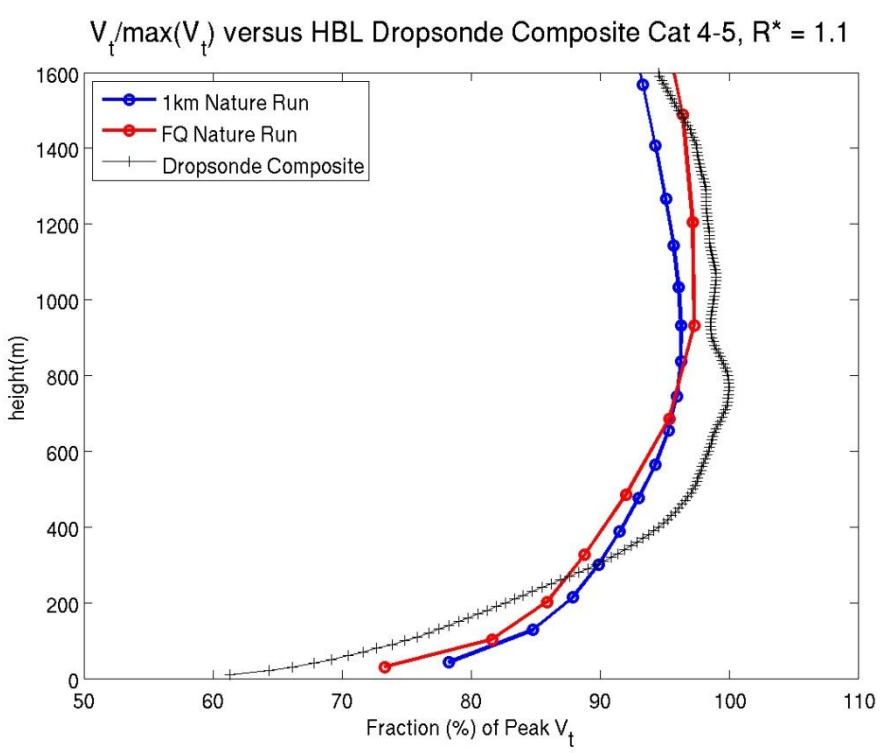
Composite boundary layer wind fields from thousands of dropsondes: Jun Zhang et al. (2011, MWR)

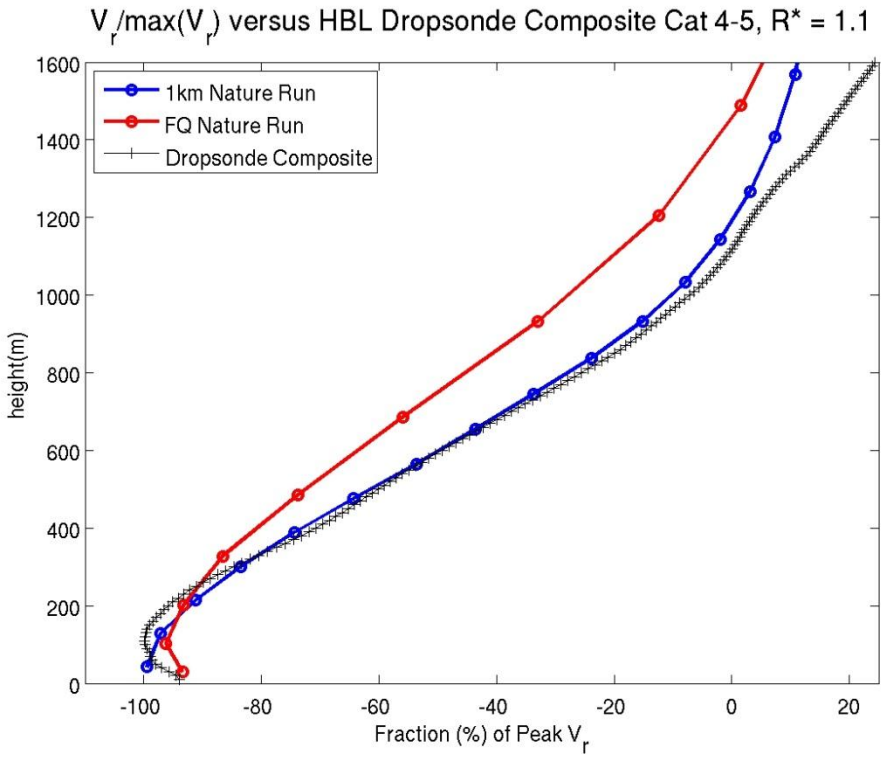




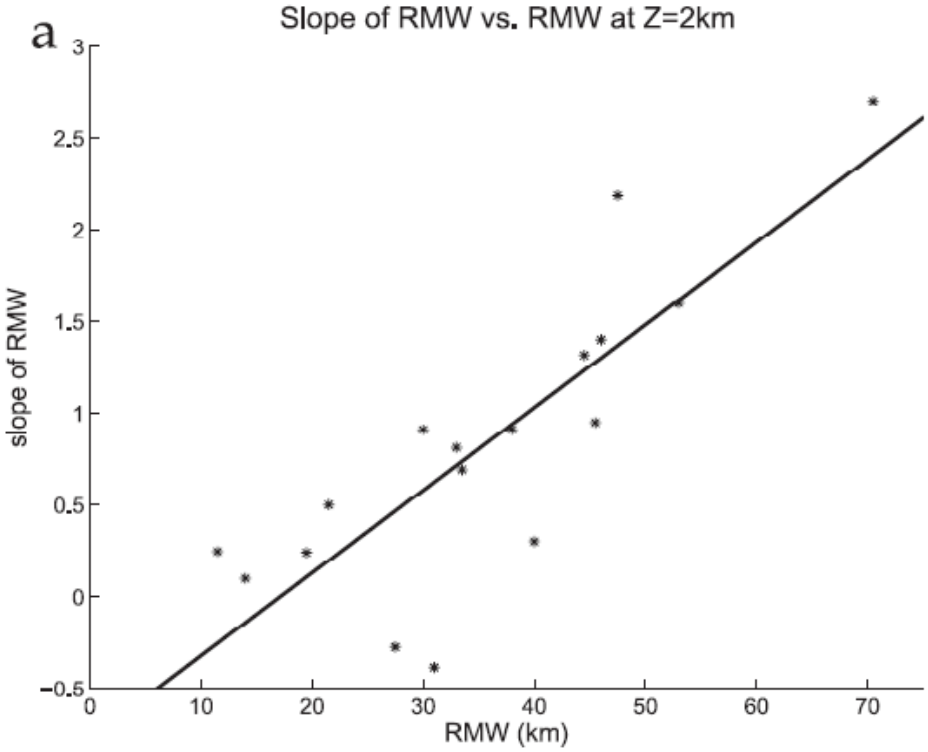


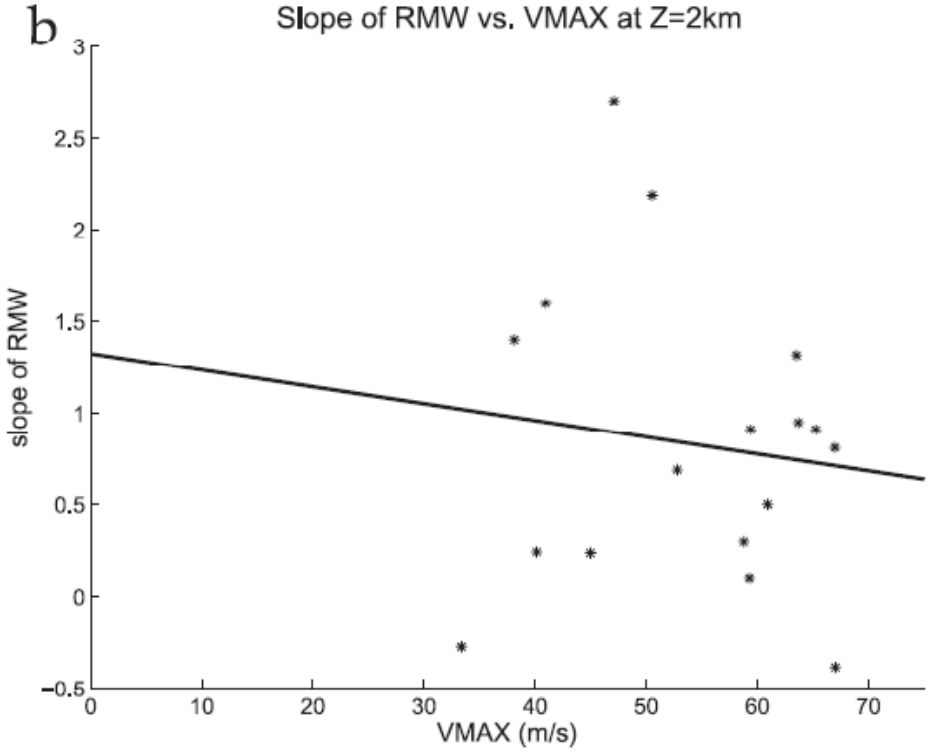



V_t/max(V_t) versus HBL Dropsonde Composite Cat 4-5, R* = 1.1
1km Nature Run
FQ Nature Run
Dropsonde Composite
height(m)
Fraction (%) of Peak V_t
0
200
400
600
800
1000
1200
1400
1600
50
60
70
80
90
100
110


V_r/max(V_r) versus HBL Dropsonde Composite Cat 4-5, R* = 1.1
1km Nature Run
FQ Nature Run
Dropsonde Composite
height(m)
Fraction (%) of Peak V_r
0
200
400
600
800
1000
1200
1400
1600
-100
-80
-60
-40
-20
0
20

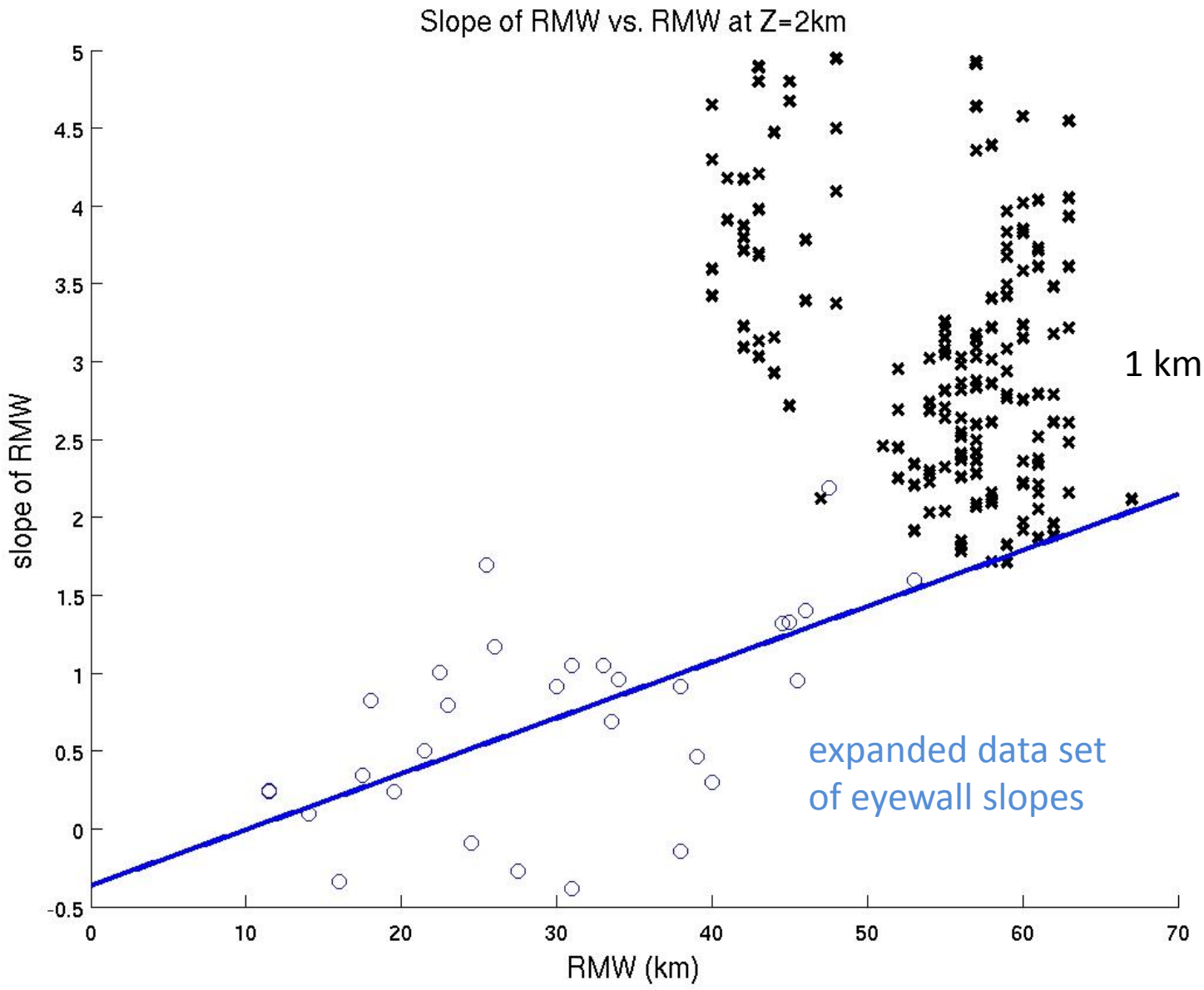
Stern and Nolan (2009, JAS):
Outward slope of the RMW from z = 2 to 8 km
from analyses of radar-observed wind fields
(HRD "swath" data).





