Drag Coefficient Behavior in Tropical Cyclones

a JHT Project

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Background

- The 2003 Nature study published the first profile-method measurements of Cd, U*, and Zo in tropical cyclones
- 330 profiles were distributed into four MBL groups of 40-100 sondes per group
- Cd was shown to level off or possibly decrease after an initial increase with increasing wind speed
- Now there are nearly 4 times more sonde profiles

Justification

- For many models momentum flux in strong winds based on extrapolating Cd (U10) from field studies in < 25 m/s winds
- Models use these Cd's for:
  - Track and intensity prediction
  - Waves and Storm Surge
  - Building code and insurance risk

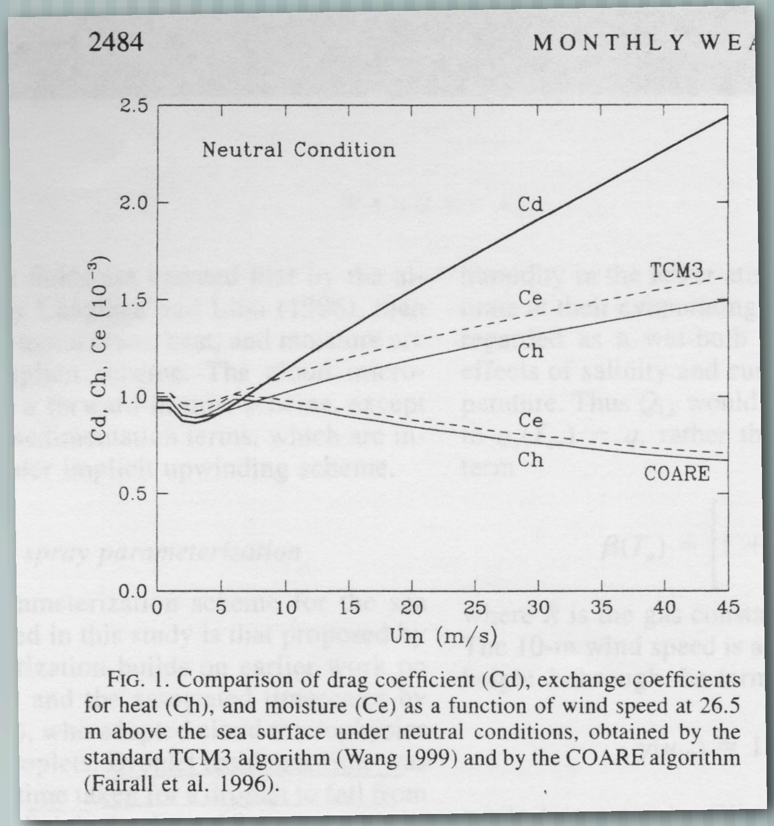


FIG. 1. Comparison of drag coefficient (Cd), exchange coefficients for heat (Ch), and moisture (Ce) as a function of wind speed at 26.5 m above the sea surface under neutral conditions, obtained by the standard TCM3 algorithm (Wang 1999) and by the COARE algorithm (Fairall et al. 1996).

