Coincident Observations with QuikSCAT and ASCAT of the Effects of Rain-Induced Sea Surface Stress During Hurricane Ike

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2009 OVWST – Boulder, CO – 18-May

Studies of Interest:

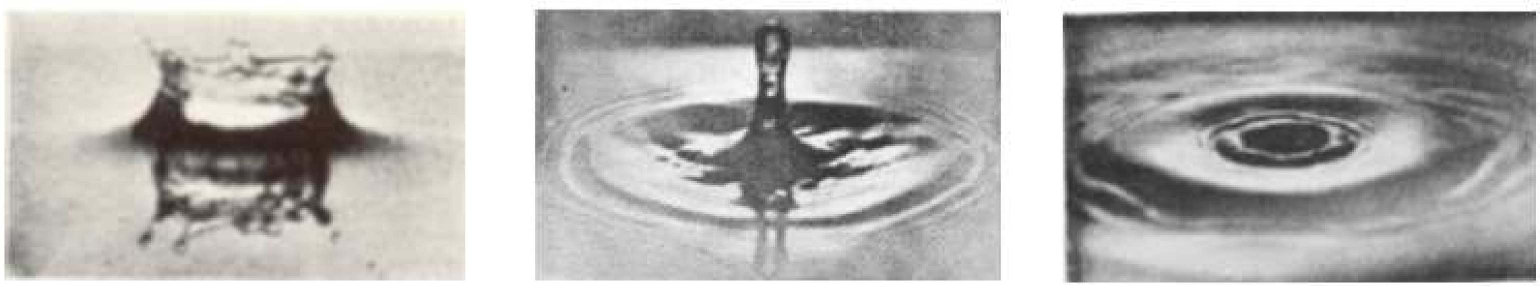
USING the *QuikSCAT Scatterometer and NEXRAD Measurements* of the 3-D Rain Volume:

1. To measure the effect of rain impacts on total sea surface roughness (Ku-band NRCS), *as a function rain rate, wind speed, polarization and azimuth look direction*

2. Develop a model for the change (increase or decrease) of the surface normalized radar cross section (NRCS for Ku-band) as a function of rainrate, wind speed, etc.

3. Interpret the results in terms of the interaction between wind waves and the splash products of rain impacts (ring waves, crowns and stalks; Sea Spray ?)

From Contreras, et al, “Ku-band ocean backscatter during rain ….”
J. Geophys. Res., May 2003



(a) Crater and Crown (b) Stalk (c) Ring–waves

Figure 1: Splash products when a raindrop falls onto a water surface. The figures are reproductions of photographs from “Worthington”, [1963]

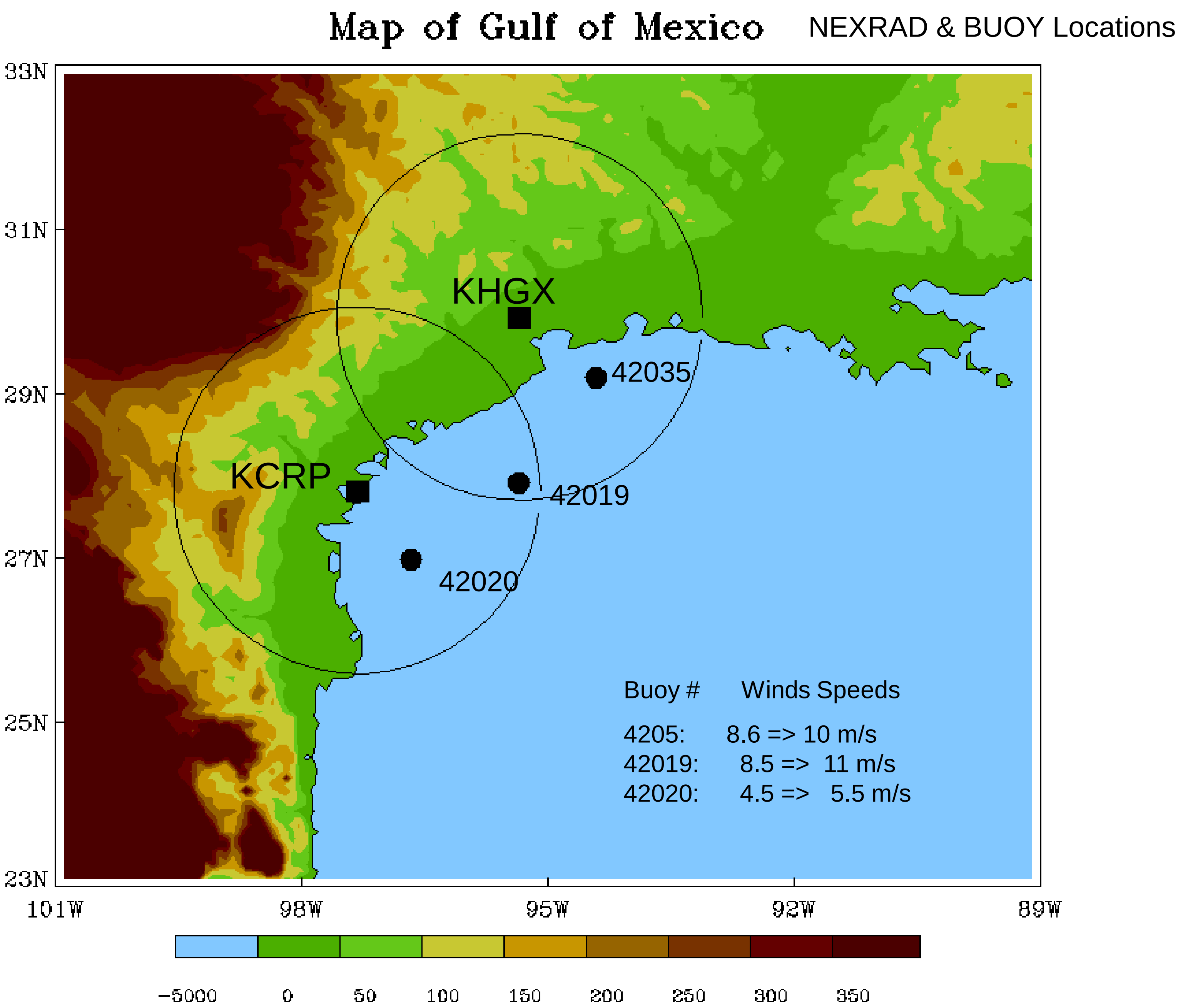
<u>HOWEVER WHEN WIND SPEEDS ARE COMPARABLE TO AND EXCEED THE RAINDROP FALL VELOCITY, THE SITUATION IS DRASTICALLY DIFFERENT</u>

DATA:

a) QuikSCAT Level 2A NRCS data, H-pol and V-pol

b) Simultaneous NEXRAD 3-D Volume
Reflectivity (S-band) within scatterometer beam

c) Surface winds from NOAA Hurricane Research
Division Analysis and buoys


Map of Gulf of Mexico
NEXRAD & BUOY Locations
33N
31N
29N
27N
25N
23N
101W
98W
95W
92W
89W
KHGX
KCRP
42035
42019
42020
Buoy #
Winds Speeds
4205: 8.6 => 10 m/s
42019: 8.5 => 11 m/s
42020: 4.5 => 5.5 m/s
-5000
0
50
100
150
200
250
300
350

Electromagnetic Model of the NRCS (σ_{ax}) Measured by the SeaWinds Scatterometer and Rain Impact NRCS, σ_{rn0}

Use of "x" subscript below will represent either "h" or "v" polarization

σ_{ax} = Total measured NRCS at Receiver; Sum of Contributions from Sea Surface and Rain Volume=L2A data

σ_{wdx} = sea surface radar cross section due to wind driven roughness alone (wind-NRCS)

σ_{rnx} = sea surface radar cross section due to rain impact roughness alone (rain-NRCS)

α_x(r)= attenuation, in nepers/m for each polarization, function of local volume rainrate or precipitation water content

σ_{ox} (r)= surface equivalent of volumetric rain RCS, = constant * Zx
(the radar reflectivity factor for Ku-band, Zx, varies with position, "r")

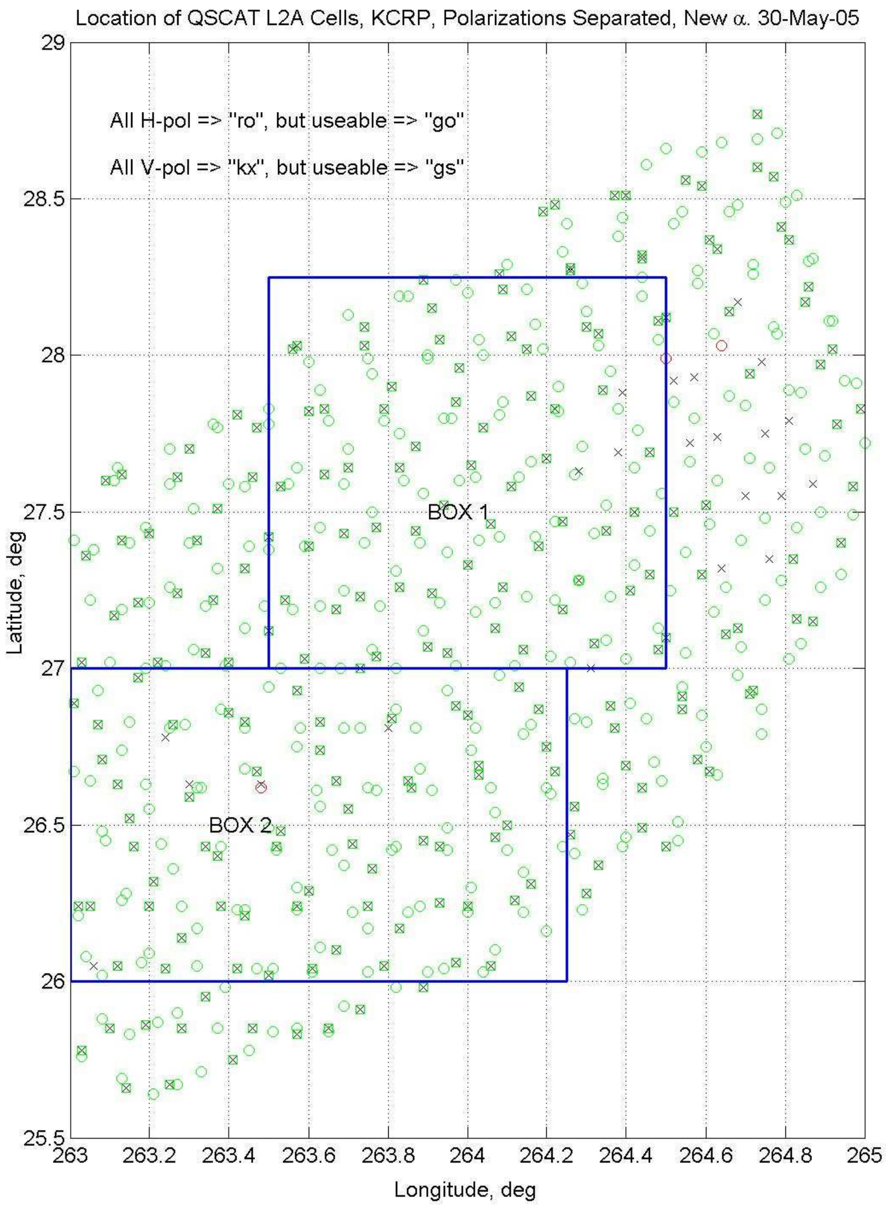
lenx=path length of radar beam for each polarization = len/Cos(θx)
(rain column height, over scatterometer footprint = len, $\theta_h=46^o$ & $\theta_v=54^o$)

$$\sigma_{ax} = \int_0^{lenx} \sigma_{ox}\, e^{-4\int_r^{lenx} \alpha_x(s)\,ds}\, dr + (\sigma_{wdx} + \sigma_{rnx}) * e^{-4\int_0^{lenx} \alpha_x(s)\,ds}$$

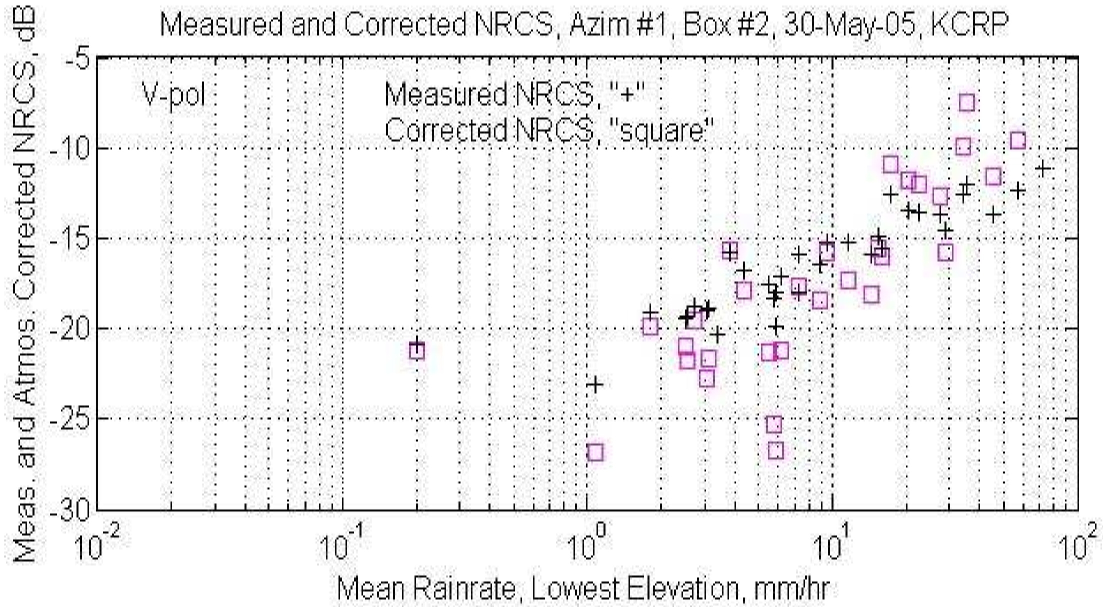
σ_{rn0} = model function for the normalized radar cross section due to rain impact; depends on wind magnitude and rainrate