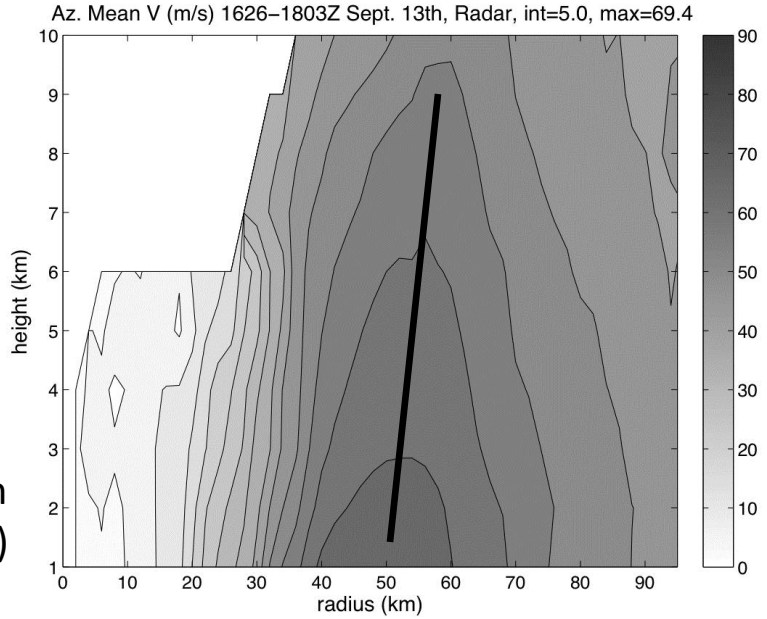
RMW slope increases linearly with RMW size

No clear relationship with V_{max}

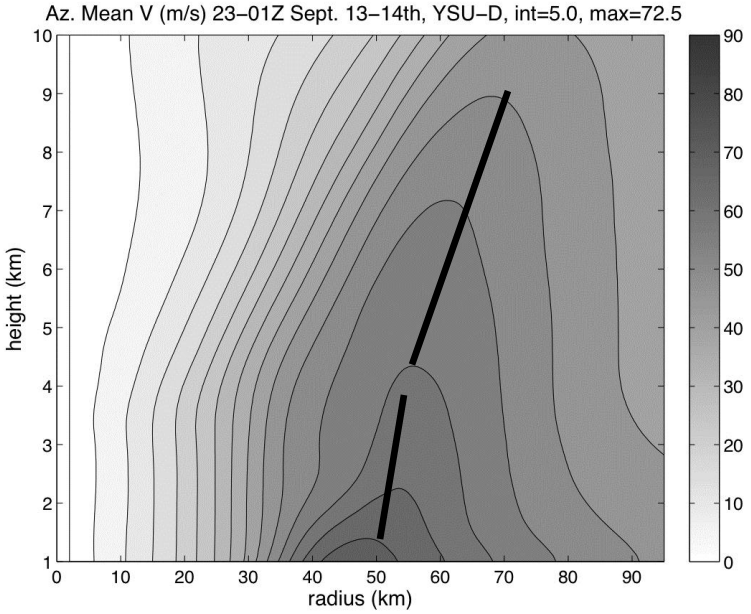

Slope of RMW vs. RMW at Z=2km
slope of RMW
RMW (km)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
10
20
30
40
50
60
70
1 km nature run
expanded data set
of eyewall slopes

- This discrepancy has been seen previously in numerical simulations of hurricanes:

Isabel Obs.



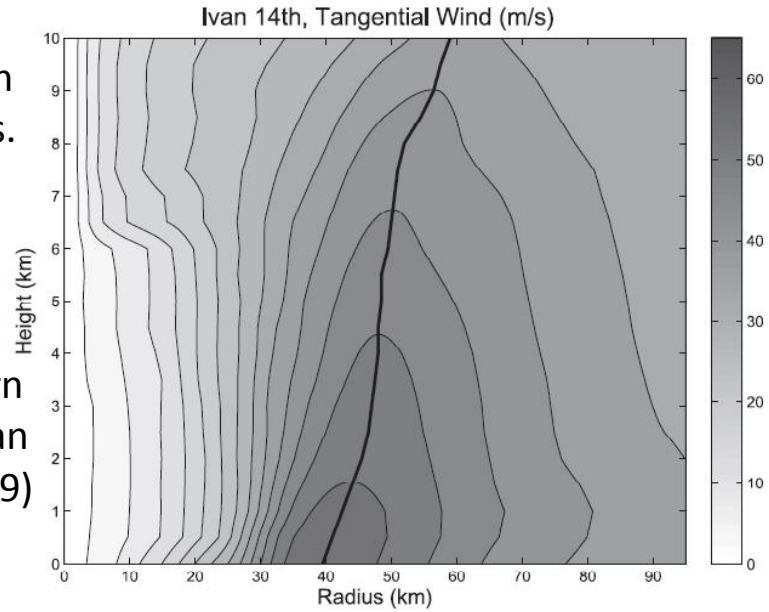
Isabel Simulation



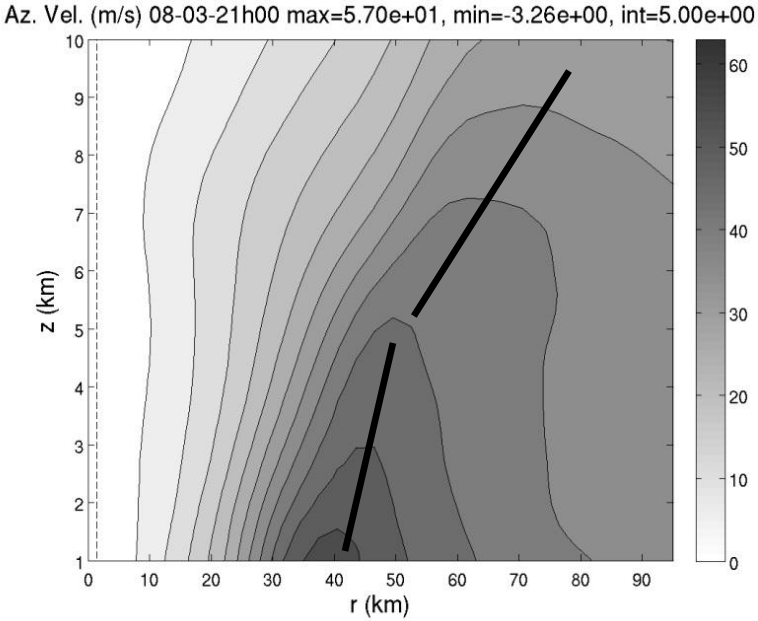
Kozich (2004)

(Nolan et al. 2009)

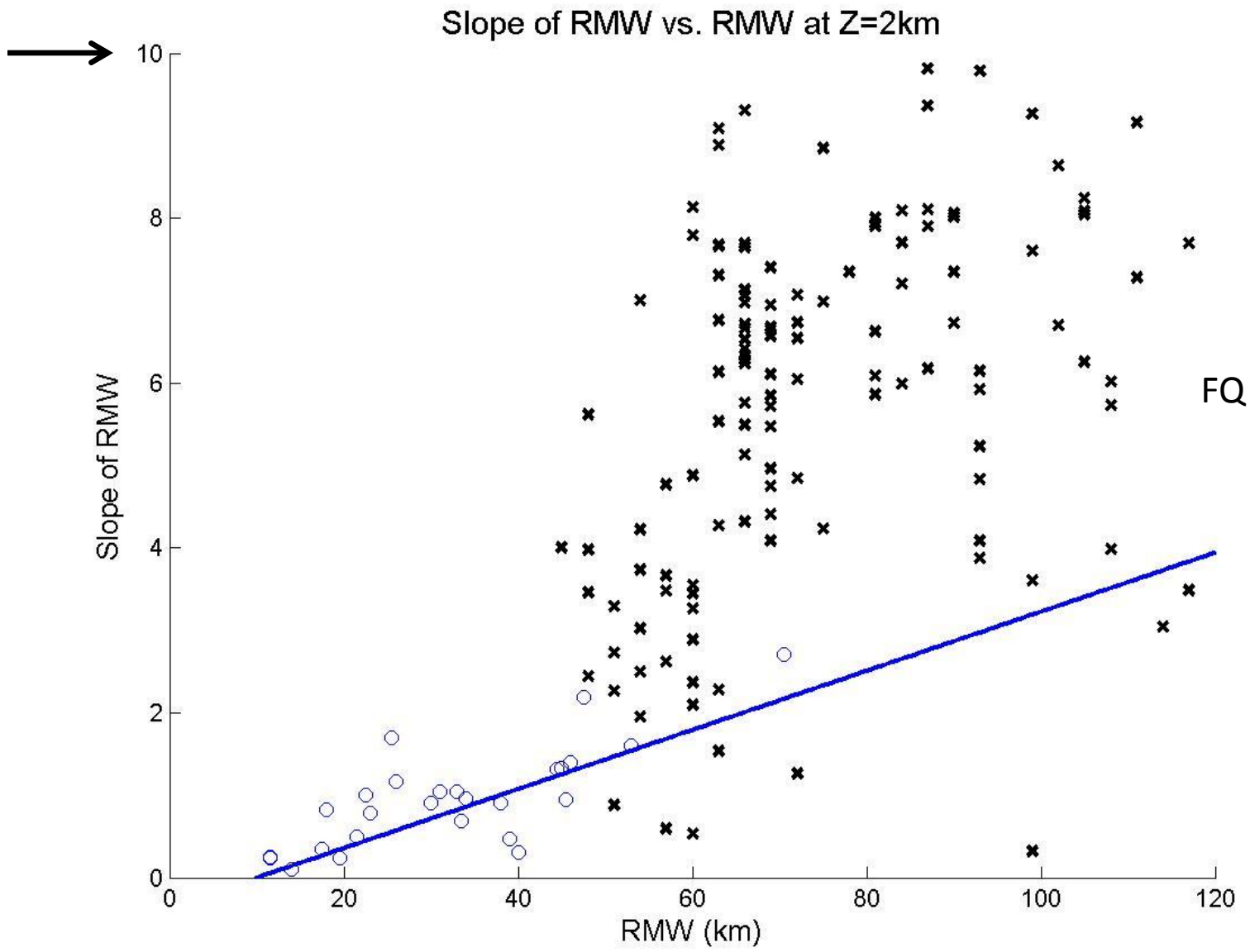
Ivan Obs.