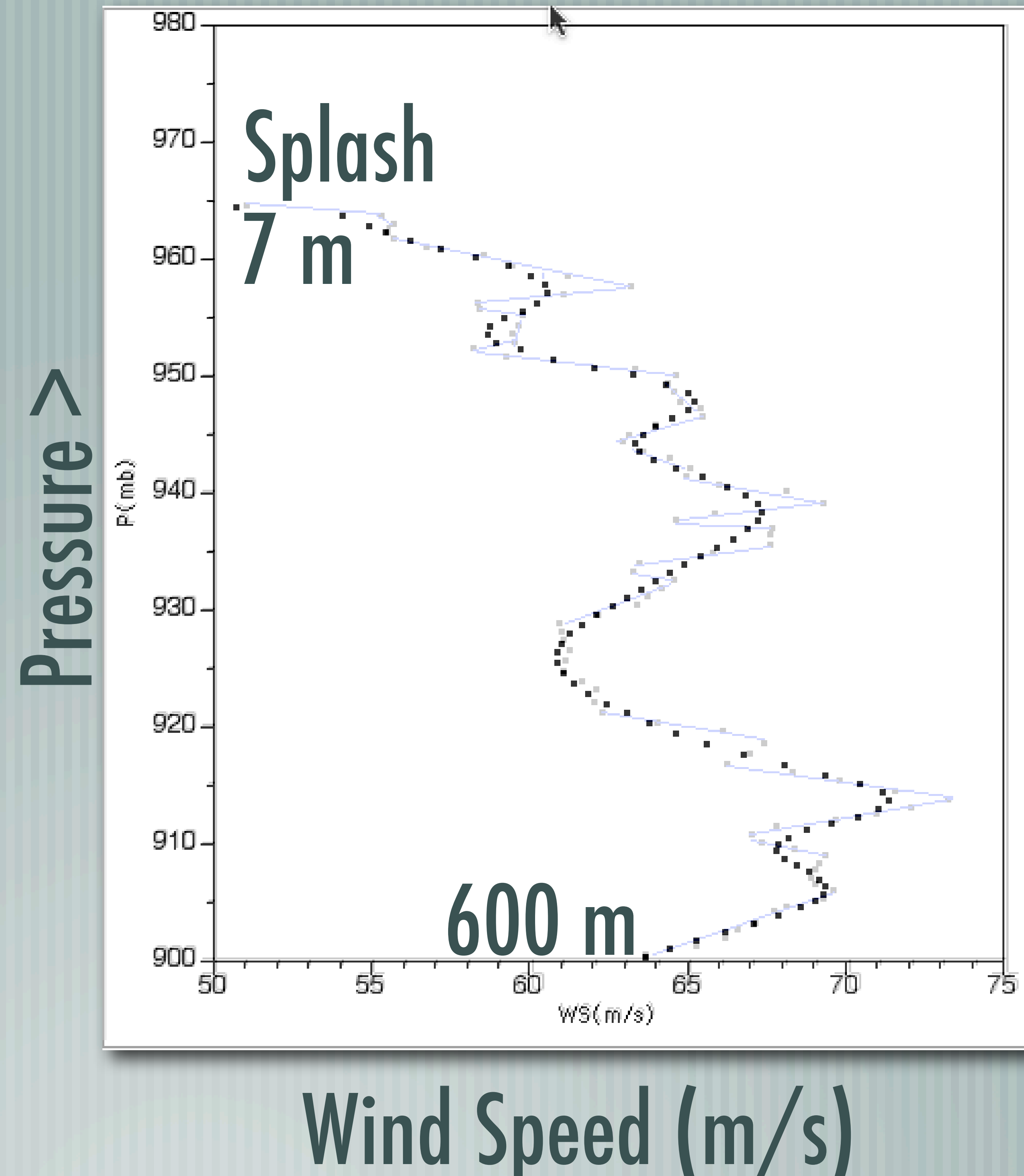
TC Modeling

- Charnock type roughness is used by most models
- Some modelers also include a wave age or sea state dependence which can increase Charnock alpha by order of magnitude
- Model parameterizations of momentum flux in the hurricane boundary layer are changing to limit or cap increase in Cd (Andreas 2004, Moon et al., 2004, Wang and Wu 2004)

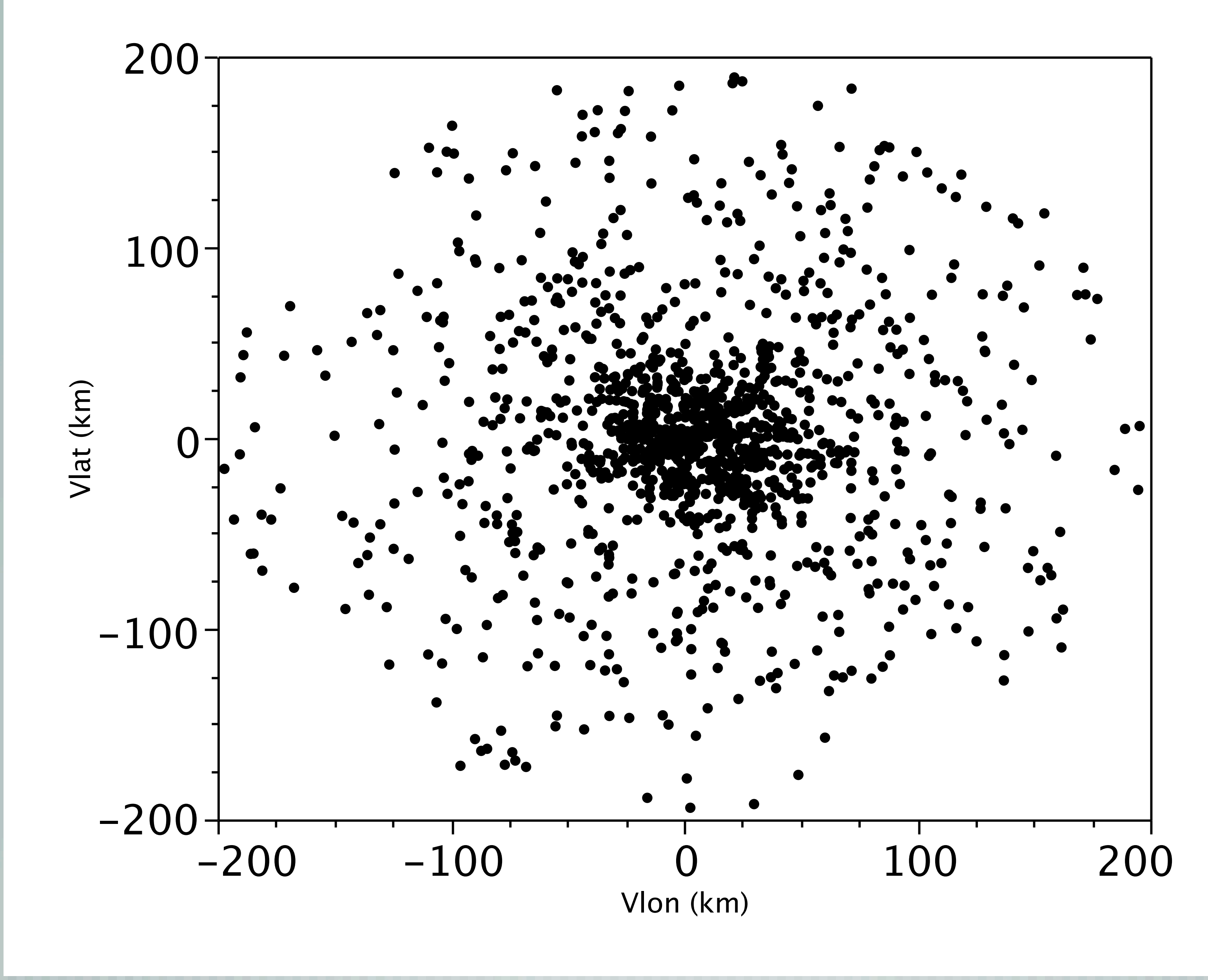
Analysis Methods:GPS Sonde

- Hock and Franklin (1999)
- 10-12 m/s fall speed
- 2 Hz Samples P, T, RH, Position
- Accuracy 0.5-2m/s, 2 m height
- Filtered by 5 s low pass filter to remove undersampled scales and noise from satellite switching
- Corrected for acceleration bias
- Wind errors large below 5-8 m