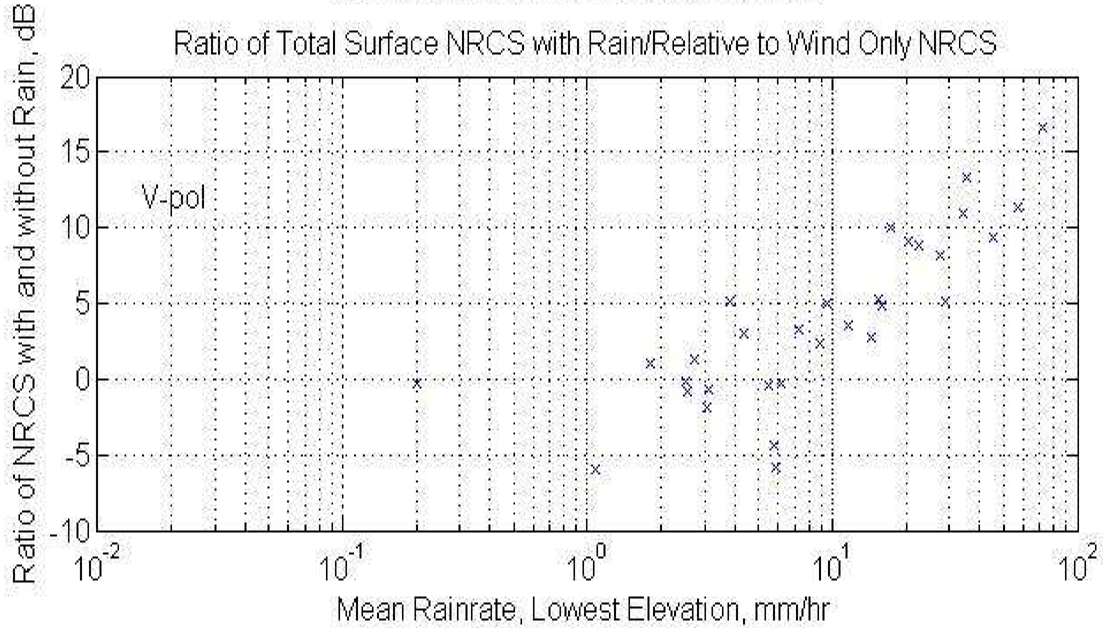
After solving for the total surface NRCS = $(\sigma_{wdx} + \sigma_{rnx})$ from a rain affected area, the wind-driven term alone is estimated from a nearby rain-free area: σ_{wdx}. Then their ratio σ_{rn0} is computed, producing:

$$\sigma_{rn0} = \left(\frac{\sigma_{wdx} + \sigma_{rnx}}{\sigma_{wdx}}\right)$$



The locations of the QScat L2A cells within a rain event near the KCRP NEXRAD. The usable H-pol and V-pol points are designated with green <u>circles</u> or green <u>squares</u> respectively. QuikSCAT cell size typically 30-by-40 km.



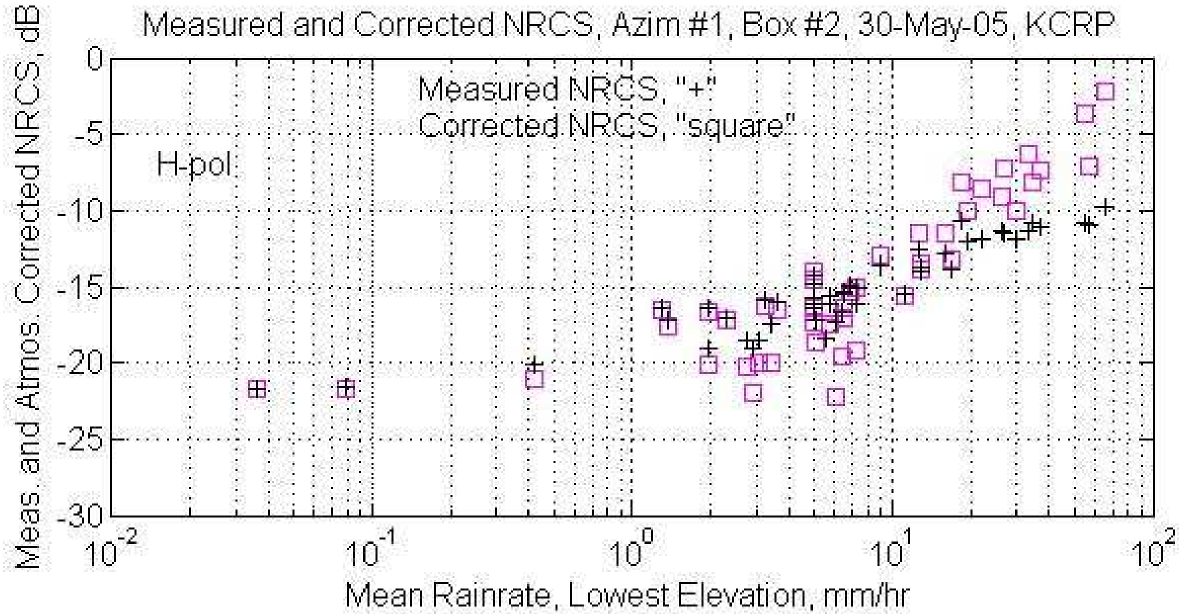


Box # 2, Azimuth Angle #1

Winds = 5 m/s

Upper plot: Uncorrected and corrected (for atmospheric rain) V-pol NRCS versus mean rainrate at each QSCAT cell.

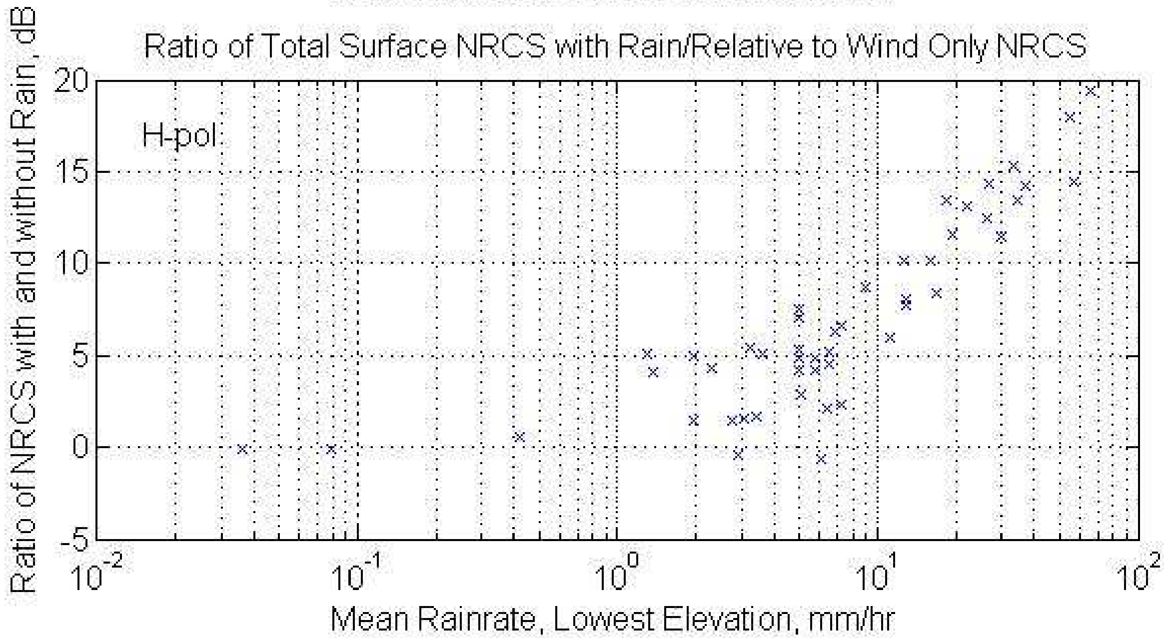
Lower Plot: Ratio of total surface NRCS to wind-driven NRCS vs. rainrate.



Box # 2, Azimuth Angle #1

Winds = 5 m/s

Upper plot: Uncorrected and corrected (for atmospheric rain) H-pol NRCS versus mean rainrate at each QSCAT cell.

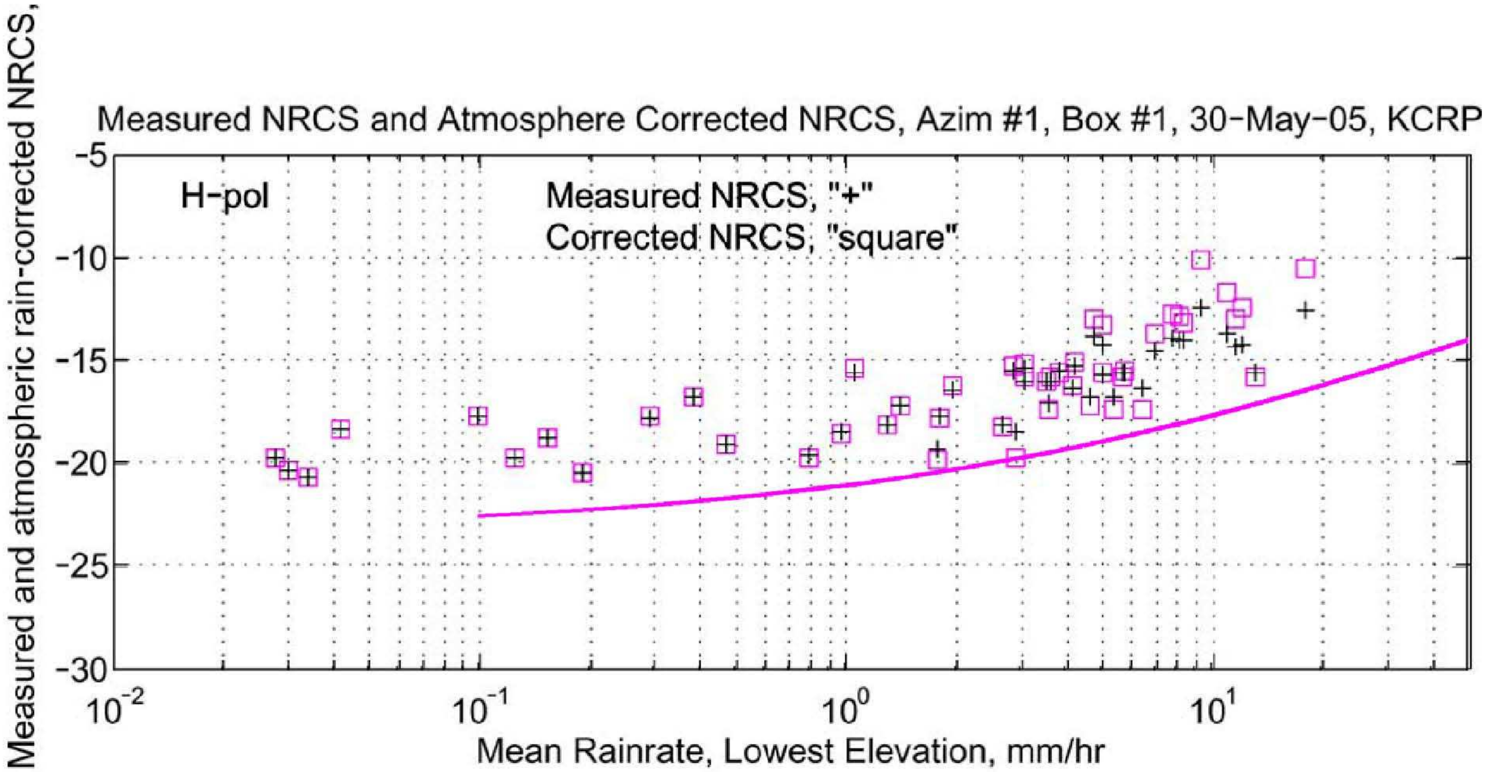


Lower Plot: Ratio of total surface NRCS to wind-driven NRCS vs. rainrate.