Nature Run



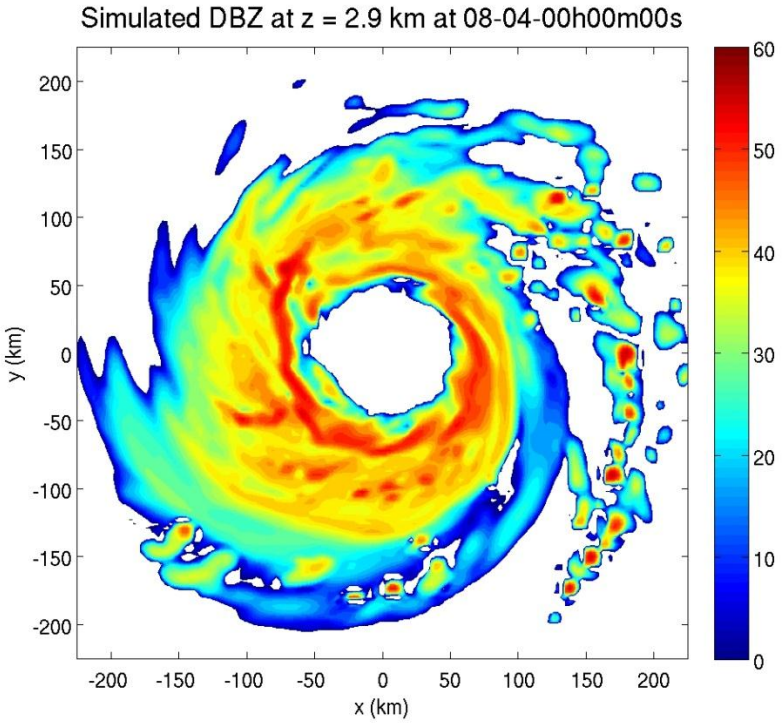
Stern Nolan (2009)

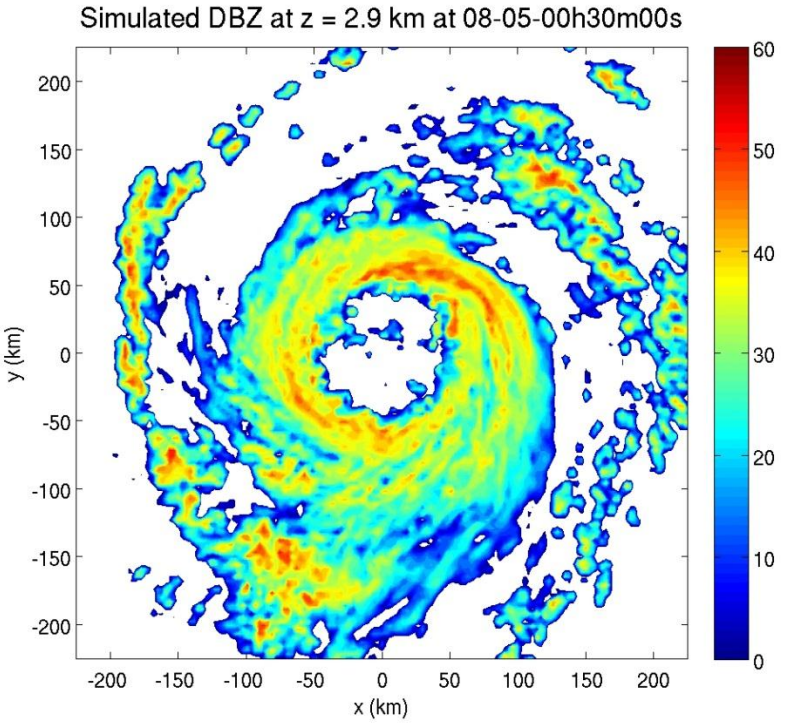


FQ nature run

Simulated Reflectivity (→ rainfall distribution)

(both plots from 3km nests)

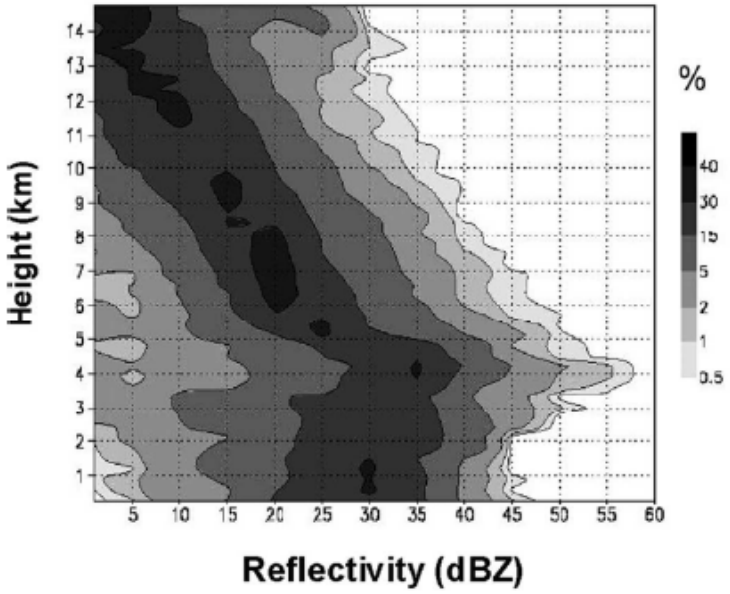




One clearly “looks better.” But how do we quantify that?

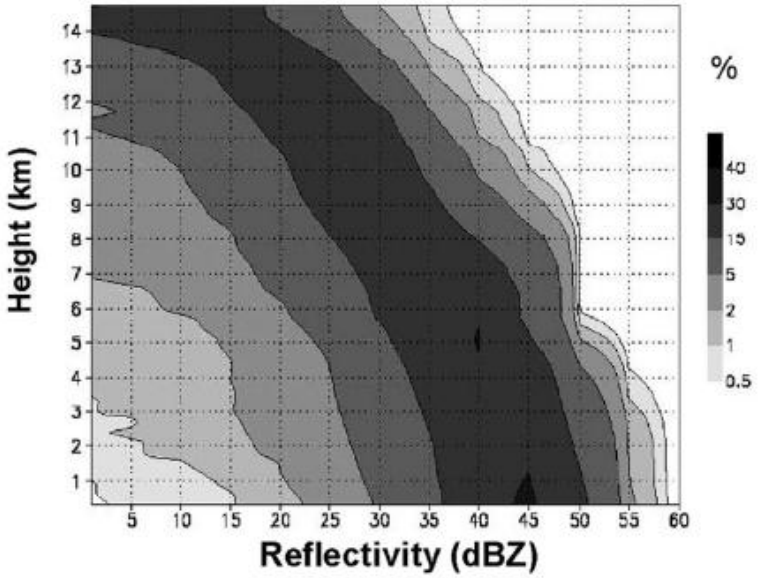
We use “contoured frequency by altitude diagrams”: CFADS.