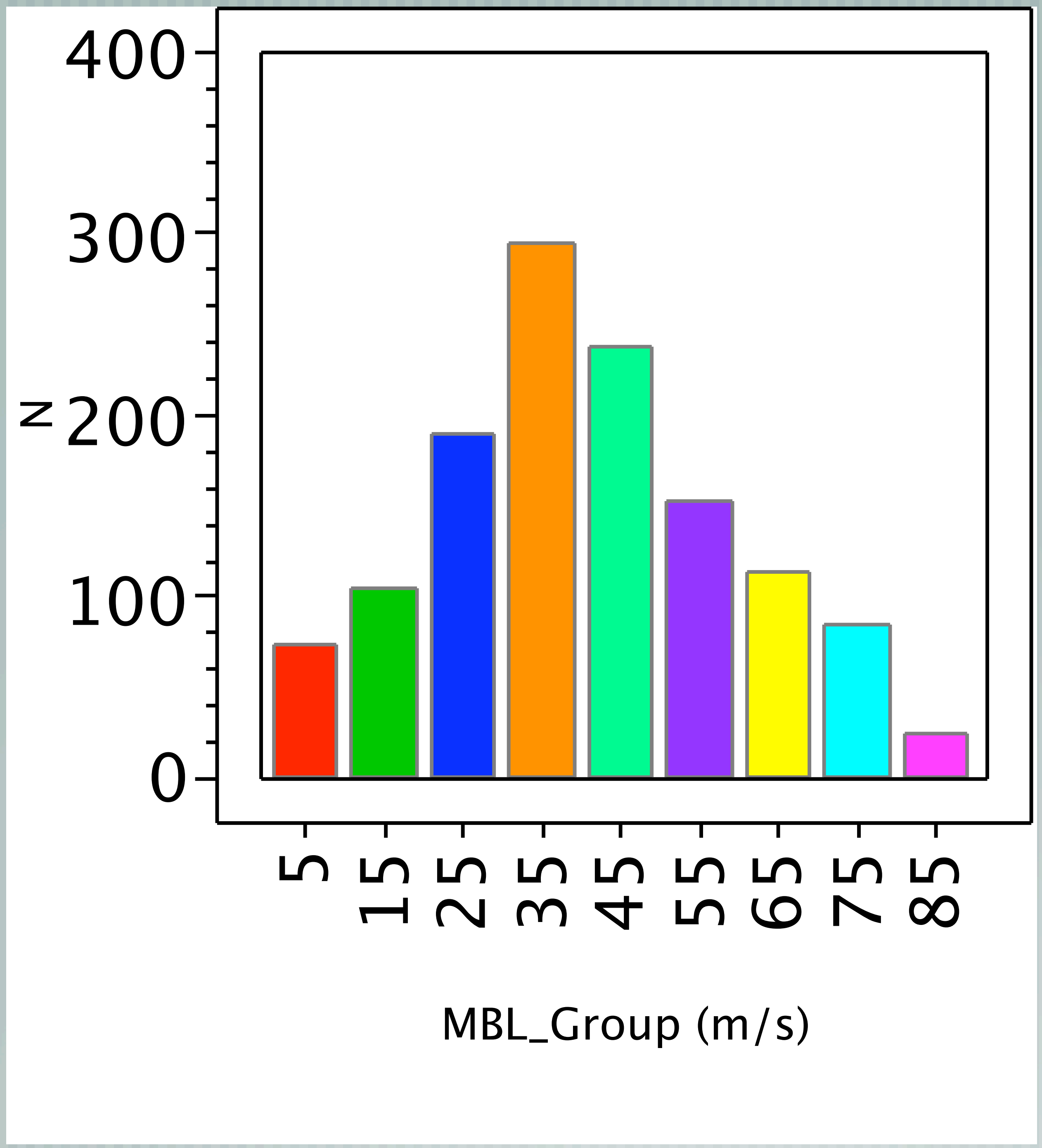
GPSSonde filtering:
A 5 sec. (~ 10 point or ~50 m) digital Fourier filter removes noise associated with satellite switching, individual satellites, undersampled scales



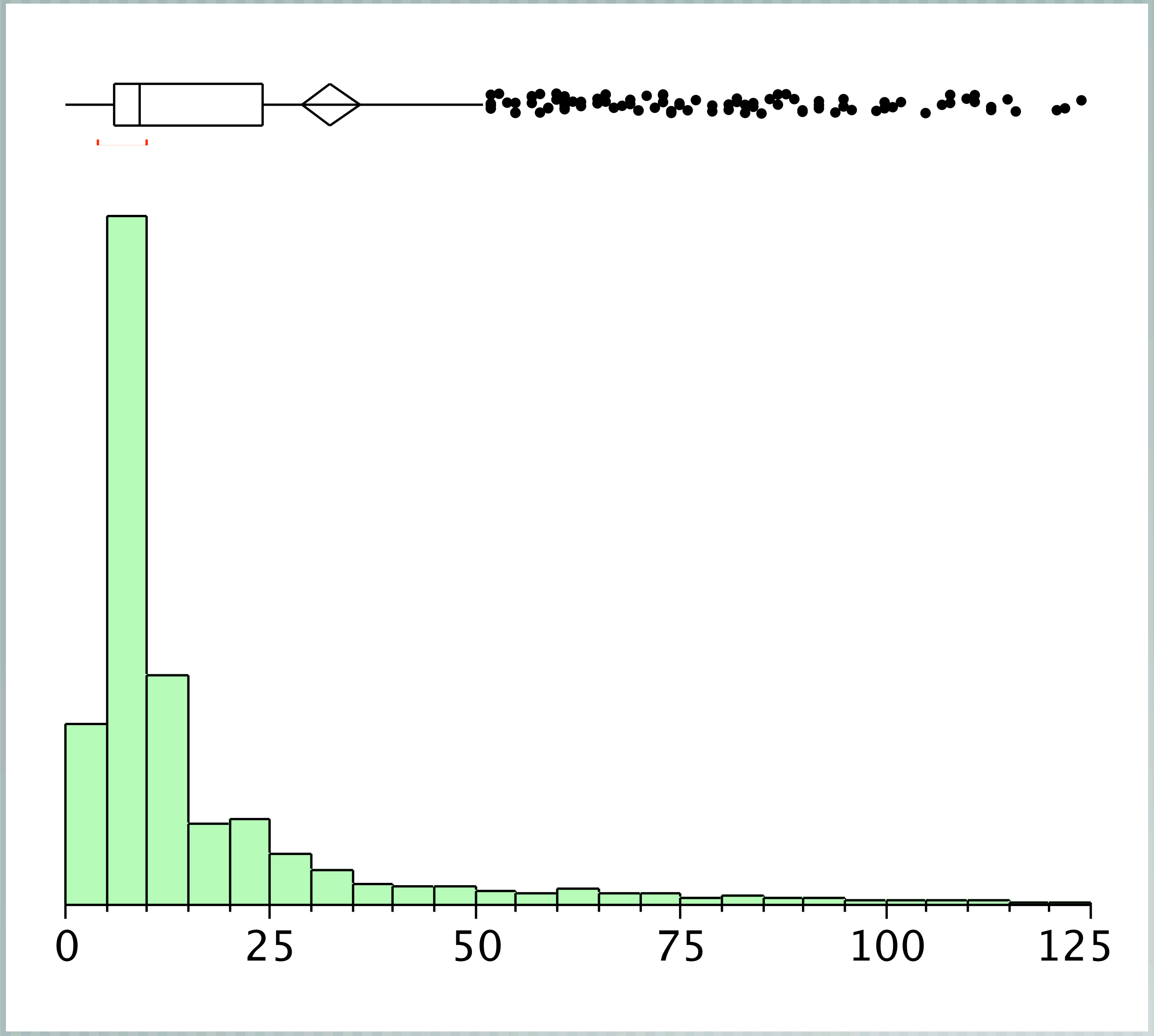
Storm Relative Distribution (1270 sondes) 1997-2005 between 2-200 km splash radius