Results published in IEEE Transactions on Geoscience and Remote Sensing, October, 2008, D.E. Weissman and M.A. Bouassa

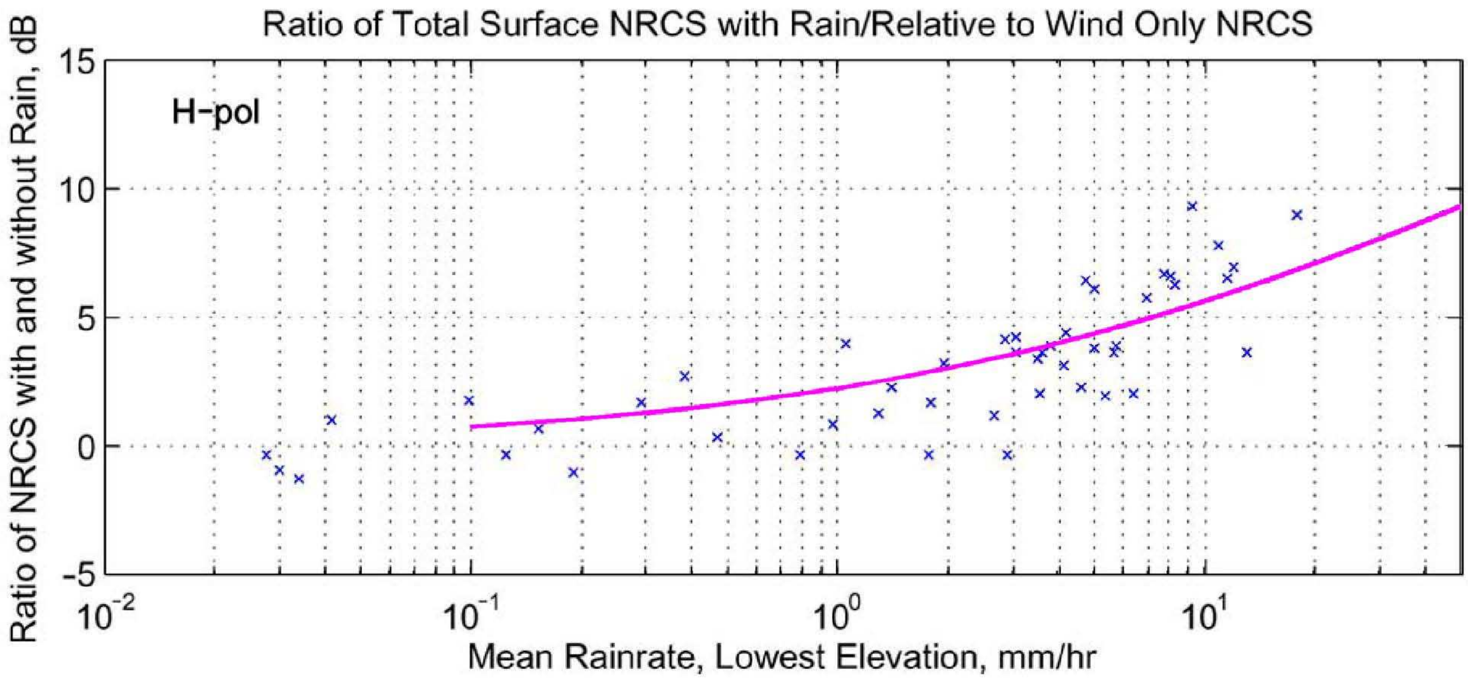
Personal communication from Drs. Piotr Sobieski and Christophe Craeye, of Catholic University de Louvain, Belgium *to show normalized radar cross section of rain impacting a wind driven sea*

Theoretical model by Sobieski and Craeye



H pol, U10=7m/s Weissman,Bourassa 2008, fig 9a

Theoretical model by Sobieski and Craeye



H pol, U10=7m/s   Weissman,Bourassa 2008, fig 9b

The theoretical results from Sobieski & Craeye is a validation of the 3-D rain reflectivity model and the attenuation and volume backscatter calculations

A fundamental study to: ".. establish a theory on the interaction between rain and water waves, based on momentum exchanges, and to assess its relative importance regarding the wave prediction models" was published by LeMehaute and Khangaonkar, J.Phys.Oceanogr, Dec. 1990

Rain horizontal momentum transfer (☺$_R$),

☺$_R$ = raindrop mass density x rainrate x horizontal wind speed

For example: for rainrate = 25 mm/hr and U_{10} = 25 m/s, the ratio

☺$_R$ / wind stress = 8.4 %

However this number gives no direct indication about the roughness properties to which Ku-band radar responds.

SPRAY STRESS REVISITED by E.L. Andreas
J.Phys.Oceanog. – June 2004

1. Spray stress increases to the 4^{th} power of wind speed
2. Spray can redistribute momentum at surface; the total stress can remain same, but consists of spray stress and interfacial stress.
3. The mass flux created by spray falls back to ocean and can suppress wave growth ("knocks down the waves")
It acts like rain at winds > 30 m/s to suppress short waves.
4. His drag coefficient saturates at 35 m/s and then decreases

Suggested View of Physical Dependence of

NRCS on Air-Sea Conditions:

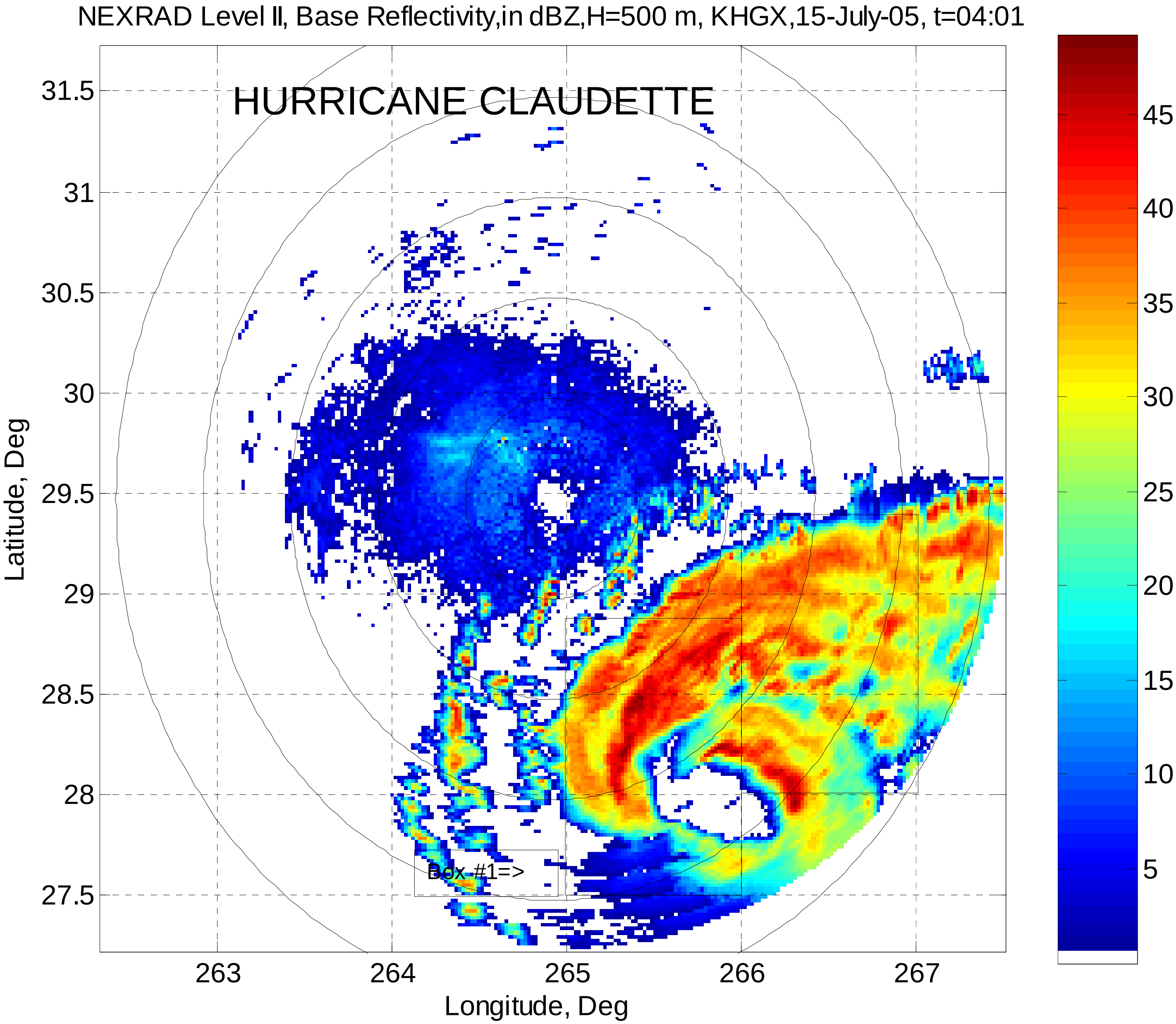
NRCS= SUM (Effects of wind-wave spectrum controlled by friction velocity (at low winds/no-rain, equilibrium spectrum,“Phillips, etc”, Bragg scattering, U < 15 m/s)

+Effects high wind spray stress and breaking (no-rain)

+ Effects of rain impact stress (low-to-moderate wind)

+ Effects of combination of high-wind sea & spray & rain

Wind: 17 m/s
@ 58 deg
at #42035
Buoy



Azim #2 =
305 deg

Azim # 1=205
deg

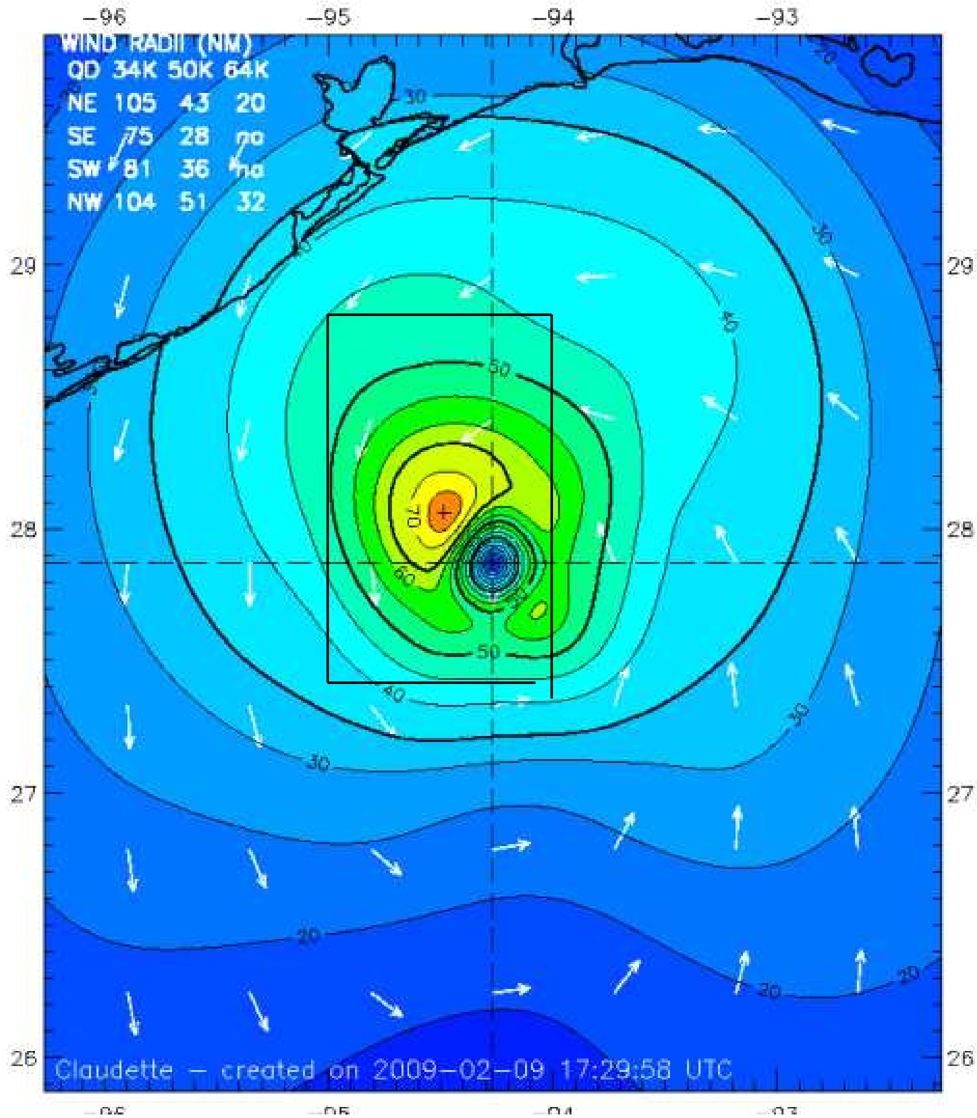
Hurricane Claudette 0400 UTC 15 JUL 2003