Vertical Incidence Radar

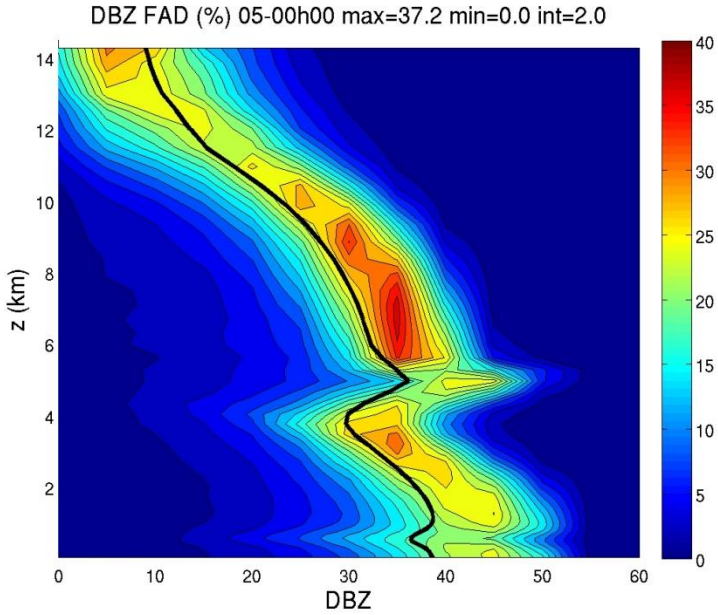


Rogers et al. 2007

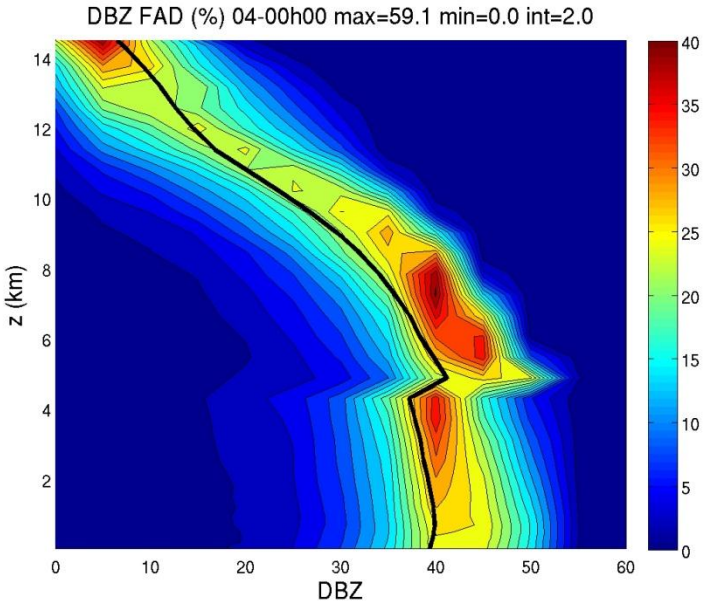
MM5 of Floyd, Bonnie



NR

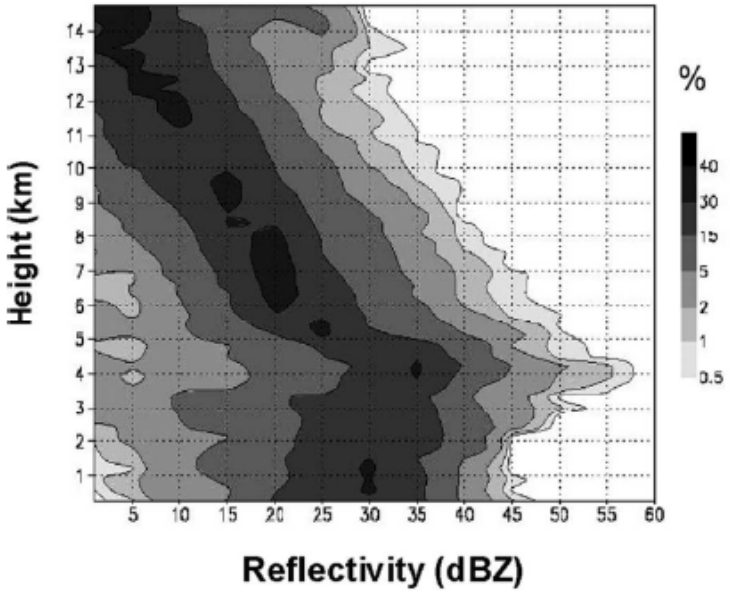


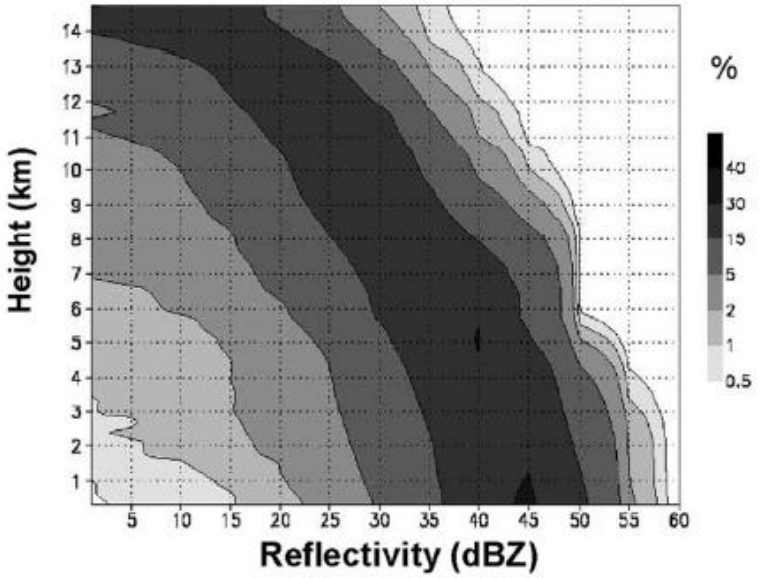
FQ



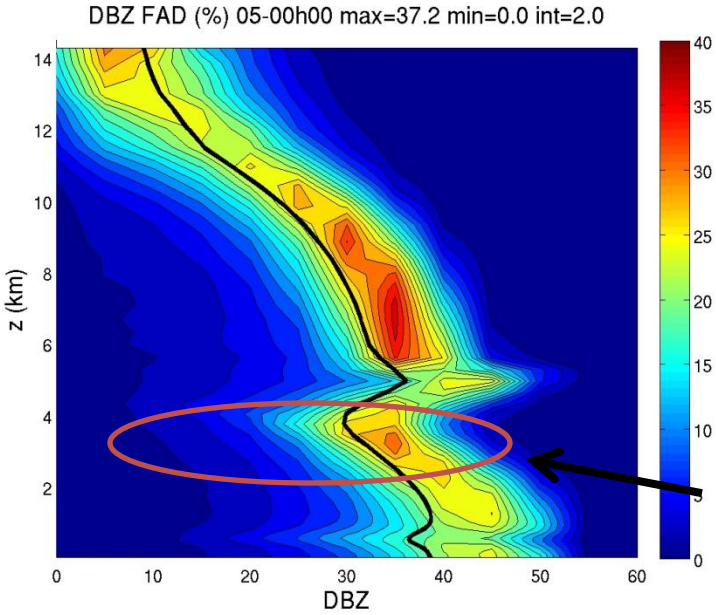
We use “contoured frequency by altitude diagrams”: CFADS.

Vertical Incidence Radar Rogers et al. 2007 MM5 of Floyd, Bonnie



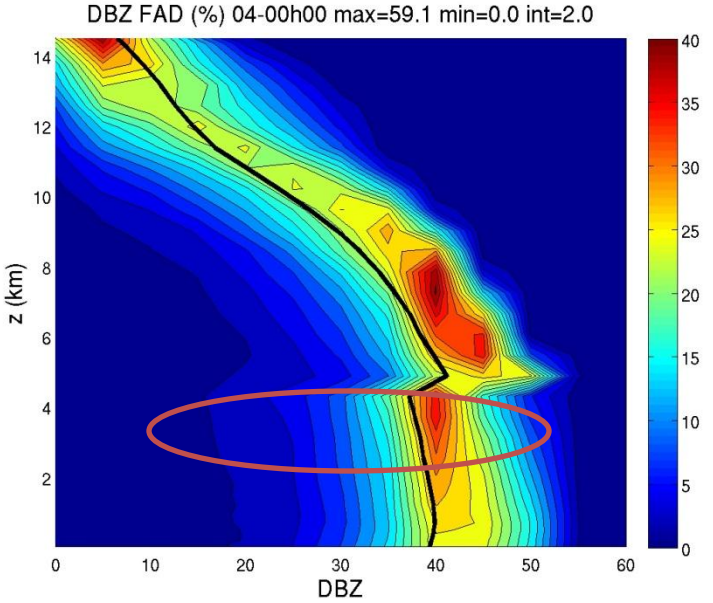


NR



lower mean,
wider spread

FQ



IV. Summary

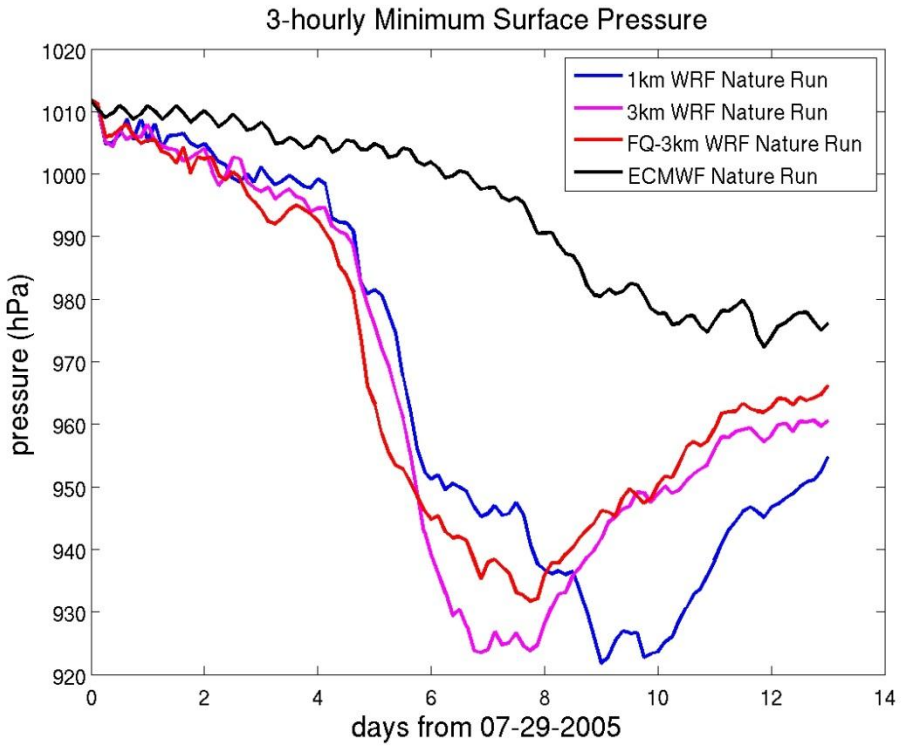
Except for the pressure-wind relationship, the 1km WRF/ECMWF nature run has better structure than a 3 km, “forecast-quality” version of the same simulation:

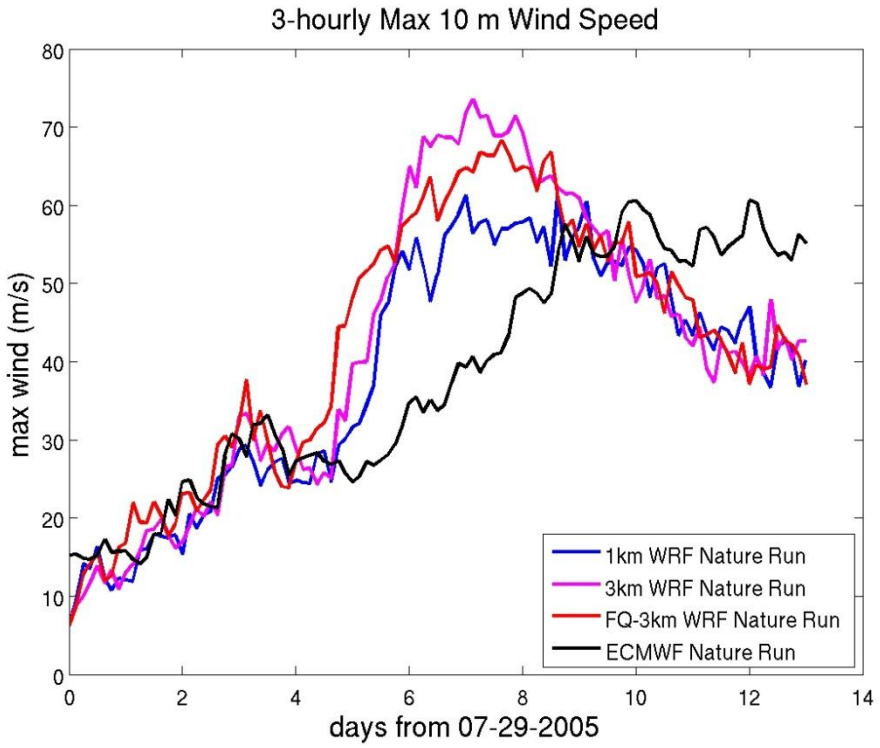
- Smaller size, smaller eyewall slope, better inner-core size evolution
- Slightly shallower boundary layer inflow
- Better distribution of reflectivity around flight level.

But – how much of the changes are due to resolution, and how much are due to better physics??

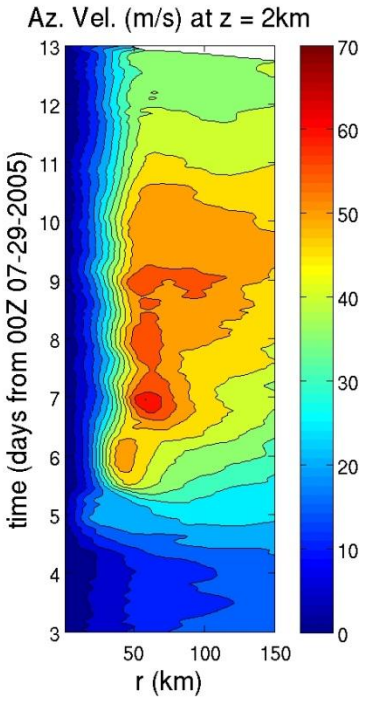
As it happens – we have an intermediate simulation!

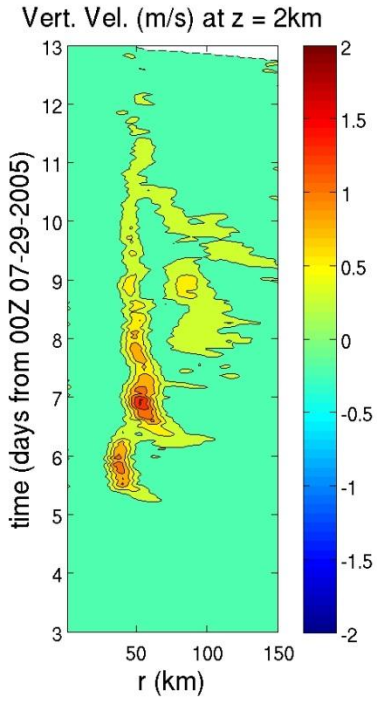
A 3km version of the nature run, with same physics and vertical levels.