Number of wind profiles by MBL Group



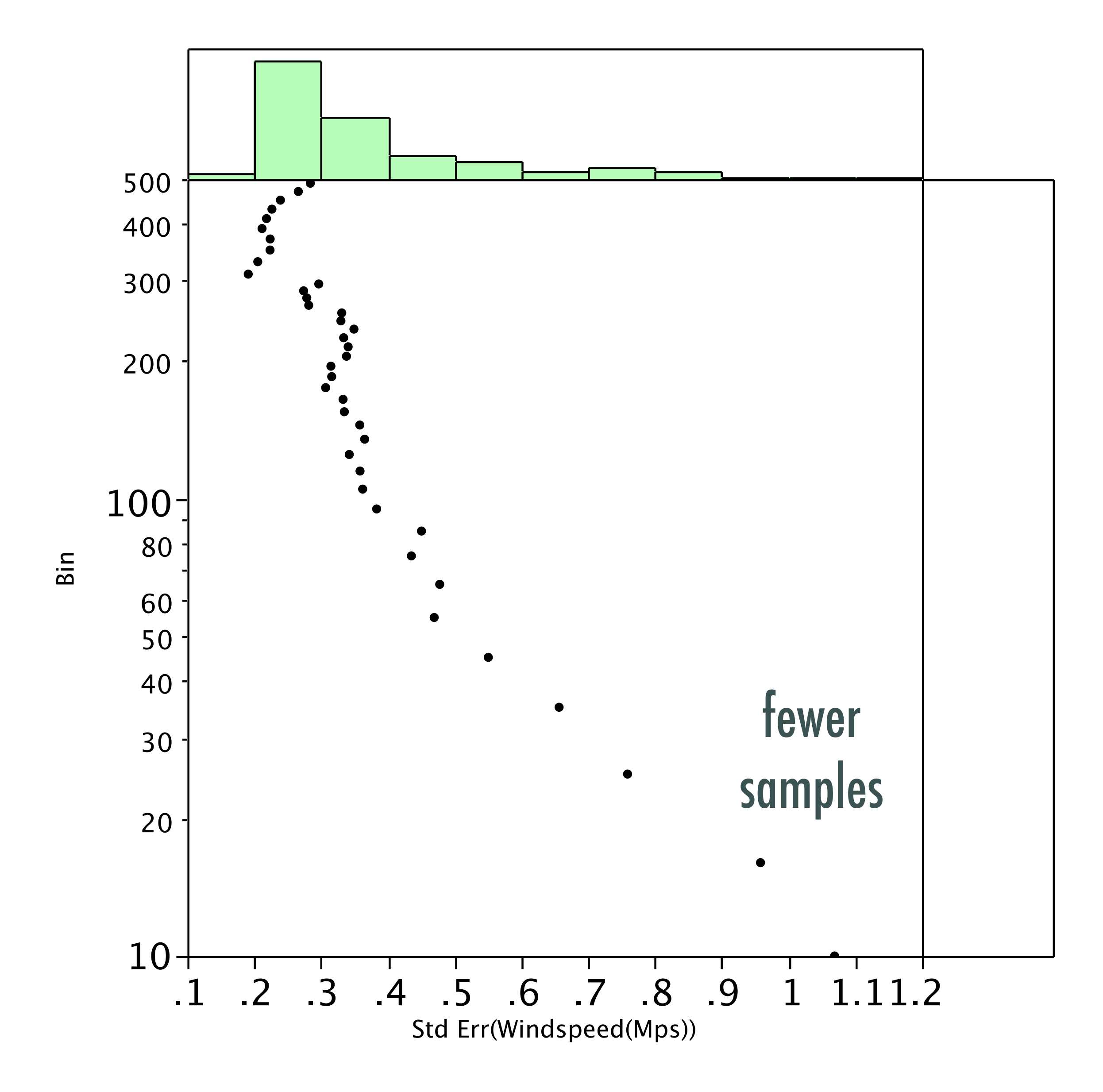
90% of the profiles measure winds to 83 m
75% of the profiles measure winds to 24 m
60% of the profiles measure winds to 10 m