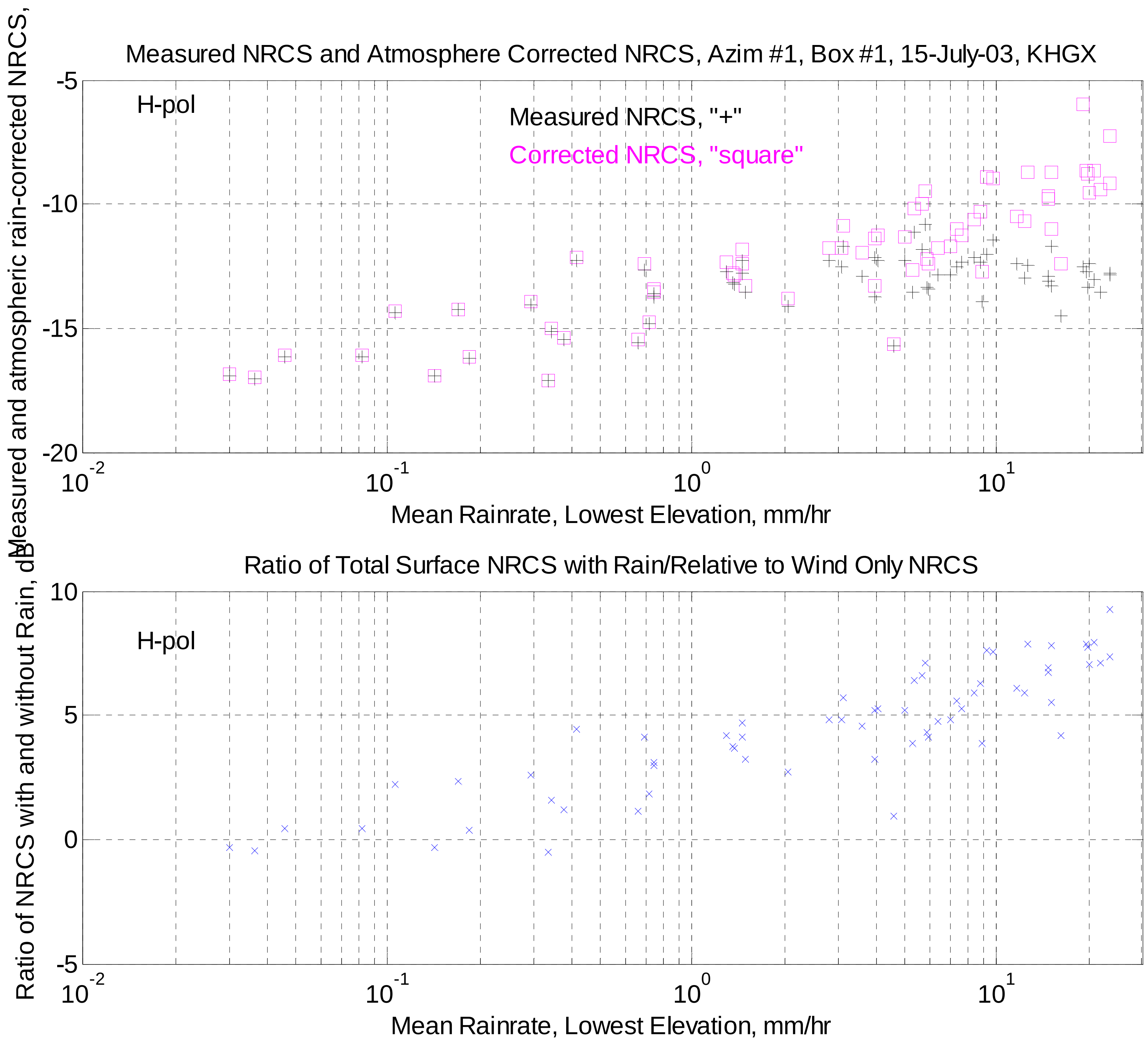
Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land

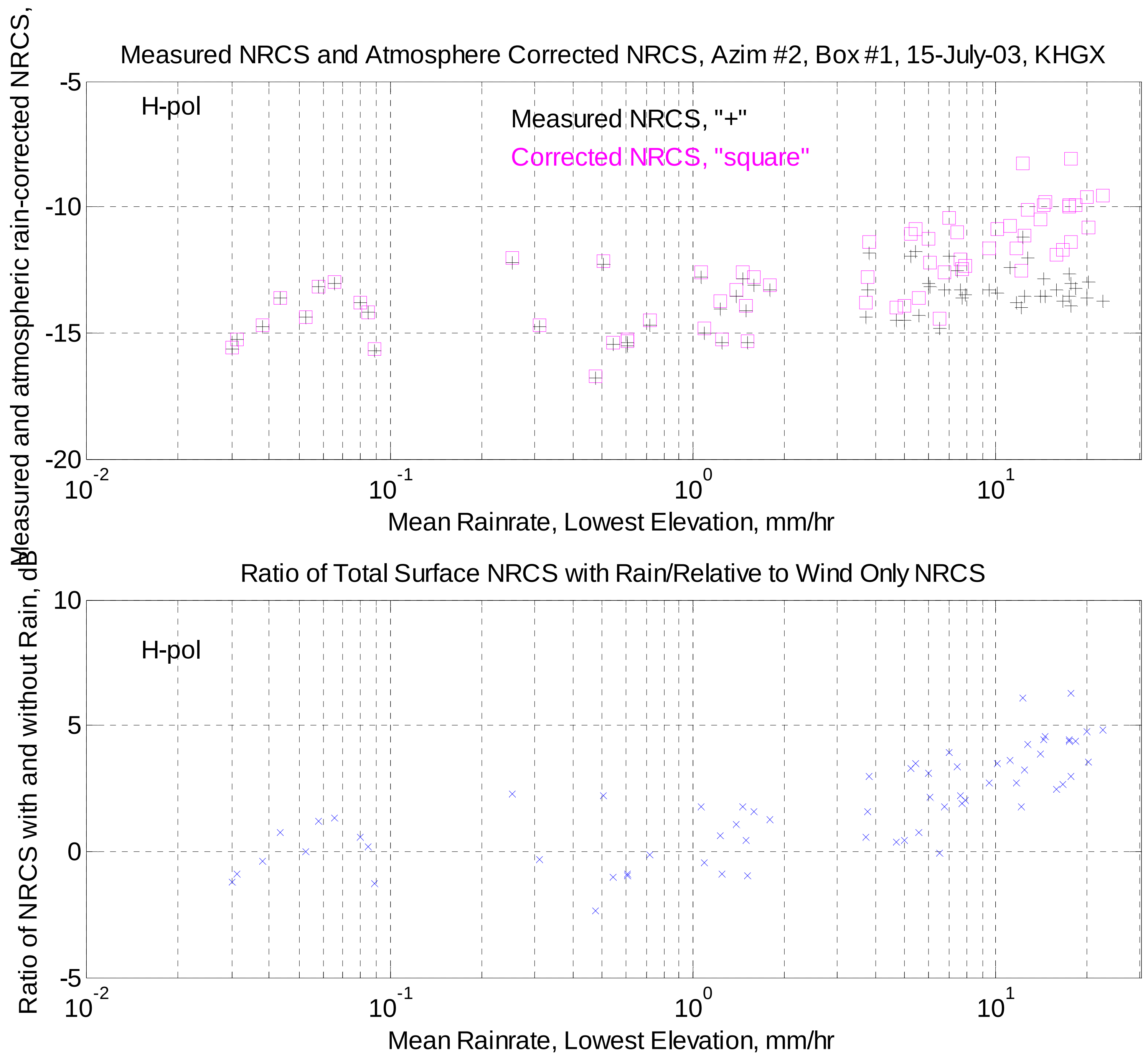
Analysis based on AFRC (SFMR-2007 adjusted) from 0019 - 0816 z; GOES_SWIR from 0402 - 0402 z
GPSSONDE_SFC from 0239 - 0818 z; GPSSONDE_WL150 from 0134 - 0818 z;
QSCAT from 0058 - 0100 z; MOORED_BUOY from 0039 - 0750 z;
CMAN from 0100 - 0800 z; METAR from 0025 - 0805 z;

0400 z position interpolated from 0354 Vortex; mslp = 989.0 mb

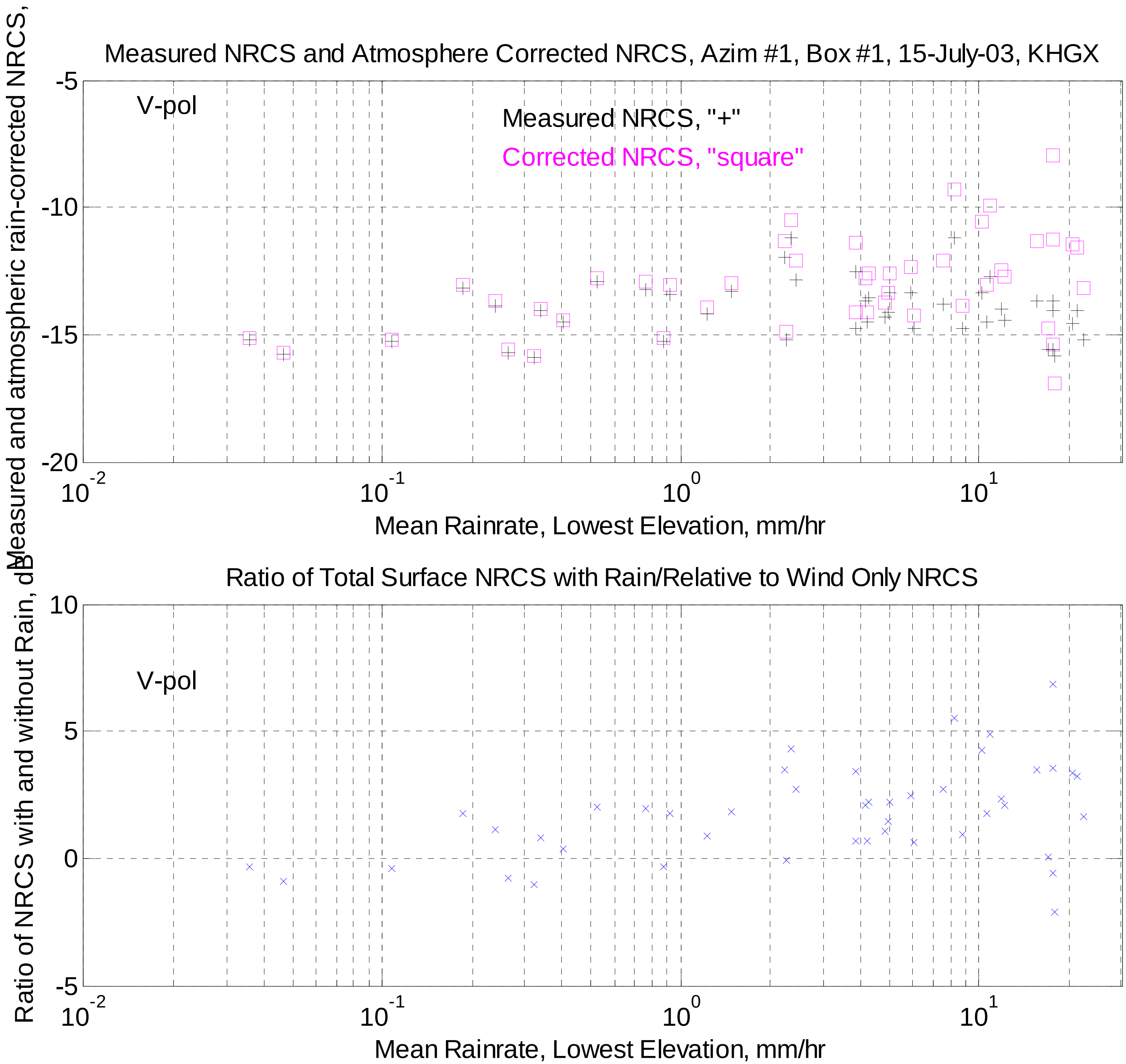




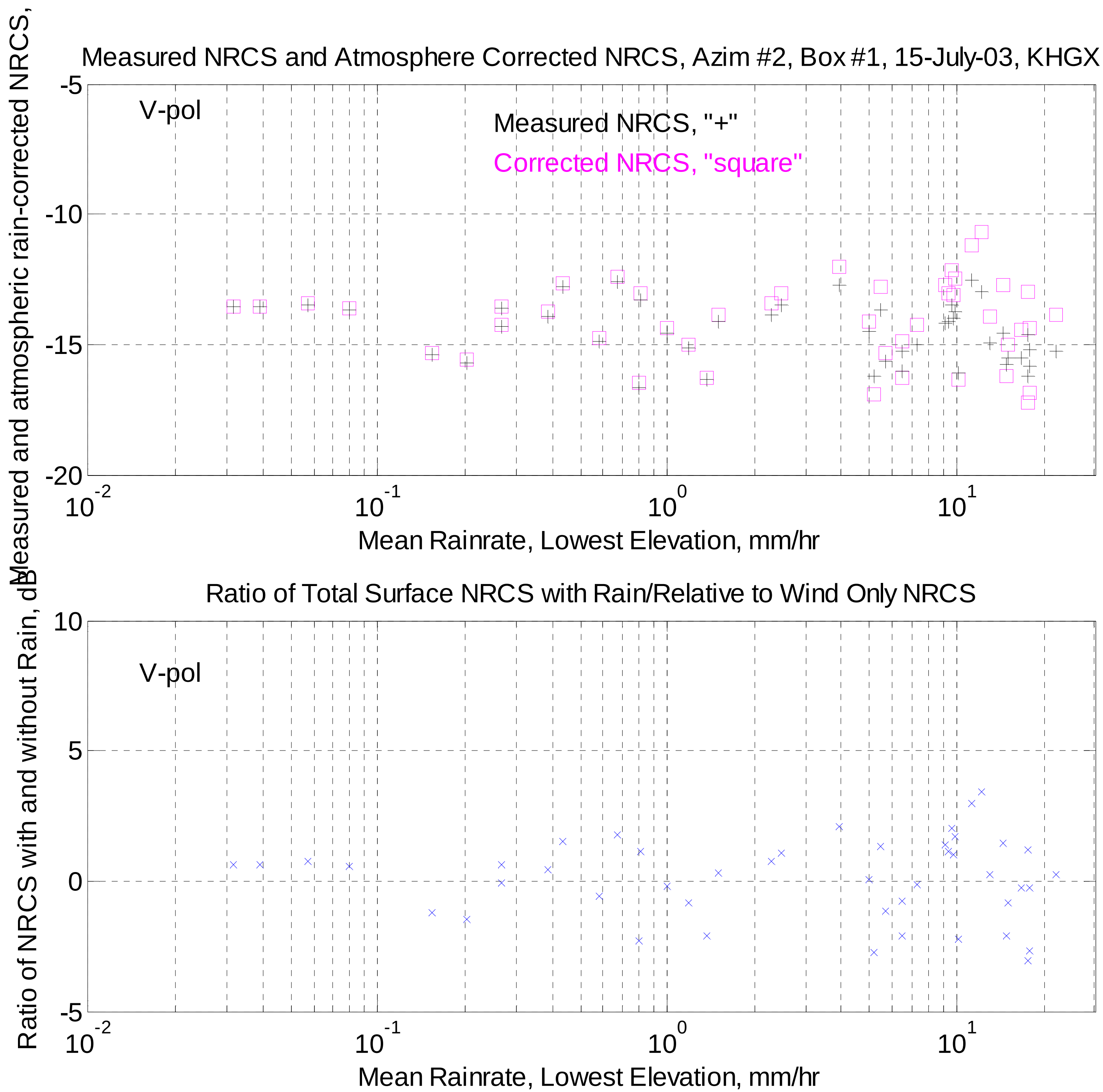
Measured NRCS and Atmosphere Corrected NRCS, Azim #1, Box #1, 15-July-03, KHGX
H-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
-5
-10
-15
-20
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr
Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
H-pol
Ratio of NRCS with and without Rain, dB
10
5
0
-5
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr