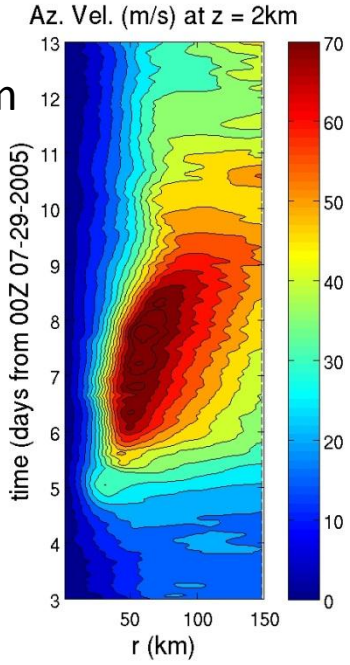


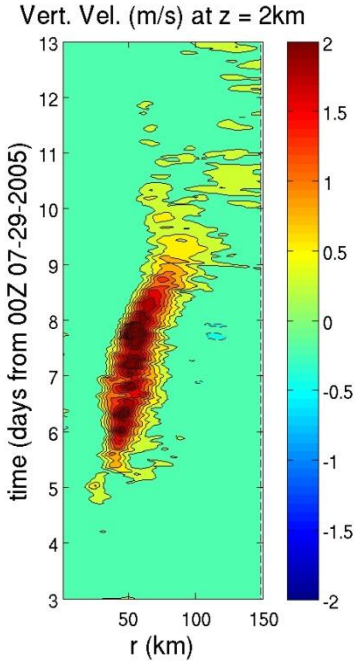
NR


Az. Vel. (m/s) at z = 2km
time (days from 00Z 07-29-2005)
r (km)

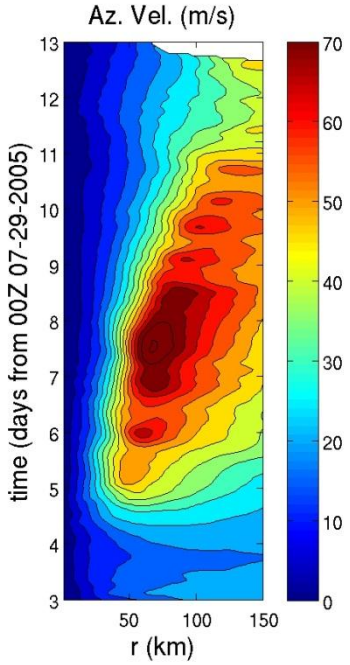

Vert. Vel. (m/s) at z = 2km
time (days from 00Z 07-29-2005)
r (km)

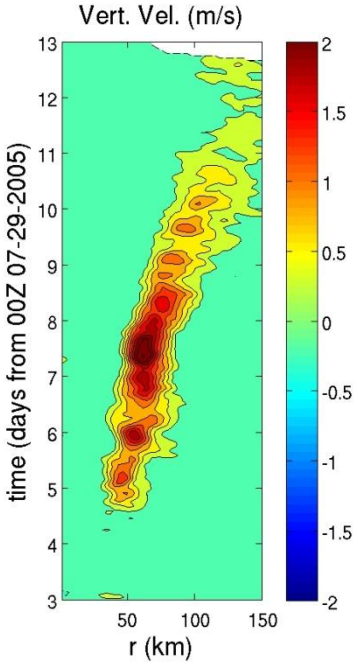
3km


Az. Vel. (m/s) at z = 2km
time (days from 00Z 07-29-2005)
r (km)

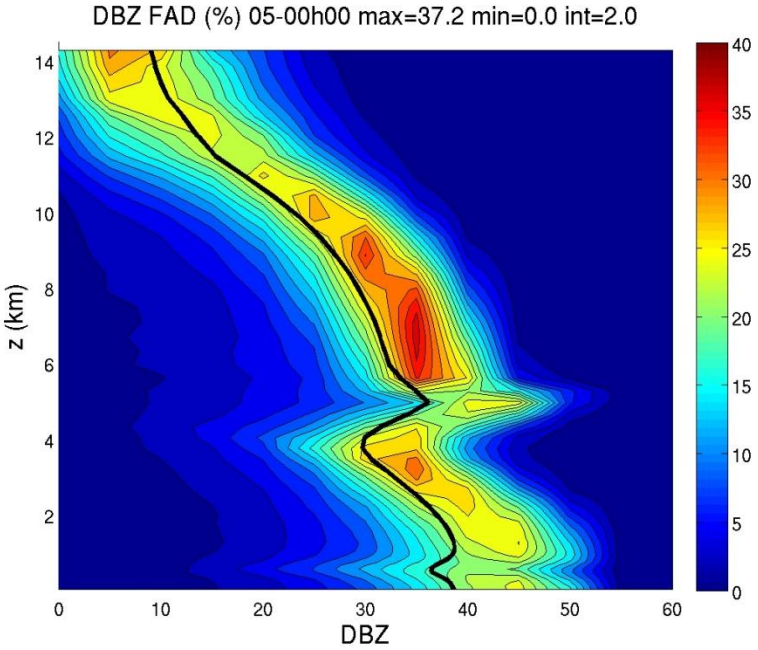

Vert. Vel. (m/s) at z = 2km
time (days from 00Z 07-29-2005)
r (km)

FQ

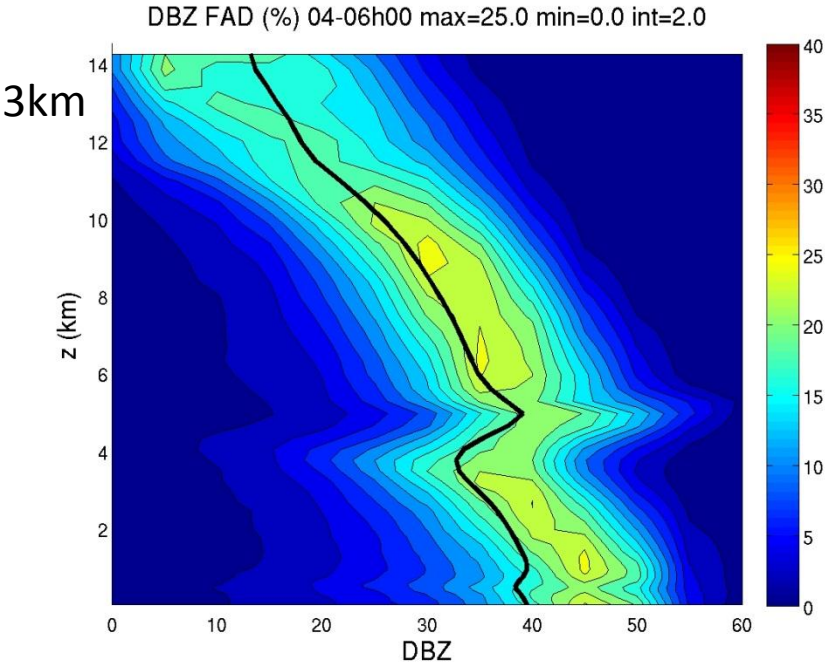

Az. Vel. (m/s)
time (days from 00Z 07-29-2005)
r (km)


Vert. Vel. (m/s)
time (days from 00Z 07-29-2005)
r (km)

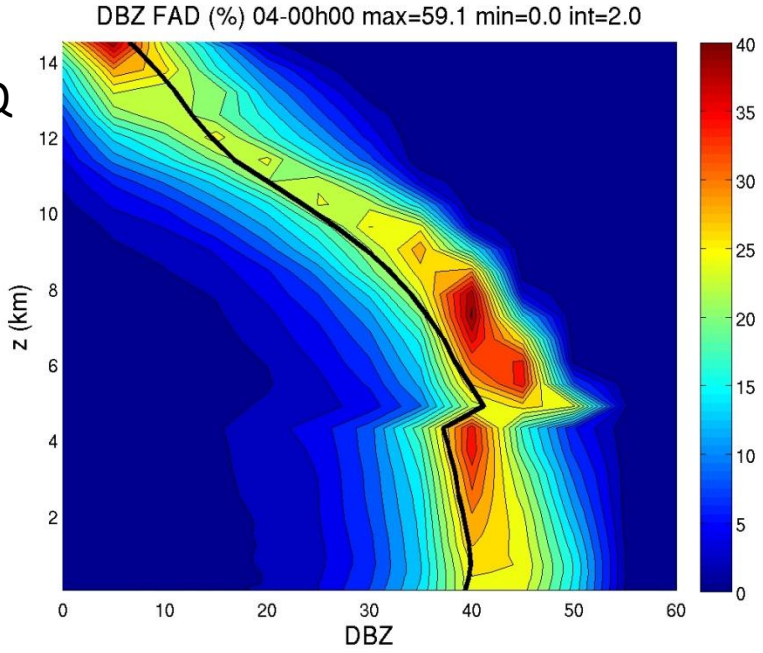
NR

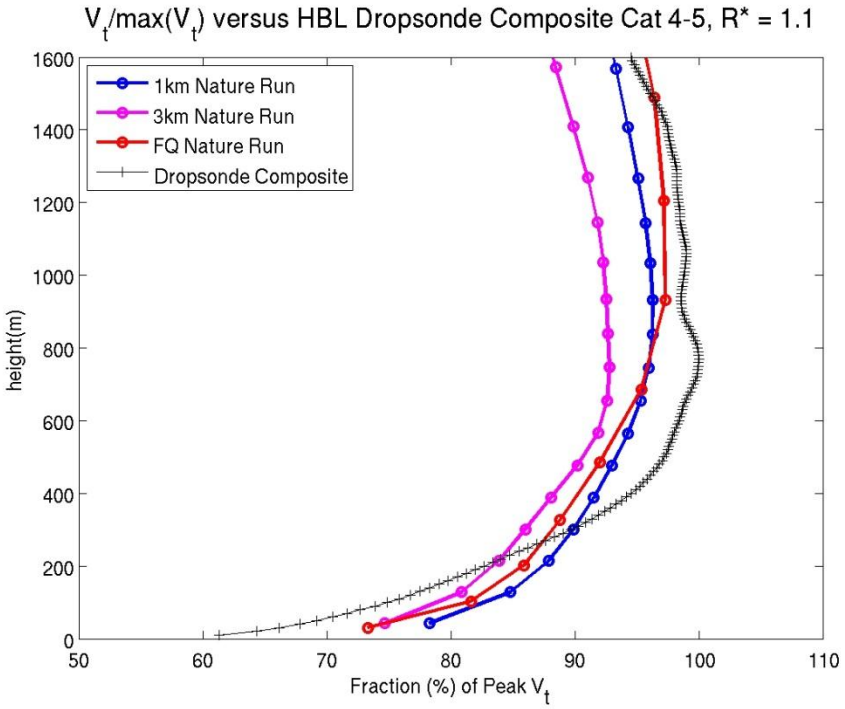

DBZ FAD (%) 05-00h00 max=37.2 min=0.0 int=2.0
z (km)
DBZ

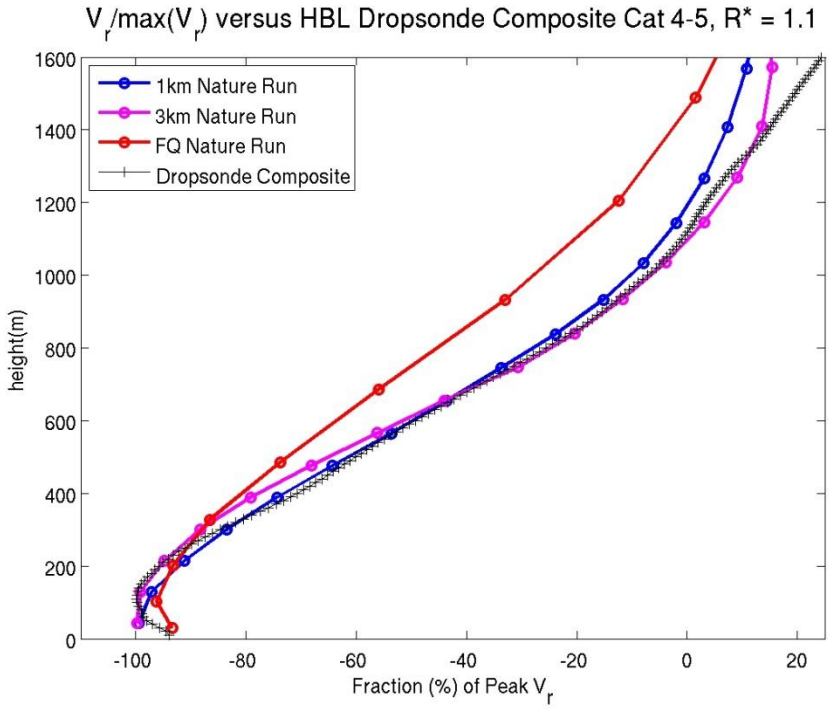
3km


DBZ FAD (%) 04-06h00 max=25.0 min=0.0 int=2.0
z (km)
DBZ

FQ


DBZ FAD (%) 04-00h00 max=59.1 min=0.0 int=2.0
z (km)
DBZ


V_t/max(V_t) versus HBL Dropsonde Composite Cat 4-5, R* = 1.1
1km Nature Run
3km Nature Run
FQ Nature Run
Dropsonde Composite
height(m)
Fraction (%) of Peak V_t
0
200
400
600
800
1000
1200
1400
1600
50
60
70
80
90
100
110