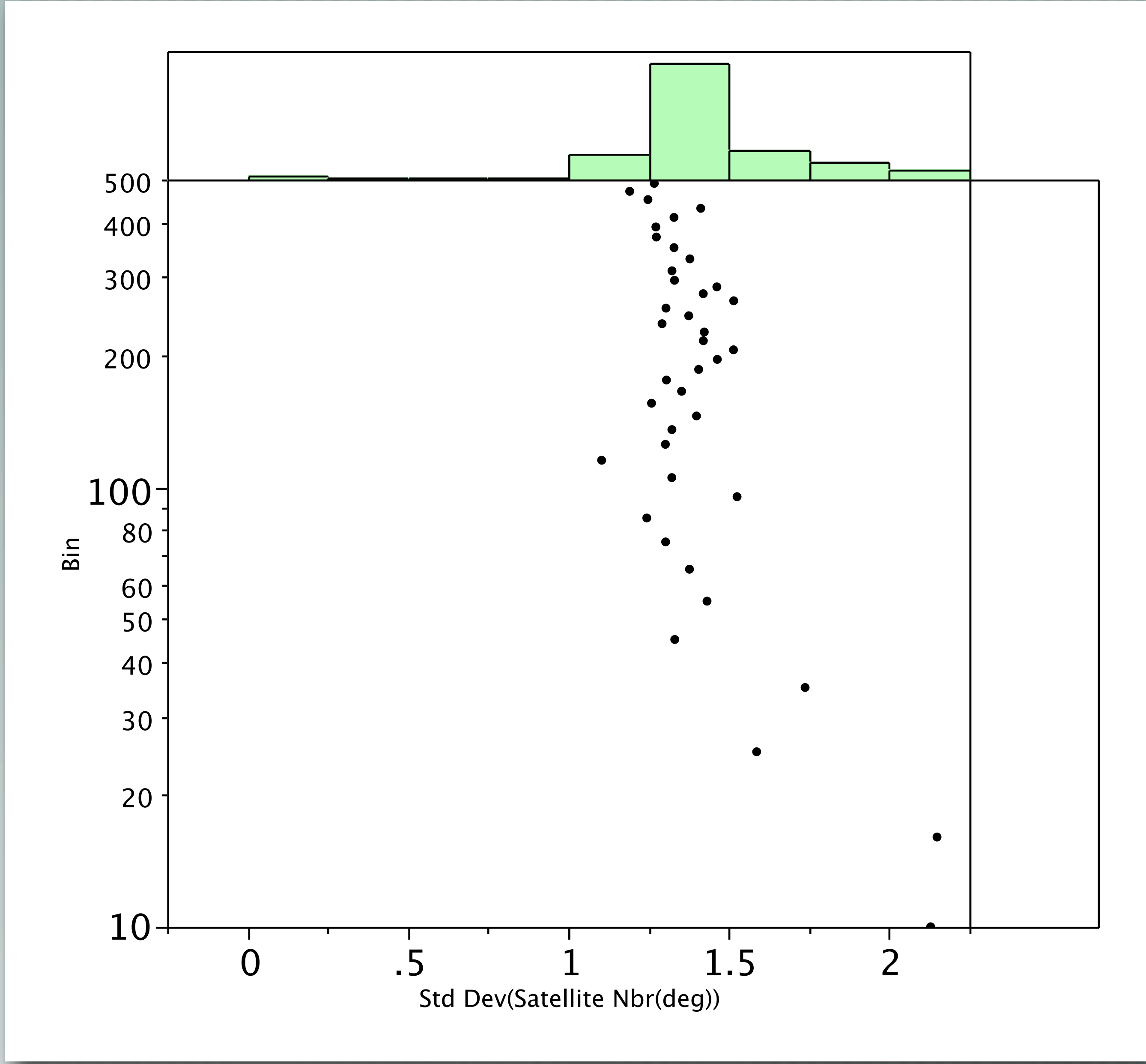
Height (m) of lowest measured wind

Note:
All sondes reach the surface!!!

Standard error of bin means increases near the surface



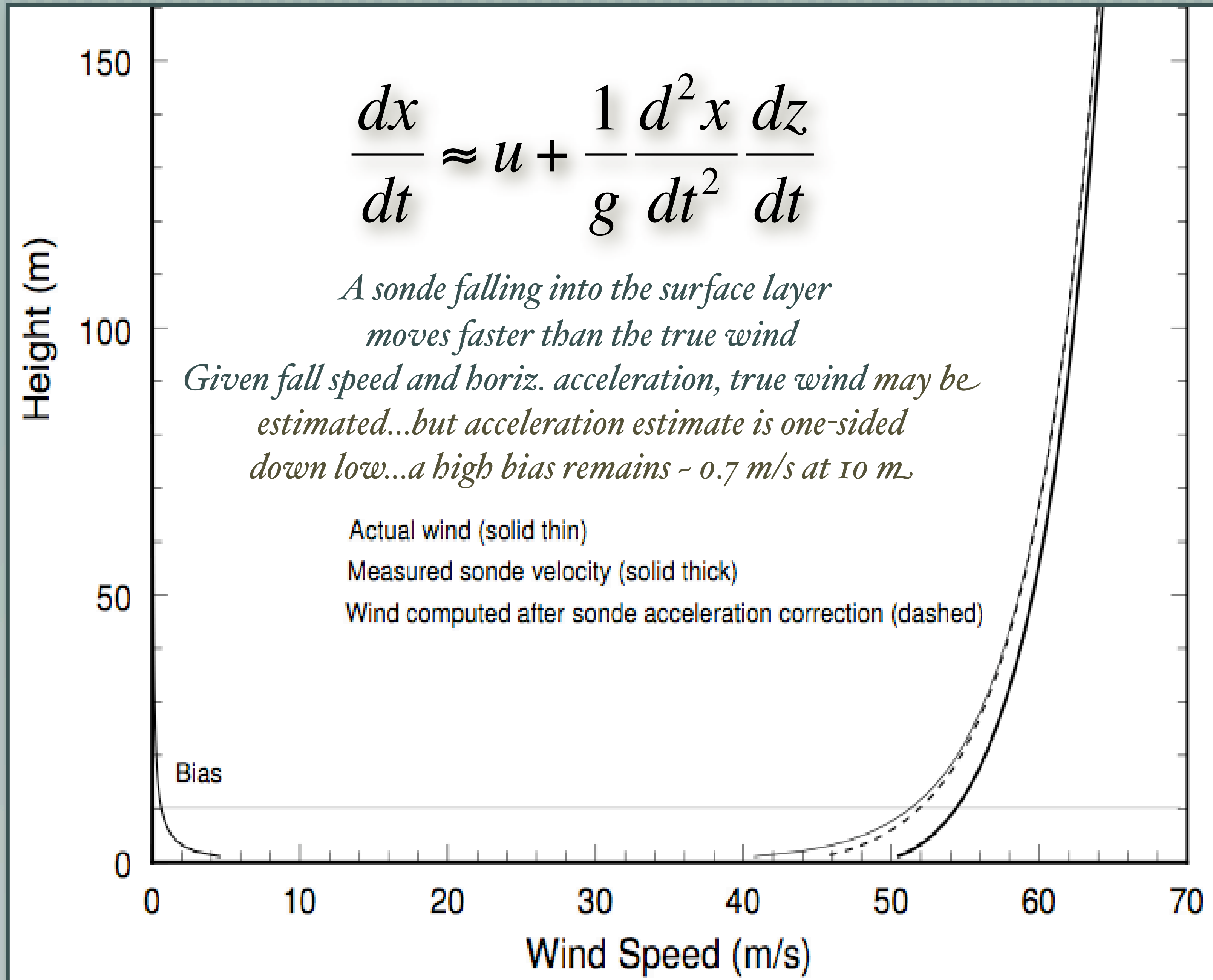
Variability in satellite reception increases near the surface