Measured NRCS and Atmosphere Corrected NRCS, Azim #2, Box #1, 15-July-03, KHGX
H-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS,
-5
-10
-15
-20
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr
Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
Ratio of NRCS with and without Rain, dB
H-pol
10
5
0
-5
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr



Measured NRCS and Atmosphere Corrected NRCS, Azim #1, Box #1, 15-July-03, KHGX
V-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
-5
-10
-15
-20
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr
Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
V-pol
Ratio of NRCS with and without Rain, dB
10
5
0
-5
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr



Measured NRCS and Atmosphere Corrected NRCS, Azim #2, Box #1, 15-July-03, KHGX
V-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
-5
-10
-15
-20
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr
Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
V-pol
Ratio of NRCS with and without Rain, dB
10
5
0
-5
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr

Summary for Hurricane Claudette:

The properties of the NRCS vs Rainrate:

For H-pol, there is a clear increase in NRCS with rainrate.

For V-pol, there is no clear increase on average, in NRCS, with increasing rainrate.

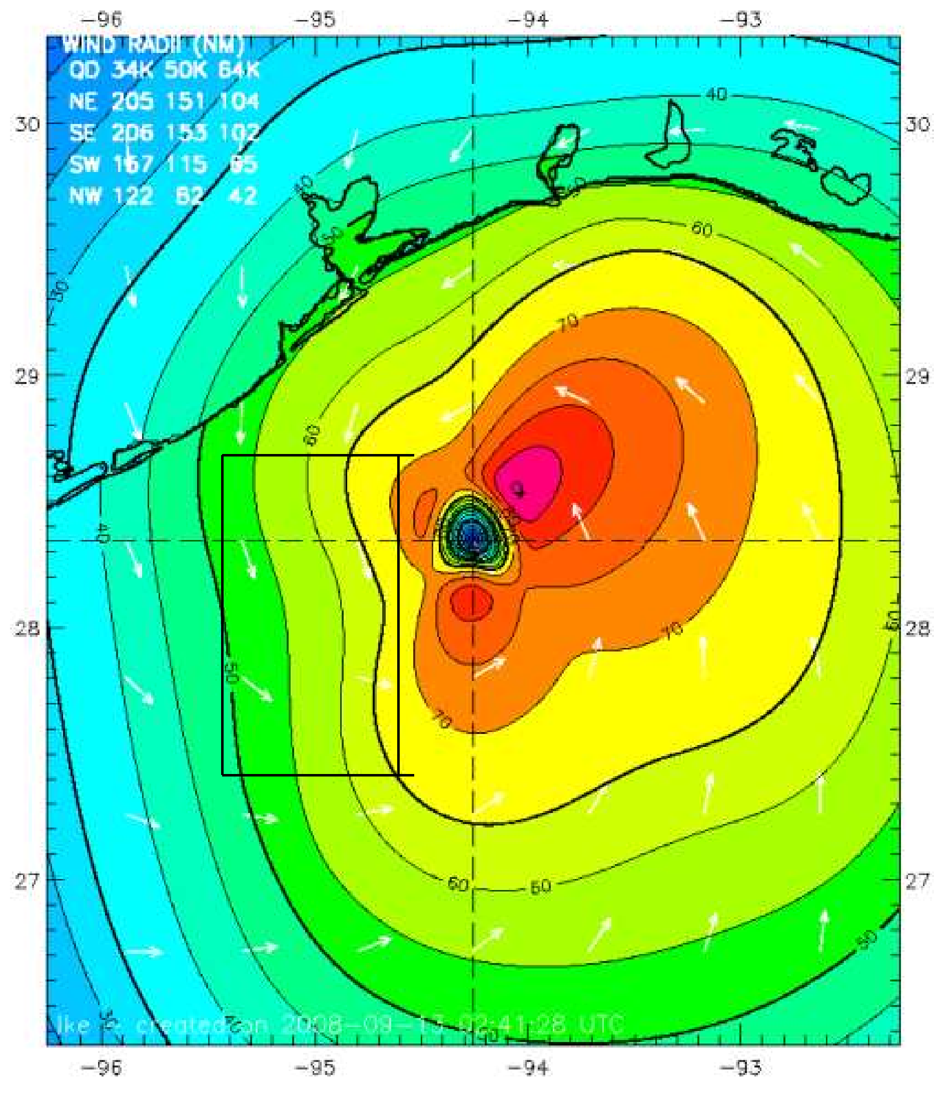
Hurricane Ike 0130 UTC 13 SEP 2008

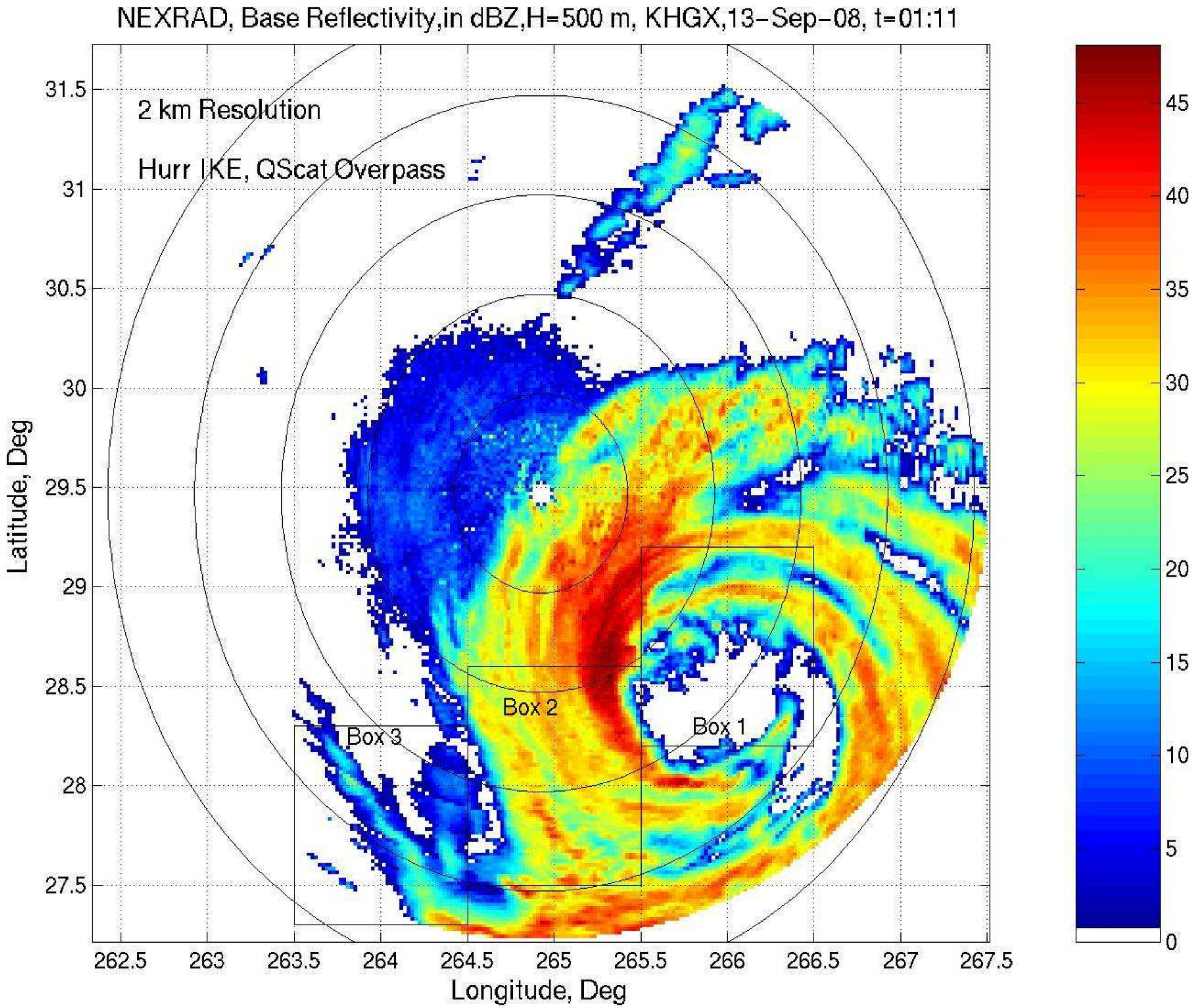
Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land

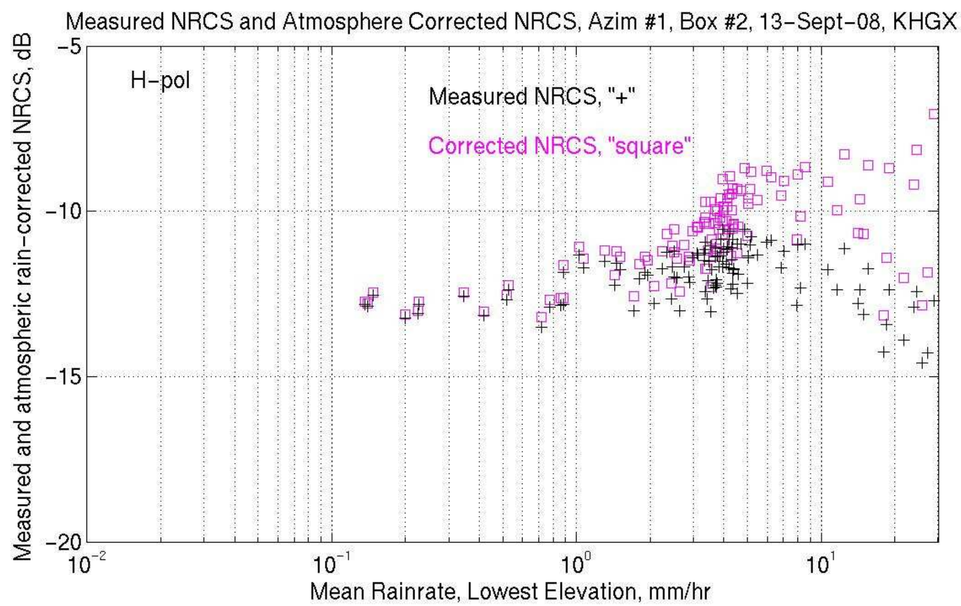
Analysis based on CMAN from 2009 - 0149 z; ASOS from 2004 - 0154 z; SFMR_AFRC from 0900 - 0156 z;
SHIP from 2000 - 0100 z; SFMR42 from 2220 - 0159 z;
FCMP_TOWER from 2005 - 0154 z; WEATHER_FLOW from 2000 - 0155 z;
GOES from 2202 - 2202 z; GPSSONDE_SFC from 2042 - 0155 z;
GPSSONDE_WL150 from 2042 - 0155 z; METAR from 2000 - 0155 z;
MOORED_BUOY from 2000 - 0149 z;