V_r/max(V_r) versus HBL Dropsonde Composite Cat 4-5, R* = 1.1
1km Nature Run
3km Nature Run
FQ Nature Run
Dropsonde Composite
height(m)
Fraction (%) of Peak V_r
0
200
400
600
800
1000
1200
1400
1600
-100
-80
-60
-40
-20
0
20

…Summary, continued:

Comparisons between 1 km Nature Run, 3km Nature Run, and FQ Nature Run suggest that:

- 3km to 1km resolution change leads to significant improvements in inner-core size, structure, and eyewall slope, and evolution.

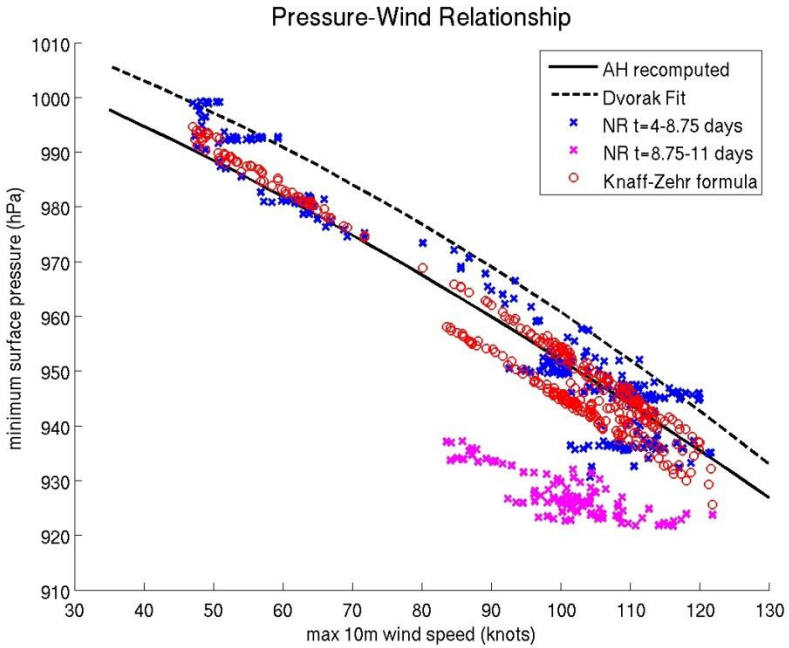
- Improved reflectivity distribution is due more to microphysics than resolution.

- Boundary layer profiles are not improved by horizontal resolution, and only slightly by improved by increased vertical resolution:

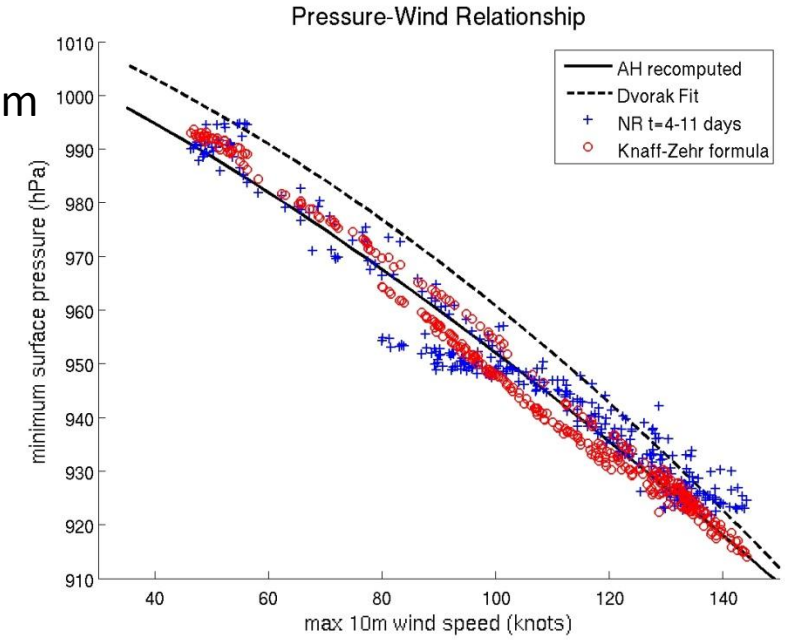
  → profiles are strongly controlled by PBL scheme

  → probably also explains very similar pressure-wind relationships

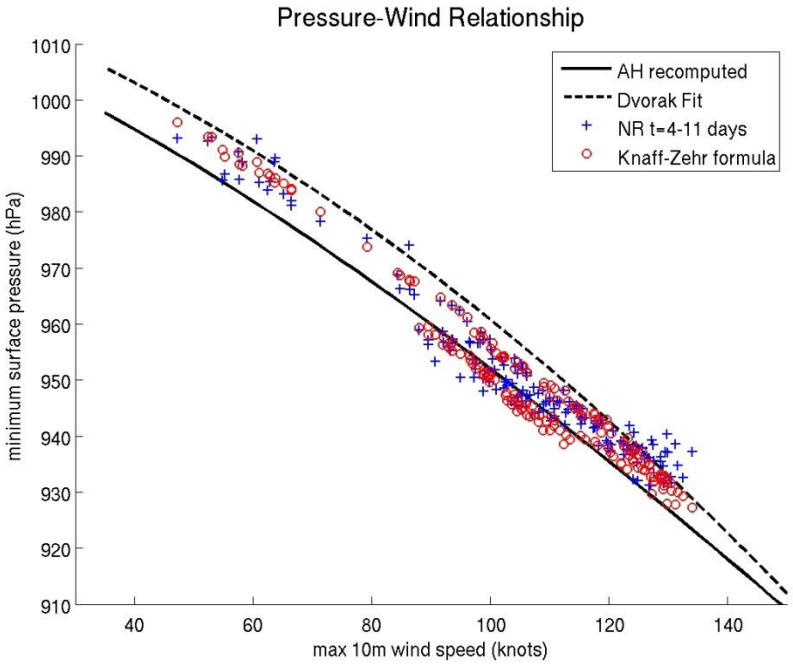
NR


Pressure-Wind Relationship
AH recomputed
Dvorak Fit
NR t=4-8.75 days
NR t=8.75-11 days
Knaff-Zehr formula
minimum surface pressure (hPa)
max 10m wind speed (knots)

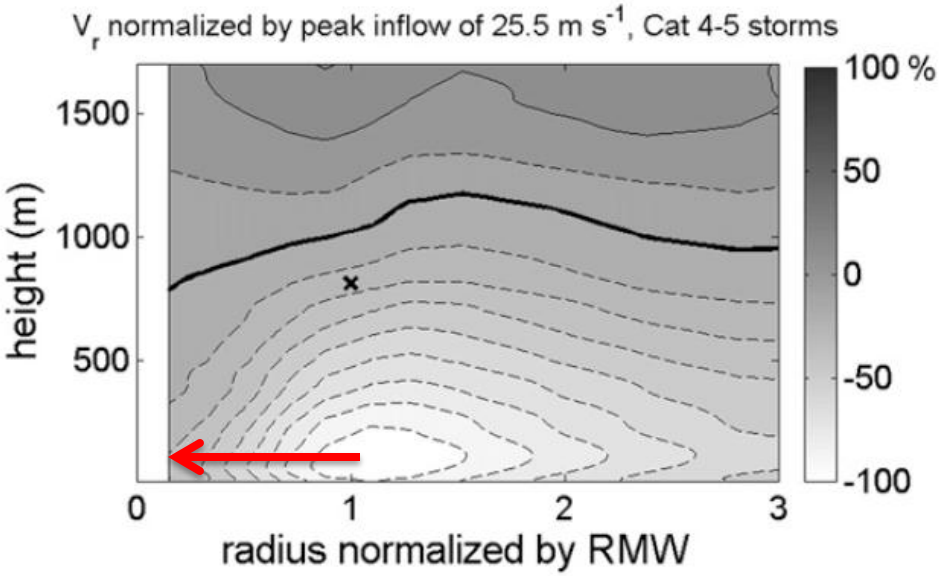
3km

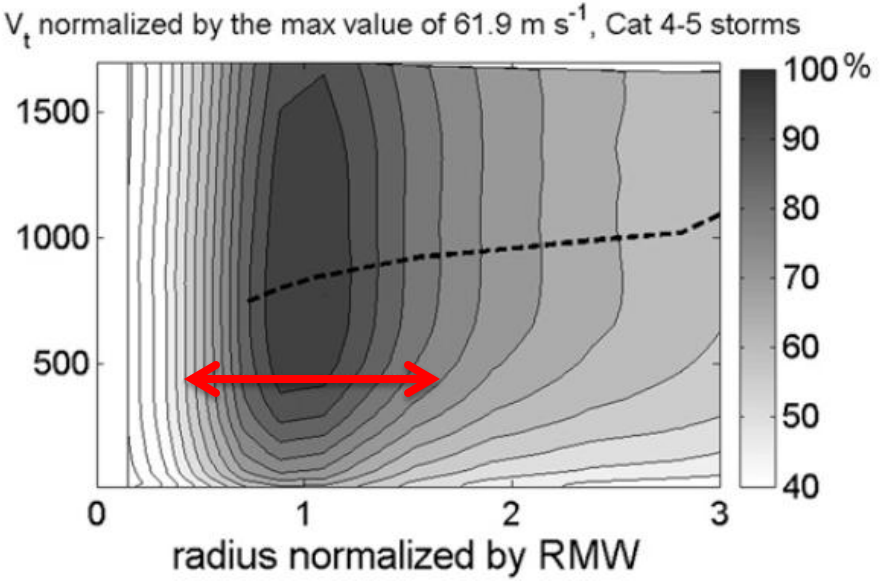

Pressure-Wind Relationship
AH recomputed
Dvorak Fit
NR t=4-11 days
Knaff-Zehr formula
minimum surface pressure (hPa)
max 10m wind speed (knots)