Quality Control

- Wind quality flag 4 data removed (questionable)
- Wind quality flag 5 data removed (subjectively determined)
- Standard error of bin-mean wind speed must be < 2 m/s
- At least 10 profile samples per height bin
- Outliers associated with large vertical motion or satellite switching removed (3 profiles)

GPS Sonde wind measurement



Bias is estimated for each MBL group and subtracted from mean profiles

Organizing:

- *MBL*: Avg. of lowest 500 m, contains max in profile, easily determined, 10 m/s bins for similar conditions.
- *Height bins*: Staggered to preserve detail, 8-12 m, 13-20, 21-30,...
- *Ergodic hypothesis*: Each profile is an instance from an ensemble of profiles in identical conditions...average of profiles within an MBL group - ensemble average.

Profile Method:

Log Law for neutral stability

$$U = U_* / k \quad Ln\,(Z / Zo)$$

$$Ln\,(Z) = (k / U_*)\, U + Ln\,(Zo)$$

slope intercept

$$\tau = \rho\, U_*^2 = \rho\, C_d\, U_{10}^2$$

$$Cd = \left(\frac{.4}{Ln\left(\frac{Zo}{10}\right)} \right)^2$$

Analysis of Mean profile fits

- by 10 m/s MBL group Cd = f(V)
  - subgroup by radial distance Cd = f(v,r)
  - combined radial and SR azimuth Cd = f(v,r,SRAz)
- Error bars based on 95% confidence limits
- Two estimates based on sfc layer 10-160m, 20-160 m

Hurricane Waves : Profiles partitioned by S-R Azimuth

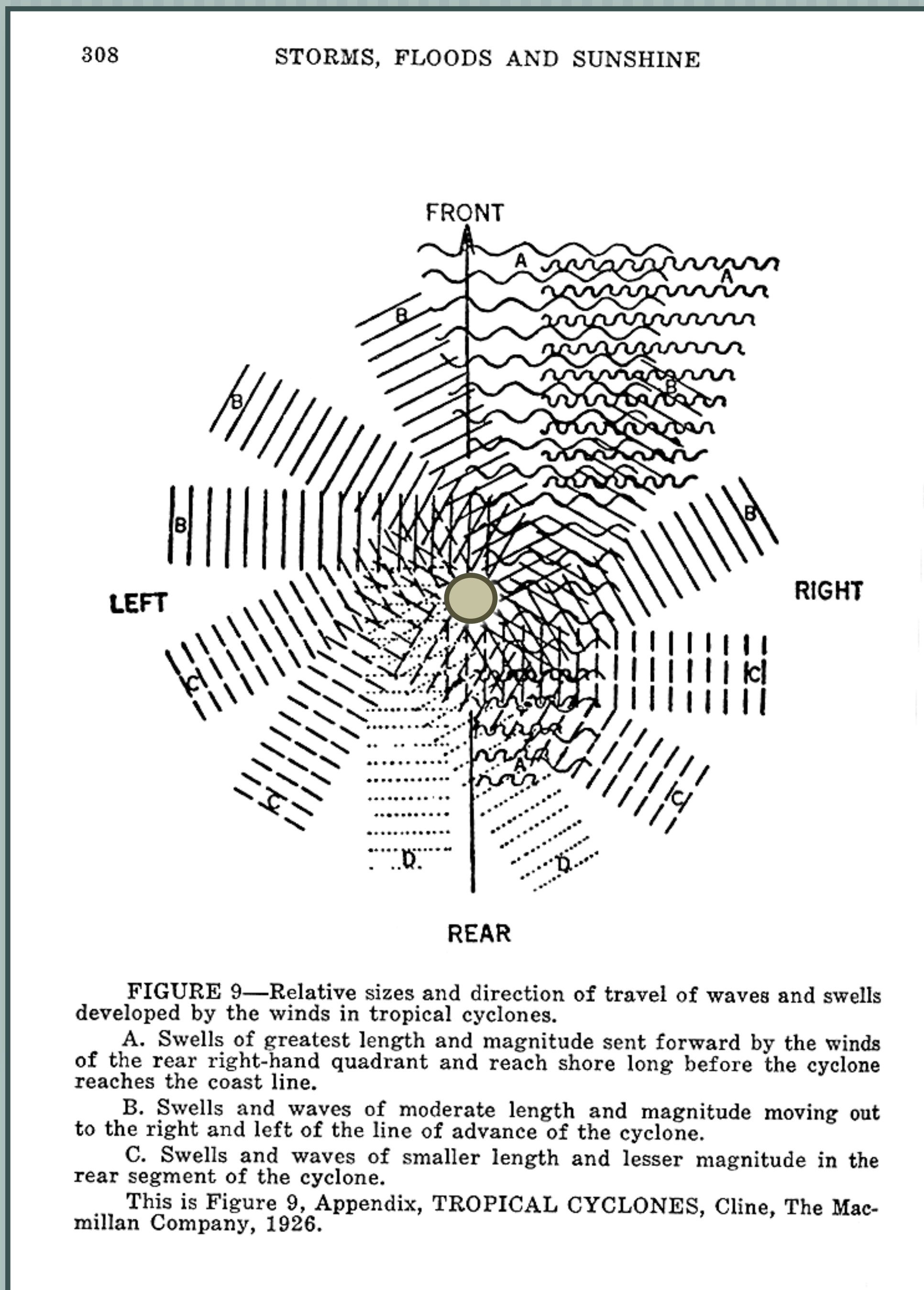

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FIGURE 9—Relative sizes and direction of travel of waves and swells developed by the winds in tropical cyclones.

A. Swells of greatest length and magnitude sent forward by the winds of the rear right-hand quadrant and reach shore long before the cyclone reaches the coast line.

B. Swells and waves of moderate length and magnitude moving out to the right and left of the line of advance of the cyclone.

C. Swells and waves of smaller length and lesser magnitude in the rear segment of the cyclone.

This is Figure 9, Appendix, TROPICAL CYCLONES, Cline, The Macmillan Company, 1926.