0130 z position interpolated from 0121 Estimator tool; mslp = 957.0 mb

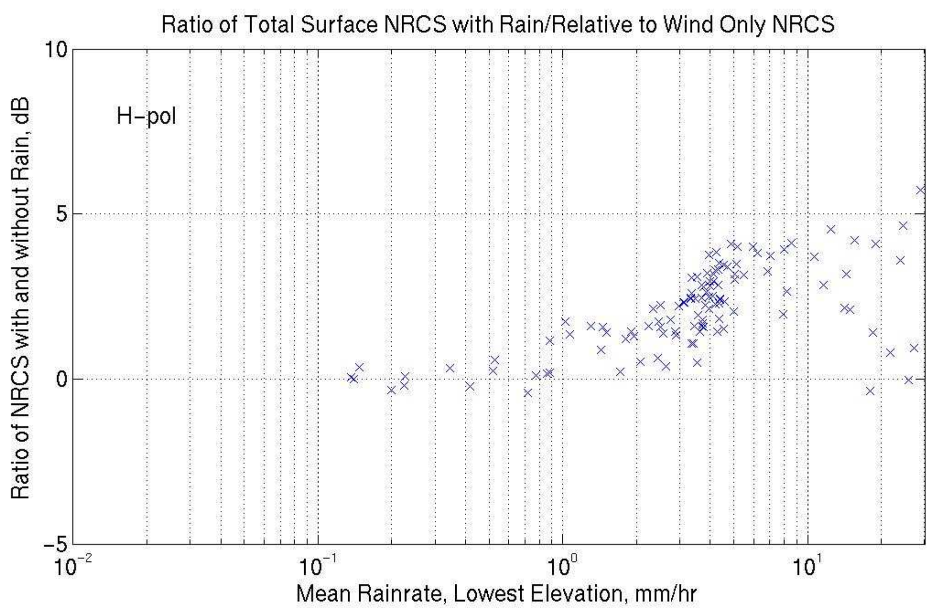




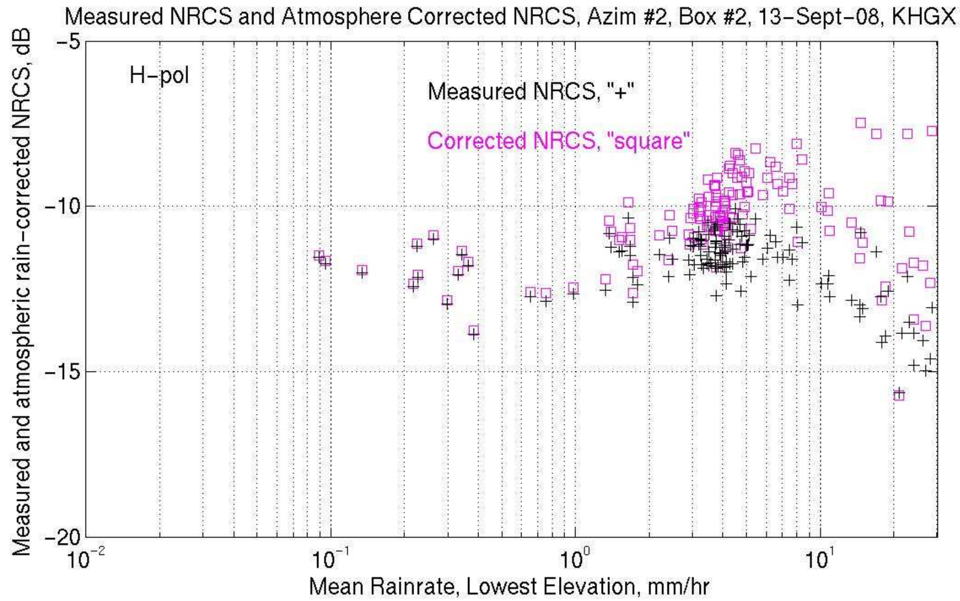
NEXRAD, Base Reflectivity,in dBZ,H=500 m, KHGX,13-Sep-08, t=01:11
2 km Resolution
Hurr IKE, QScat Overpass
Box 1
Box 2
Box 3
Latitude, Deg
Longitude, Deg
31.5
31
30.5
30
29.5
29
28.5
28
27.5
262.5
263
263.5
264
264.5
265
265.5
266
266.5
267
267.5
45
40
35
30
25
20
15
10
5
0

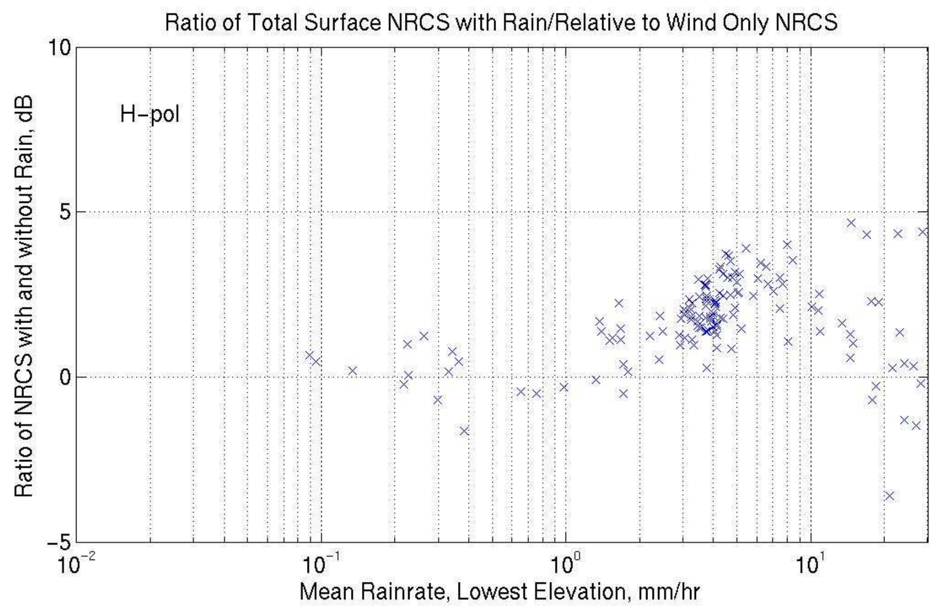


Measured NRCS and Atmosphere Corrected NRCS, Azim #1, Box #2, 13-Sept-08, KHGX
H-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
-5
-10
-15
-20
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr



Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
H-pol
Ratio of NRCS with and without Rain, dB
10
5
0
-5
10^{-2}
10^{-1}
10^{0}
10^{1}
Mean Rainrate, Lowest Elevation, mm/hr


Measured NRCS and Atmosphere Corrected NRCS, Azim #2, Box #2, 13-Sept-08, KHGX
H-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
Mean Rainrate, Lowest Elevation, mm/hr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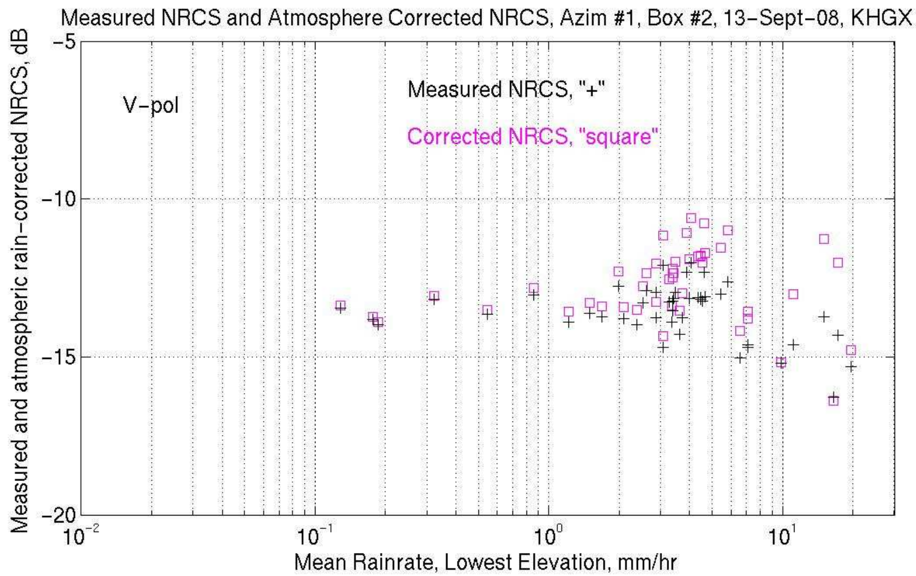
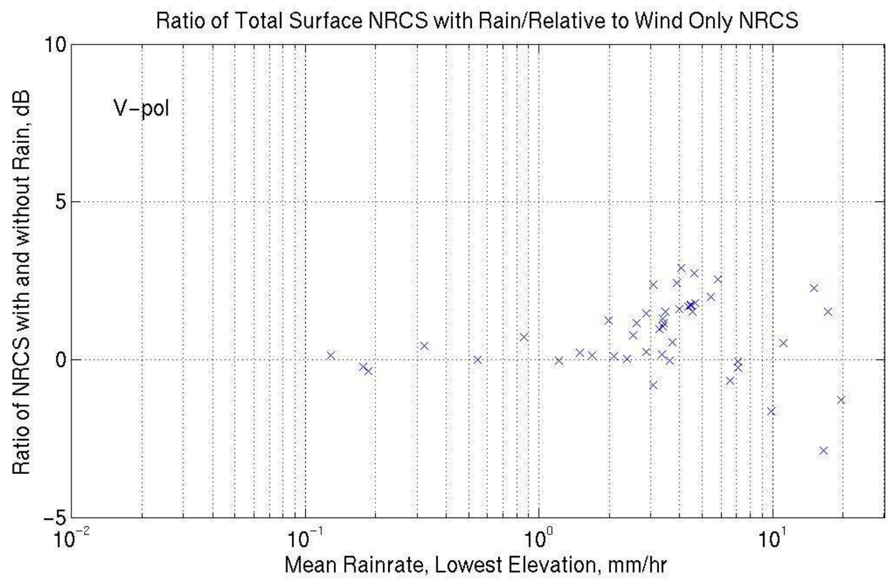
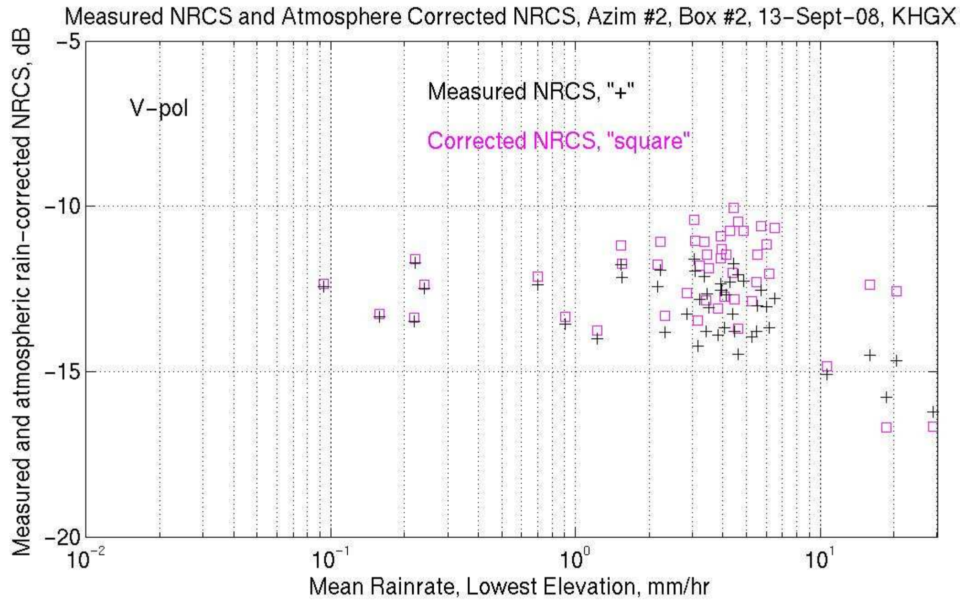
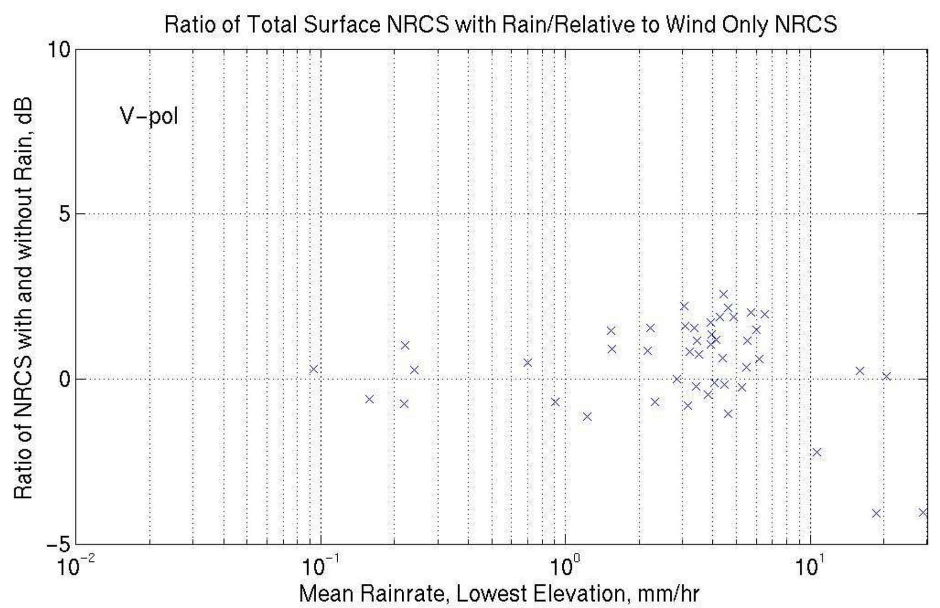
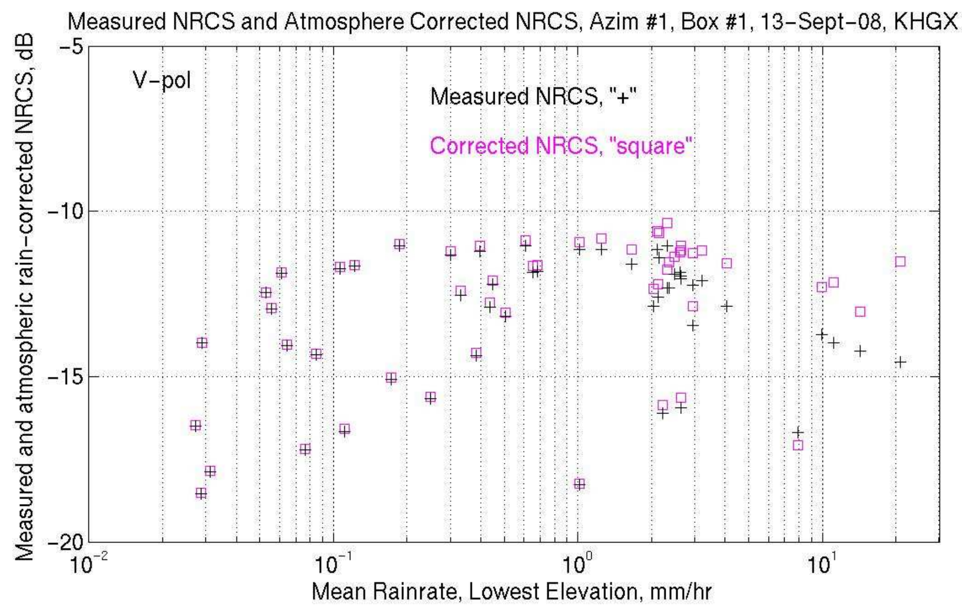
H-pol
Ratio of NRCS with and without Rain, dB
Mean Rainrate, Lowest Elevation, mm/hr