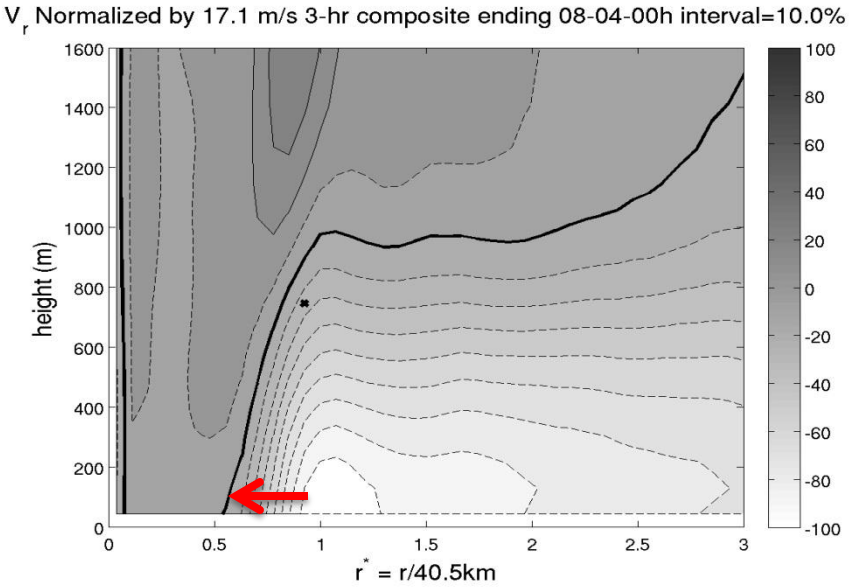
FQ

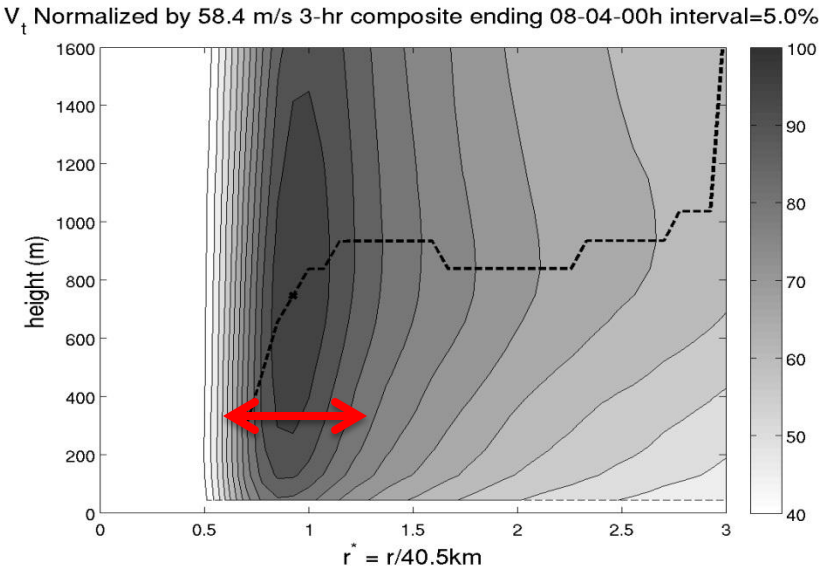

Pressure-Wind Relationship
AH recomputed
Dvorak Fit
NR t=4-11 days
Knaff-Zehr formula
minimum surface pressure (hPa)
max 10m wind speed (knots)

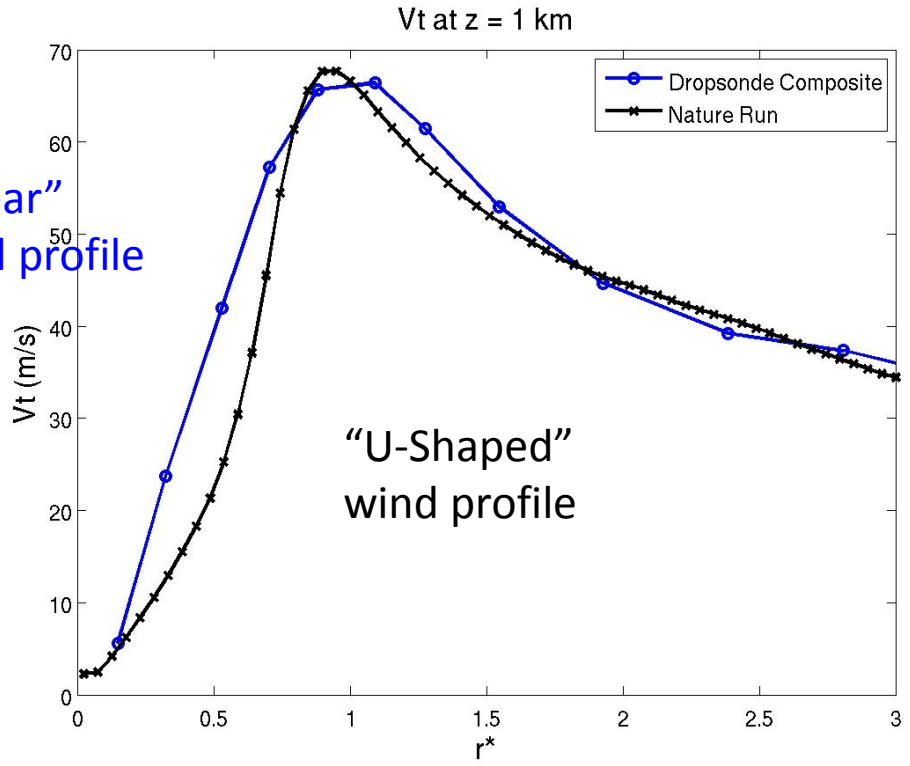
Composite boundary layer wind fields from thousands of dropsondes: Jun Zhang et al. (2011, MWR)