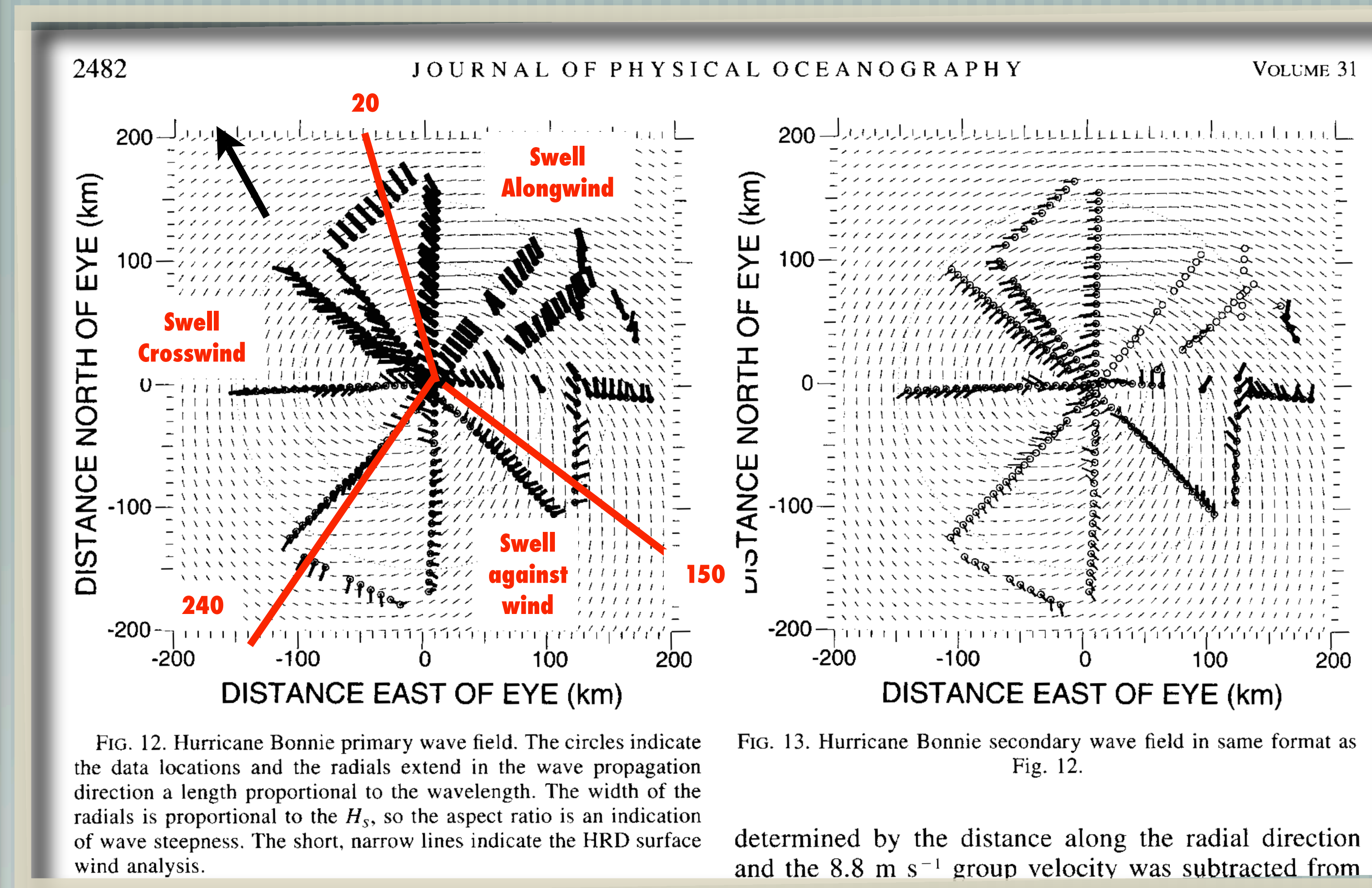
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FIG. 12. Hurricane Bonnie primary wave field. The circles indicate the data locations and the radials extend in the wave propagation direction a length proportional to the wavelength. The width of the radials is proportional to the H_s, so the aspect ratio is an indication of wave steepness. The short, narrow lines indicate the HRD surface wind analysis.

FIG. 13. Hurricane Bonnie secondary wave field in same format as Fig. 12.

determined by the distance along the radial direction and the 8.8 m s^{-1} group velocity was subtracted from

“Tropical Cyclones”
Isaac Cline (1926)