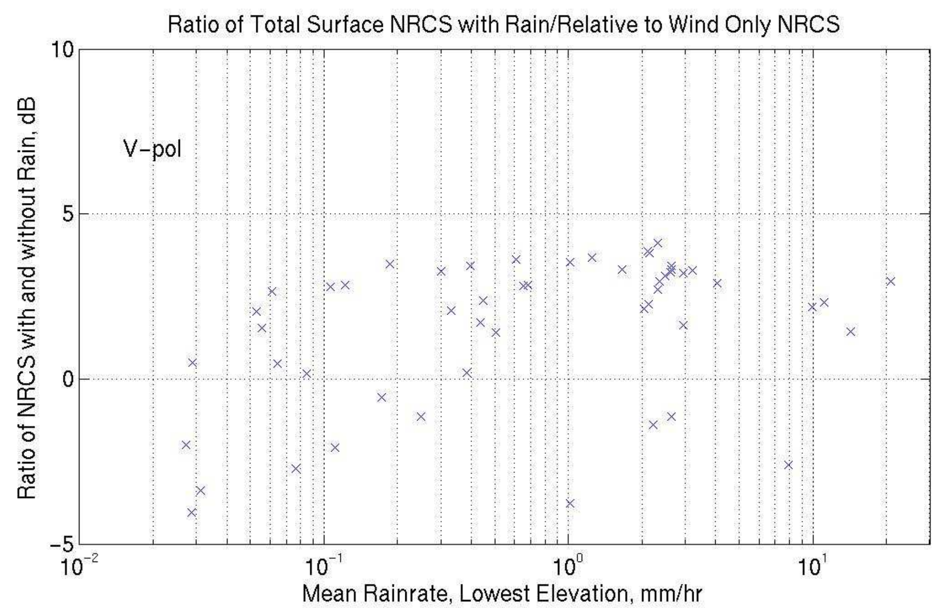

Measured NRCS and Atmosphere Corrected NRCS, Azim #1, Box #2, 13-Sept-08, KHGX
V-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
Mean Rainrate, Lowest Elevation, mm/hr


Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
V-pol
Ratio of NRCS with and without Rain, dB
Mean Rainrate, Lowest Elevation, mm/hr


Measured NRCS and Atmosphere Corrected NRCS, Azim #2, Box #2, 13-Sept-08, KHGX
Measured and atmospheric rain-corrected NRCS, dB
V-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Mean Rainrate, Lowest Elevation, mm/hr


Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
Ratio of NRCS with and without Rain, dB
V-pol
Mean Rainrate, Lowest Elevation, mm/hr


Measured NRCS and Atmosphere Corrected NRCS, Azim #1, Box #1, 13-Sept-08, KHGX
V-pol
Measured NRCS, "+"
Corrected NRCS, "square"
Measured and atmospheric rain-corrected NRCS, dB
Mean Rainrate, Lowest Elevation, mm/hr


Ratio of Total Surface NRCS with Rain/Relative to Wind Only NRCS
V-pol
Ratio of NRCS with and without Rain, dB
Mean Rainrate, Lowest Elevation, mm/hr

GENERAL SUMMARY

At low wind speeds (< 7 m/s), the changes in NRCS caused by rain roughness was very similar for both H-pol and V-pol

As the wind speed increases, and approaches the terminal velocity of gravity driven falling rain, the differences in NRCS for the two polarizations become progressively larger.

This indicates there is an interaction between the rain impact roughness products and the wind driven wave roughness. It appears that rain impacts produce new roughness characteristics that have a distinct and differential polarization response.

ASCAT Studies During Hurricane Ike

Will examine NRCS data at t=03:18 Z
Location in Gulf of Mexico, south of Houston

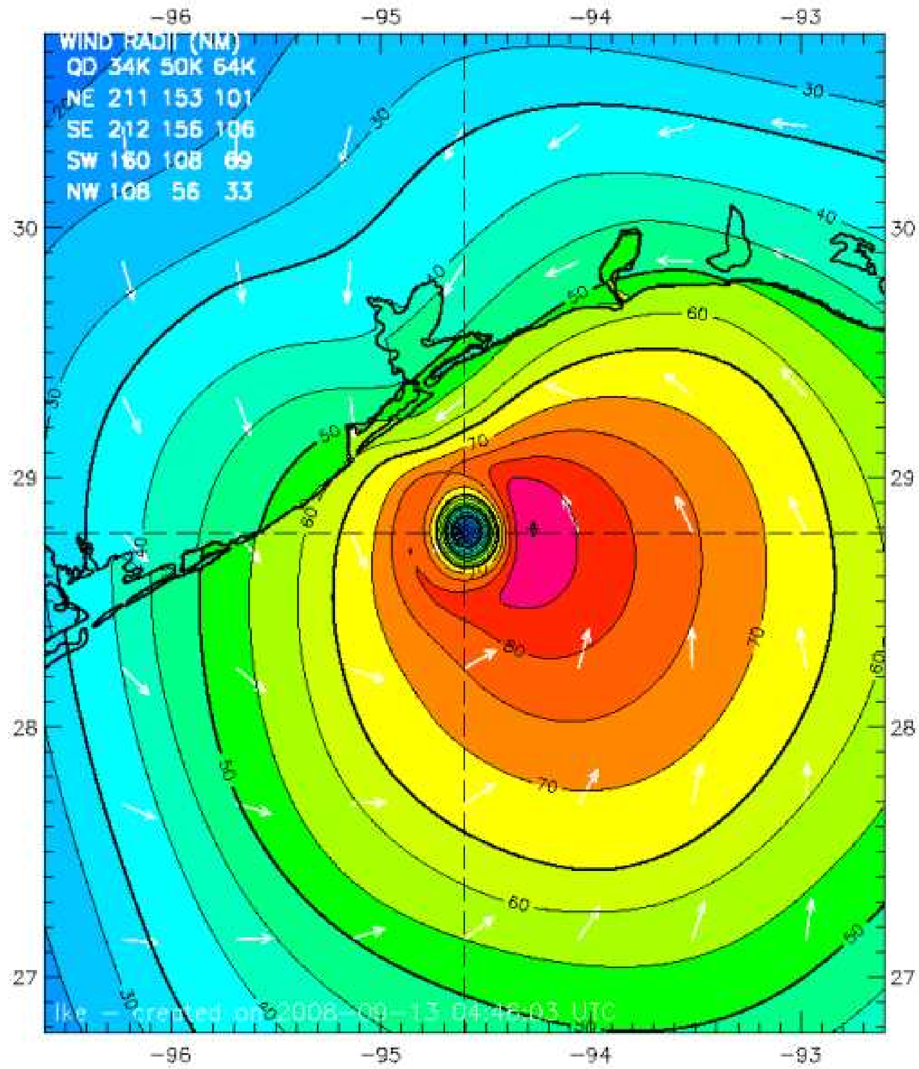
Thanks to Scott Dunbar for critical assistance

Hurricane Ike 0430 UTC 13 SEP 2008

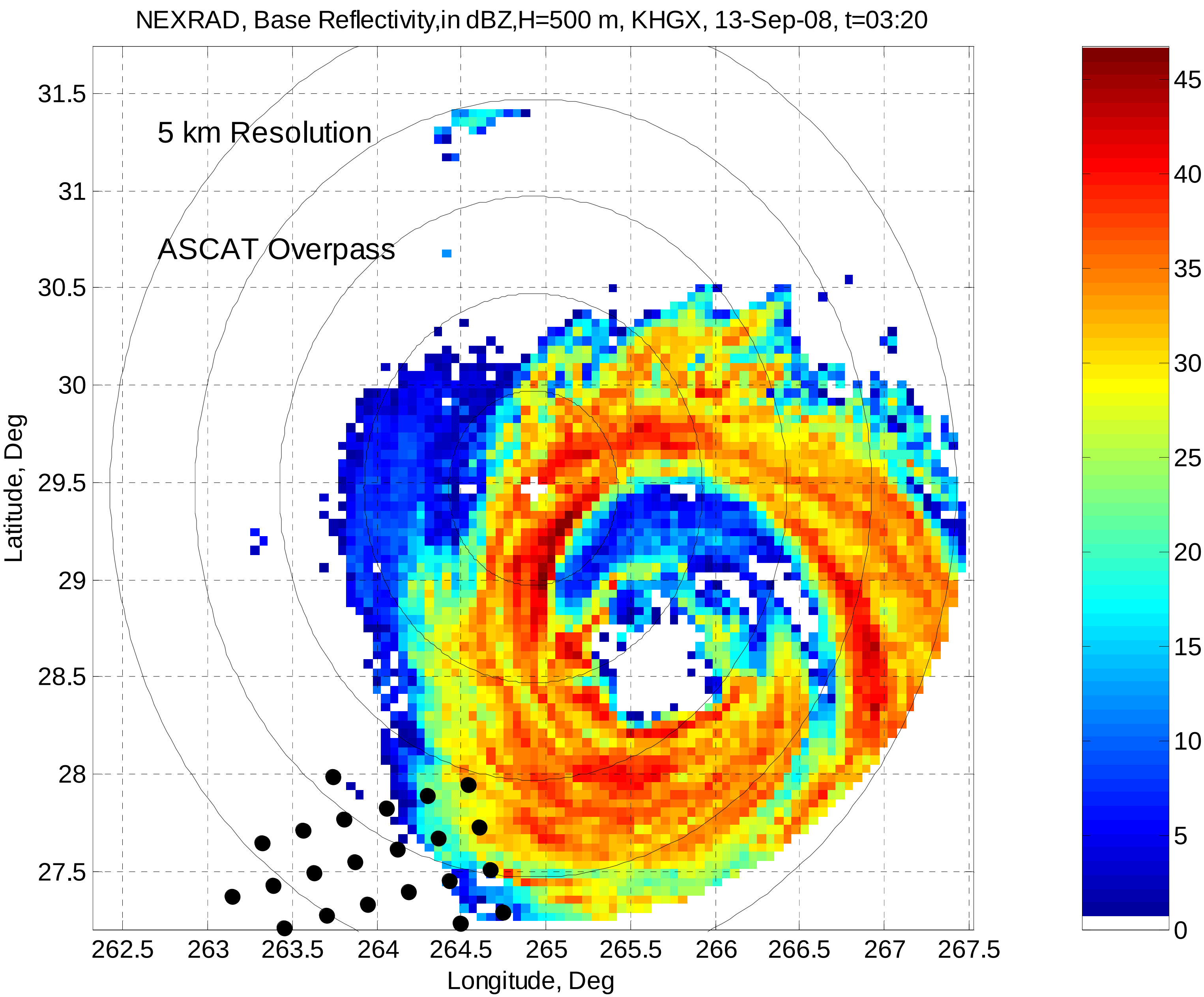
Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land

Analysis based on CMAN from 0159 - 0259 z; MOORED_BUOY from 0159 - 0349 z; ASOS from 0156 - 0401 z;
GPSSONDE_SFC from 0155 - 0314 z; SHIP from 0200 - 0400 z;
MADIS from 0202 - 0353 z; METAR from 0155 - 0408 z;
FCMP_TOWER from 0204 - 0424 z; GPSSONDE_WL150 from 0155 - 0322 z;
WEATHER_FLOW from 0155 - 0355 z; BACKGROUND_FIELD from 0430 - 0430 z;
SFMR_AFRC from 0155 - 0316 z; SFMR42 from 0159 - 0402 z;
0430 z position extrapolated from 0300 z OFCL_ATCF wind center using 315 deg @ 10 kts; mslp = 952.0 mb



Integrated Kinetic Energy for Winds > TS force 90 TJ for Winds > Hurricane Force 33 TJ