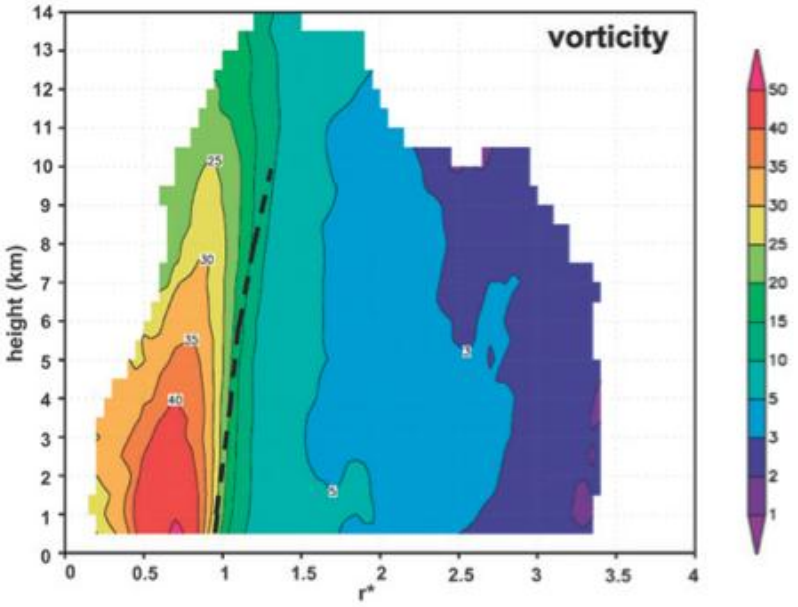






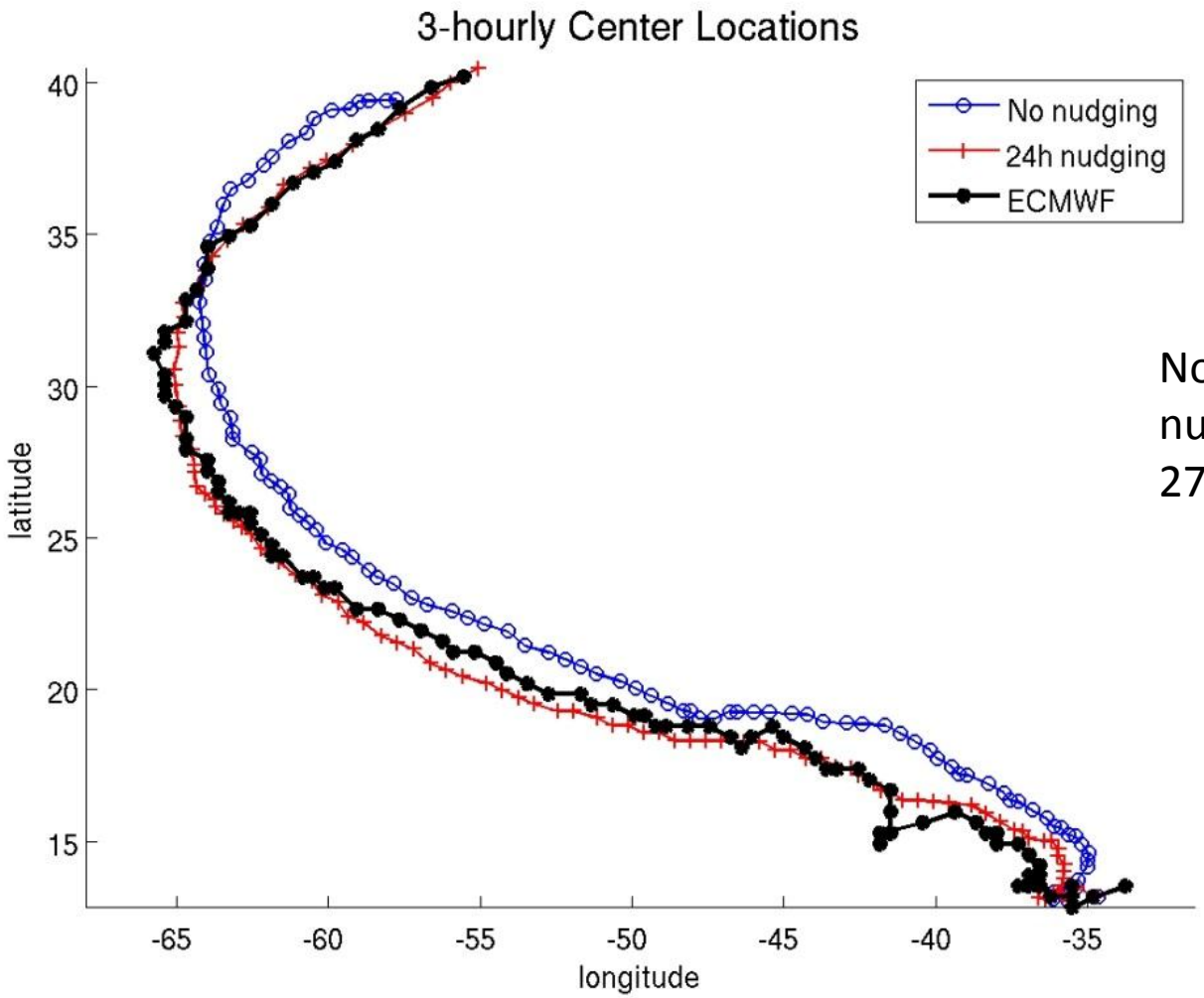
"linear" wind profile

"U-Shaped" wind profile

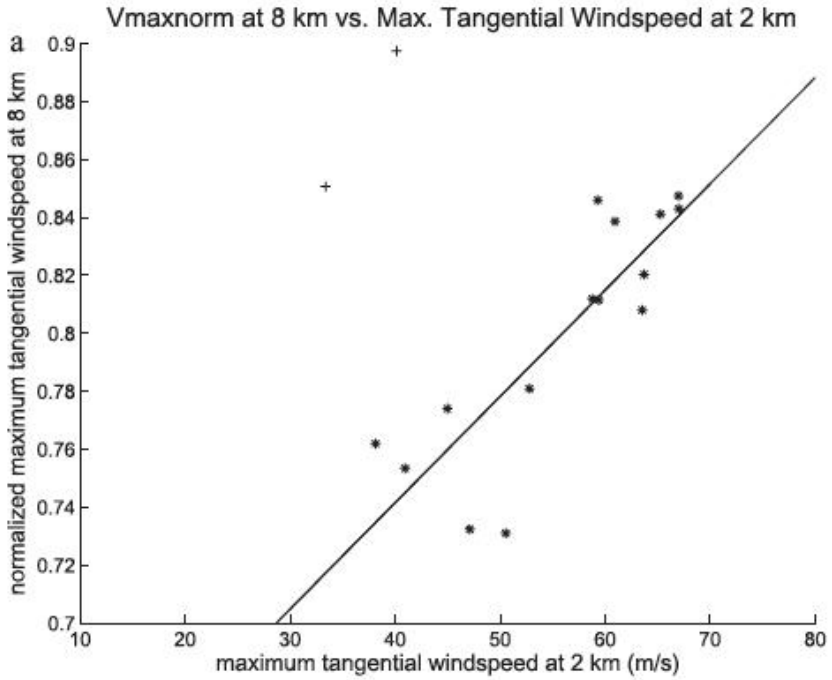


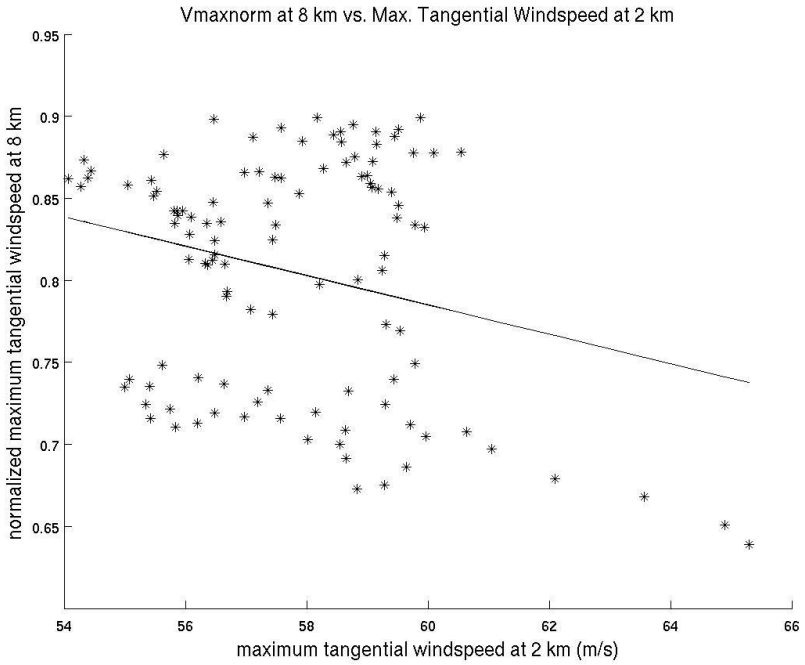
Rogers et al. (2012) Doppler wind profiles composite suggest typical wind profile *should* be U-shaped

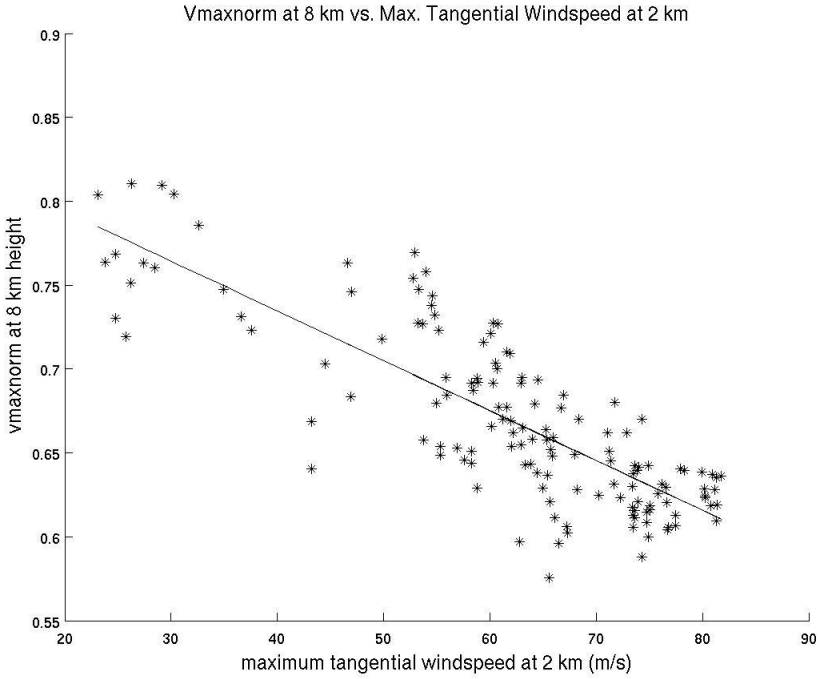
- “Nudging” on the 27 km grid to keep the WRF track as close as possible to the ECMWF track

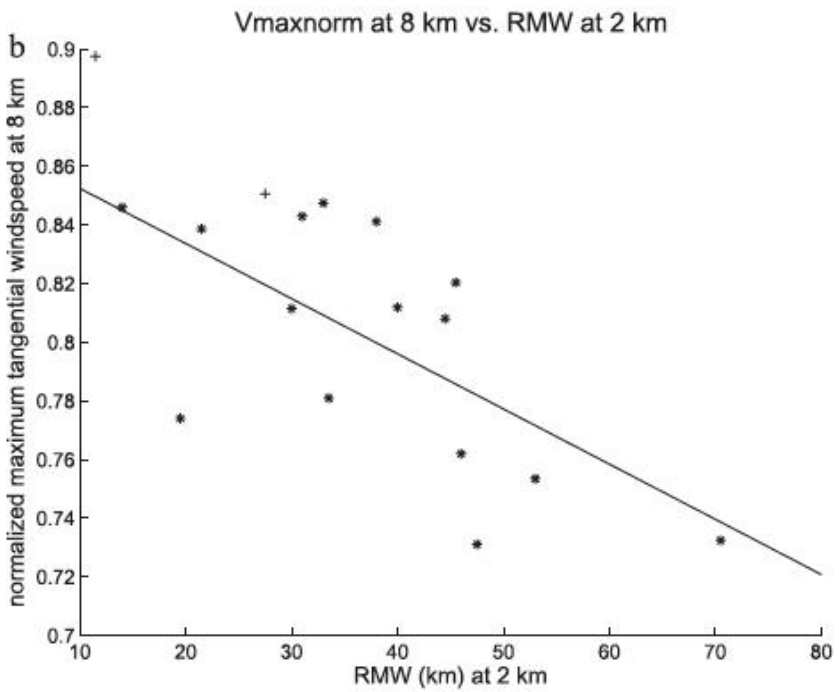


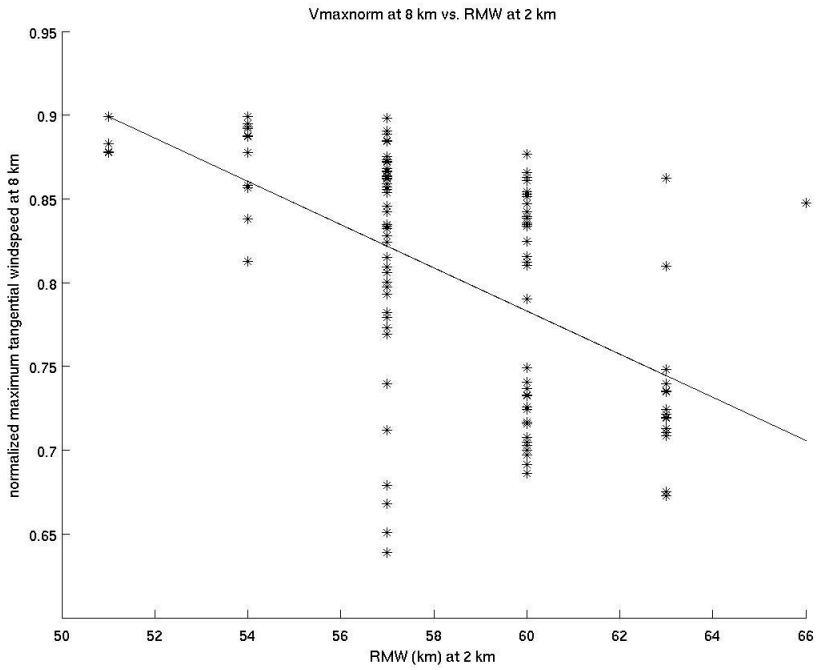
No-nudging versus nudging tests with 27 km domain only

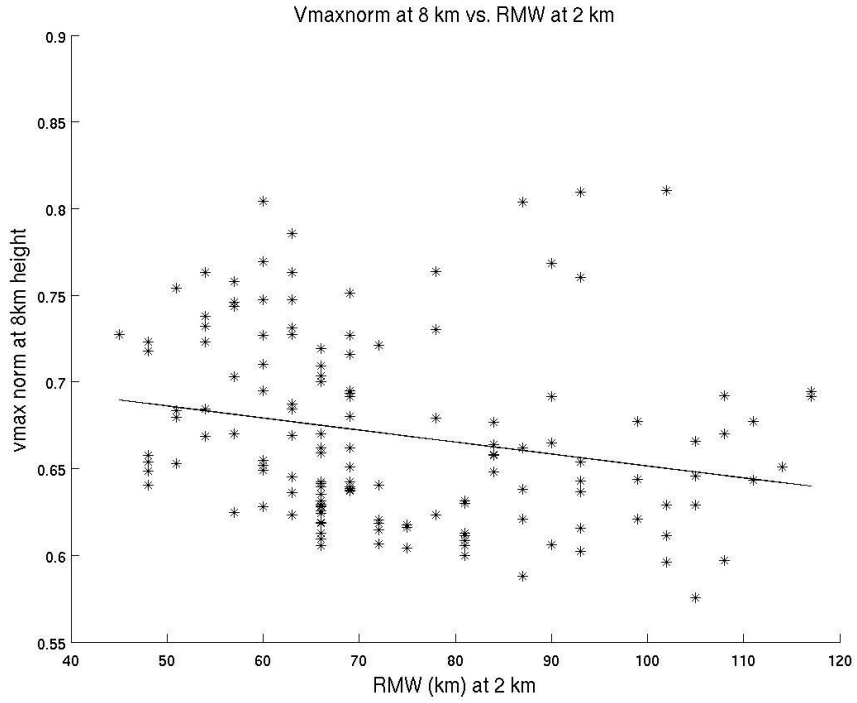

a
Vmaxnorm at 8 km vs. Max. Tangential Windspeed at 2 km
normalized maximum tangential windspeed at 8 km
maximum tangential windspeed at 2 km (m/s)
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
10
20
30
40
50
60
70
80


Vmaxnorm at 8 km vs. Max. Tangential Windspeed at 2 km
normalized maximum tangential windspeed at 8 km
maximum tangential windspeed at 2 km (m/s)
0.95
0.9
0.85
0.8
0.75
0.7
0.65
54
56
58
60
62
64
66


Vmaxnorm at 8 km vs. Max. Tangential Windspeed at 2 km
vmaxnorm at 8 km height
maximum tangential windspeed at 2 km (m/s)
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
20
30
40
50
60
70
80
90


b
Vmaxnorm at 8 km vs. RMW at 2 km
normalized maximum tangential windspeed at 8 km
RMW (km) at 2 km
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
10
20
30
40
50
60
70
80


Vmaxnorm at 8 km vs. RMW at 2 km
normalized maximum tangential windspeed at 8 km
RMW (km) at 2 km
0.95
0.9
0.85
0.8
0.75
0.7
0.65
50
52
54
56
58
60
62
64
66


Vmaxnorm at 8 km vs. RMW at 2 km
vmax norm at 8km height
RMW (km) at 2 km
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
40
50
60
70
80
90
100
110
120