NEXRAD, Base Reflectivity,in dBZ,H=500 m, KHGX, 13-Sep-08, t=03:20
5 km Resolution
ASCAT Overpass
Latitude, Deg
Longitude, Deg
31.5
31
30.5
30
29.5
29
28.5
28
27.5
262.5
263
263.5
264
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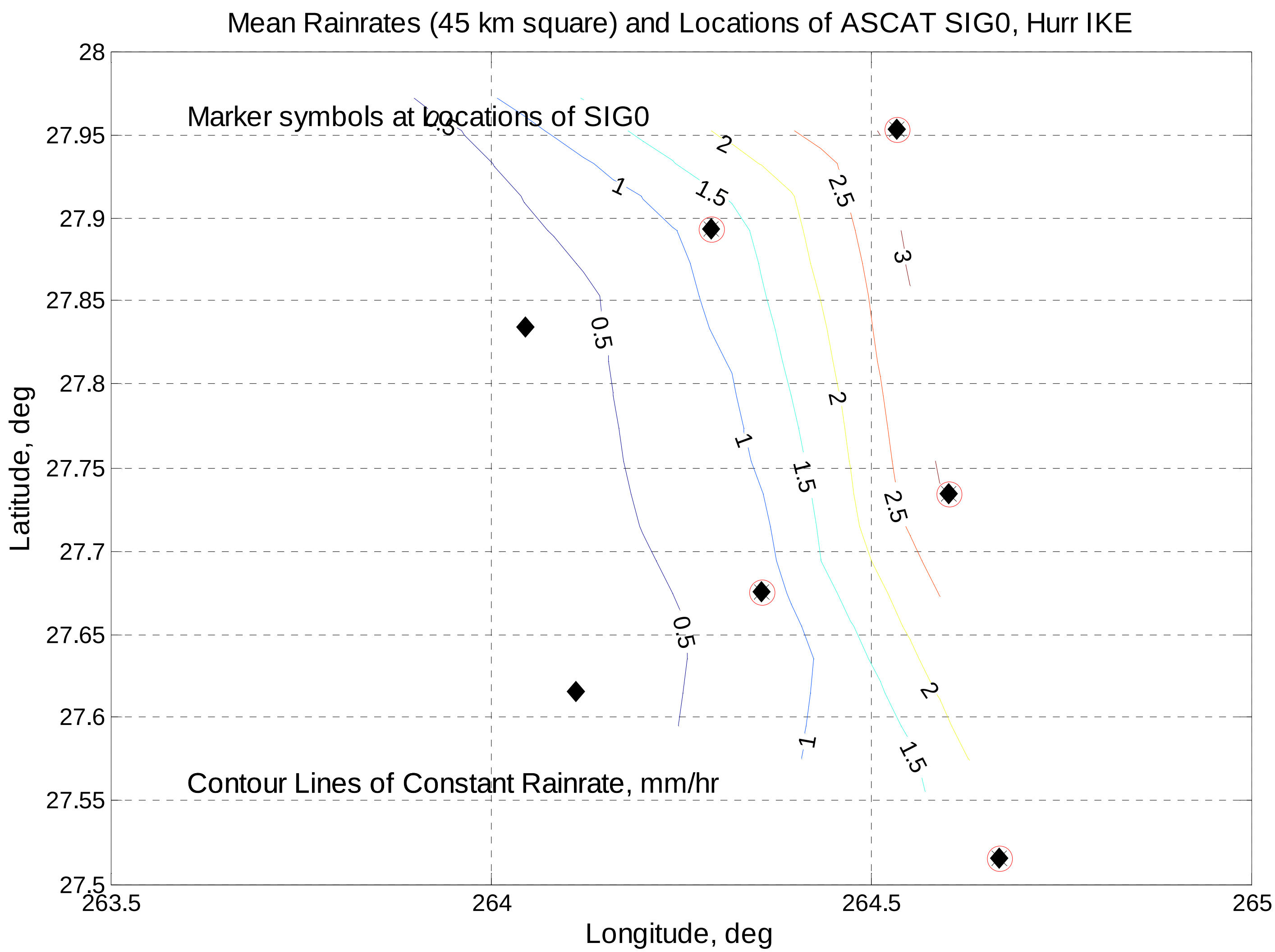
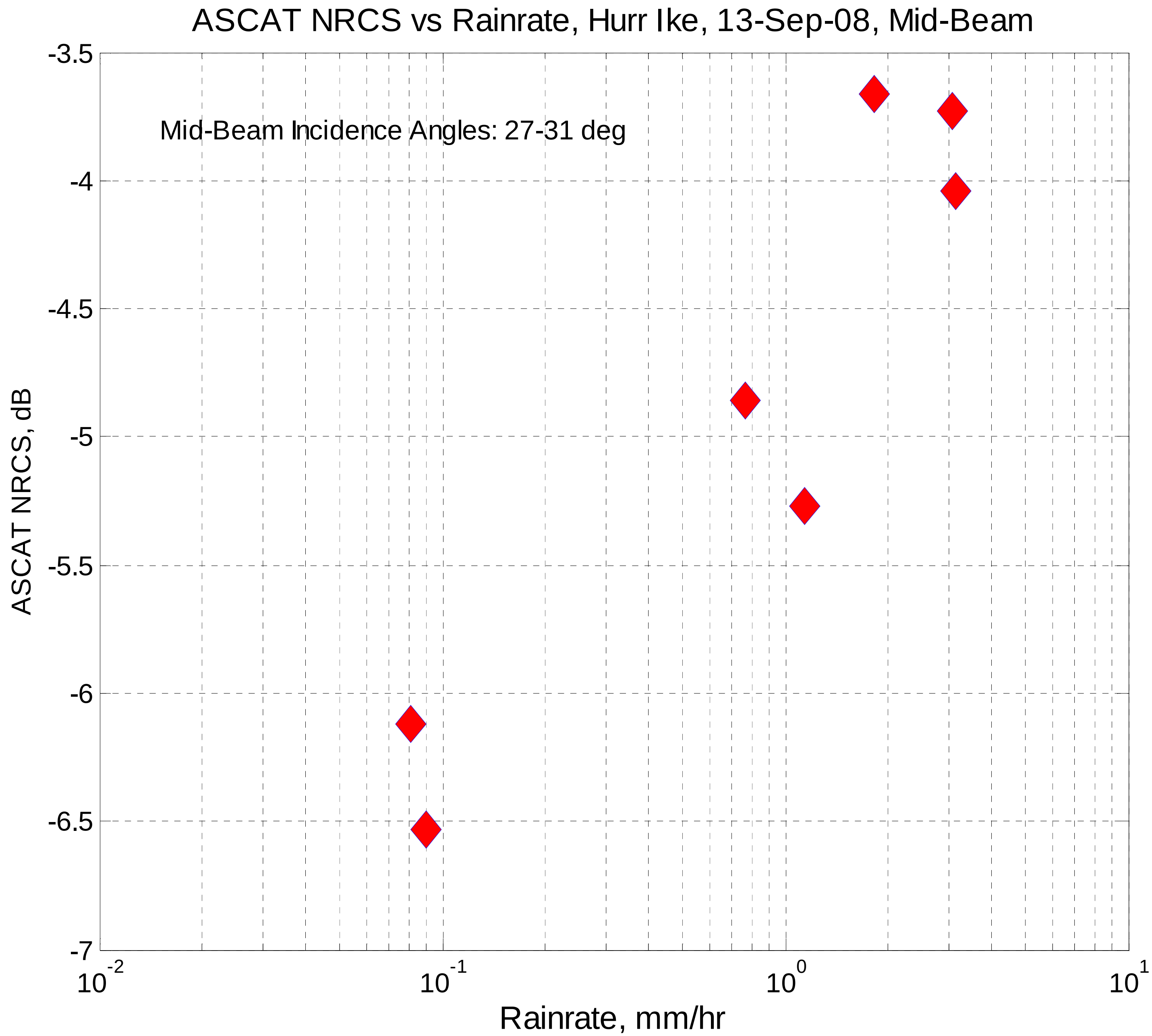
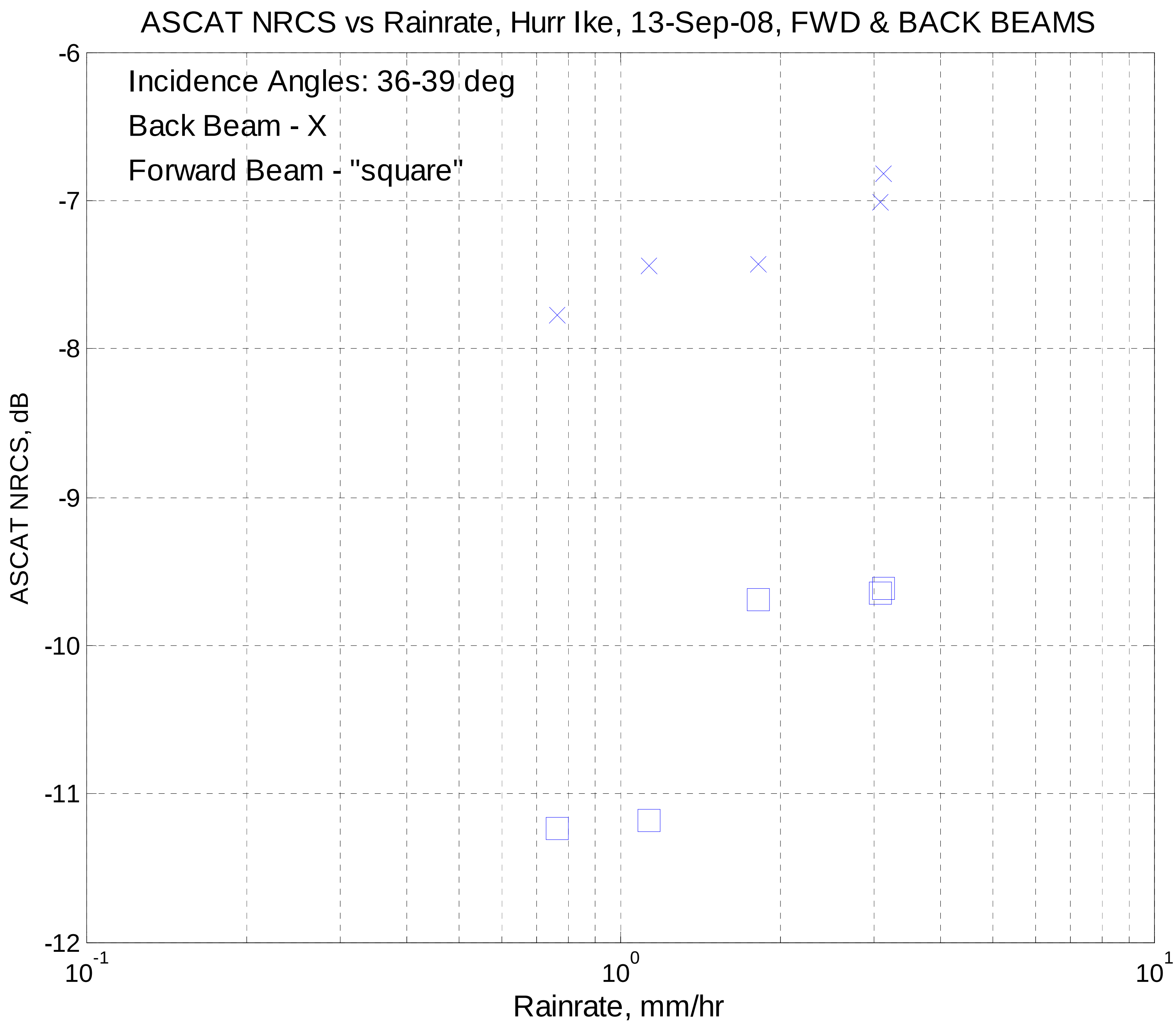
20
15
10
5
0



HRD Winds: at t=01:30z, U= 50-55 kts / at t=04:30z, U=50-60 kts /// ASCAT at 03:18z


ASCAT NRCS vs Rainrate, Hurr Ike, 13-Sep-08, Mid-Beam
Mid-Beam Incidence Angles: 27-31 deg
ASCAT NRCS, dB
Rainrate, mm/hr
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7
10^-2
10^-1
10^0
10^1


ASCAT NRCS vs Rainrate, Hurr Ike, 13-Sep-08, FWD & BACK BEAMS
Incidence Angles: 36-39 deg
Back Beam - X
Forward Beam - "square"
-6
-7
-8
-9
-10
-11
-12
ASCAT NRCS, dB
10^{-1}
10^{0}
10^{1}
Rainrate, mm/hr

Why Is This Interesting To A Meteorologist or Oceanographer

The air-sea momentum exchange in hurricanes is not well understood

- Surface drag
  - Which is related to surface roughness for $U_{10} < 25 ms^{-1}$,
  - If it continues to increase of $U_{10} > 25\ ms^{-1}$,
    - The drag is too great to produce strong hurricanes
    - Unless there is a proportional increase in evaporation
- However, the highest winds are found in or near rain bands
  - Therefore, it seems likely that surface drag is somehow reduced by rain
  - Rain and sea spray likely act to reduce the surface drag
  - Does rain act to increase sea spray via wave-wave interaction or is the process more direct?
- Current hurricane intensity forecasts do not consider these processes
  - Intensity forecasts are bad – but there could be other reasons
- Ocean mixing due to tropical cyclones could be important for climate
  - If the drag is reduced there will be less mixing than otherwise modeled!