Hurricane Bonnie: Wright et al 2001

Primary (L) and Secondary (R) wave field

Length ~ propagation direction

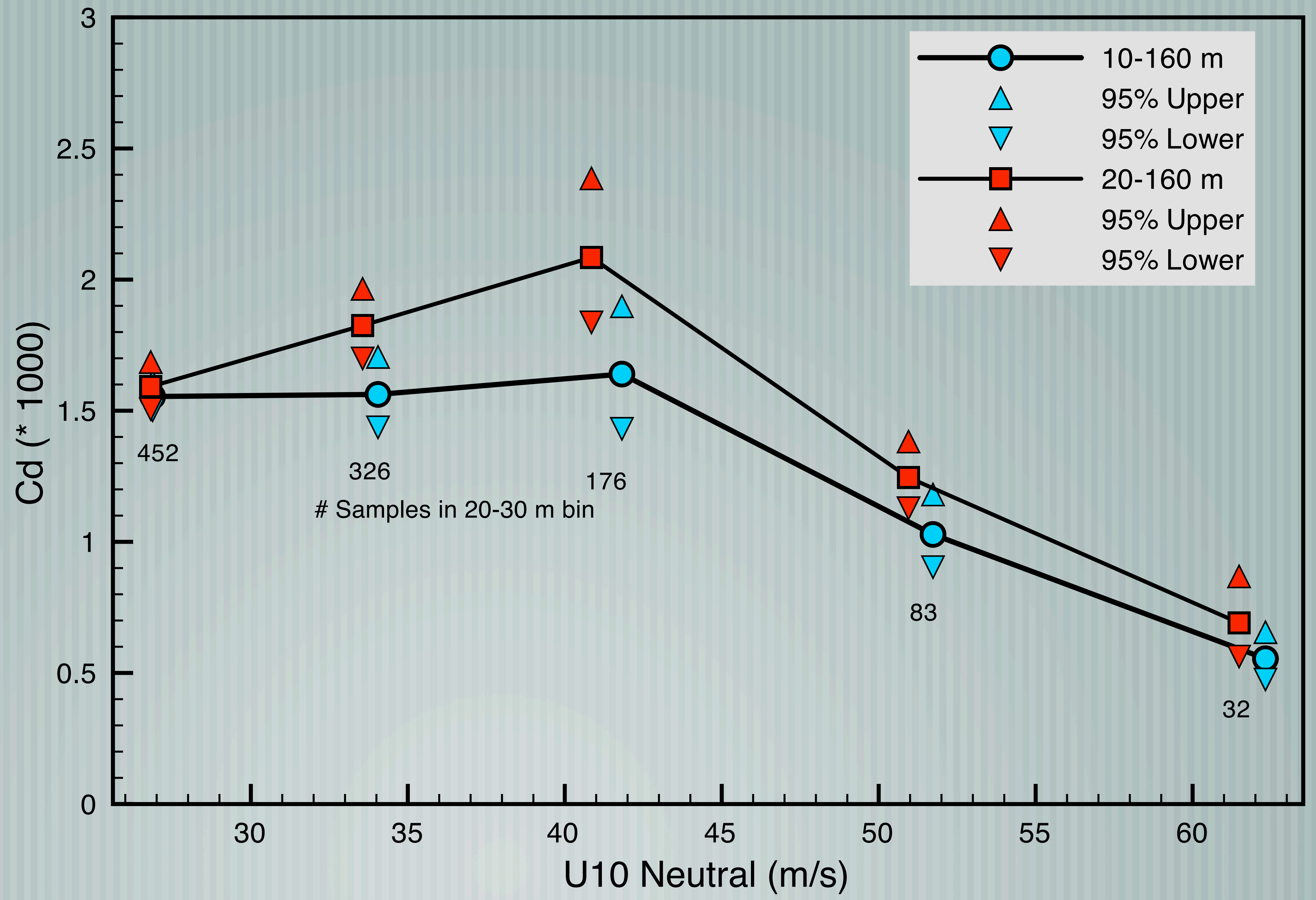
Width ~ H_s

Drag Coefficient: U10

20-160 m surface layer

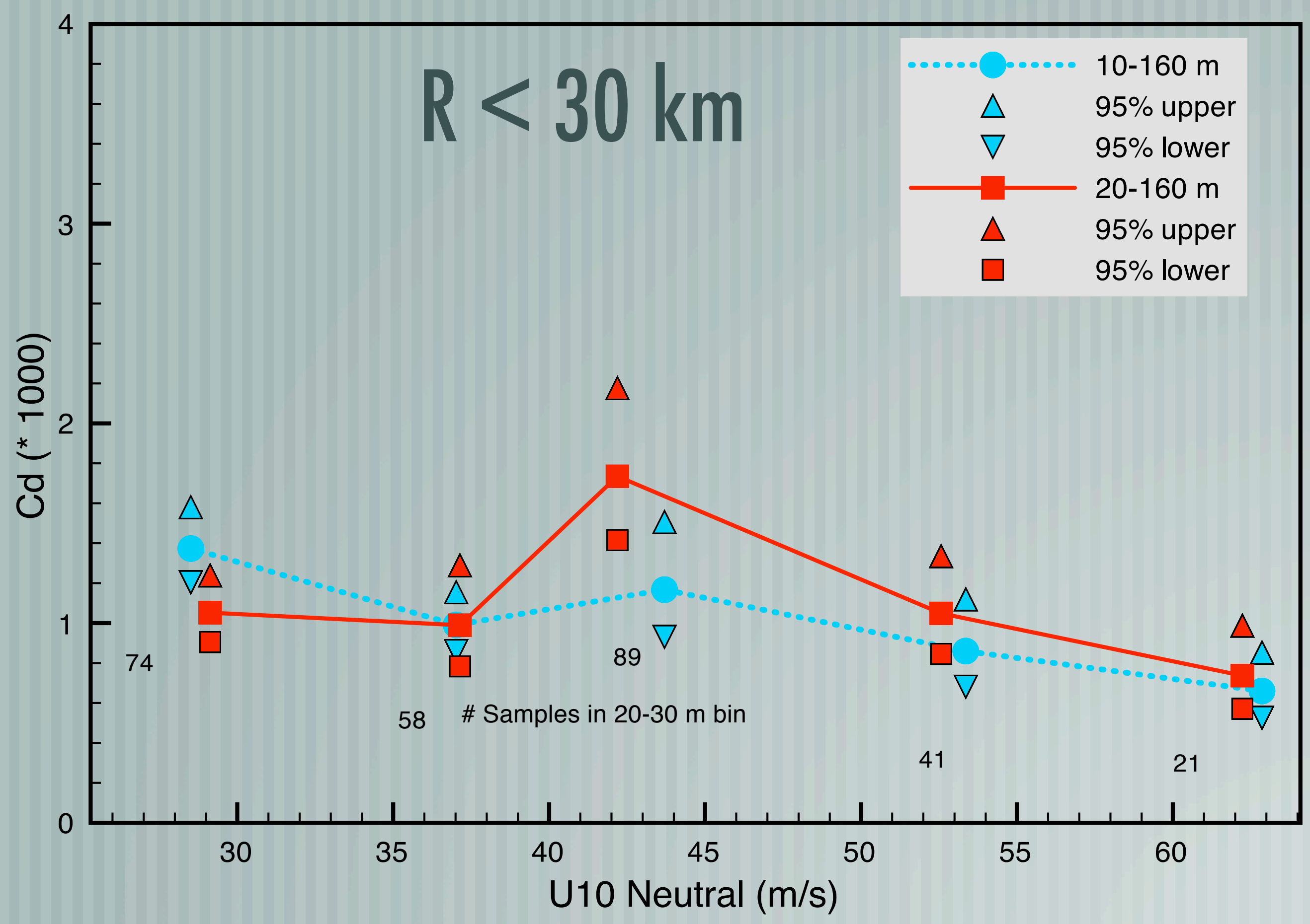
Initial increase, then decrease after ~ 42 m/s

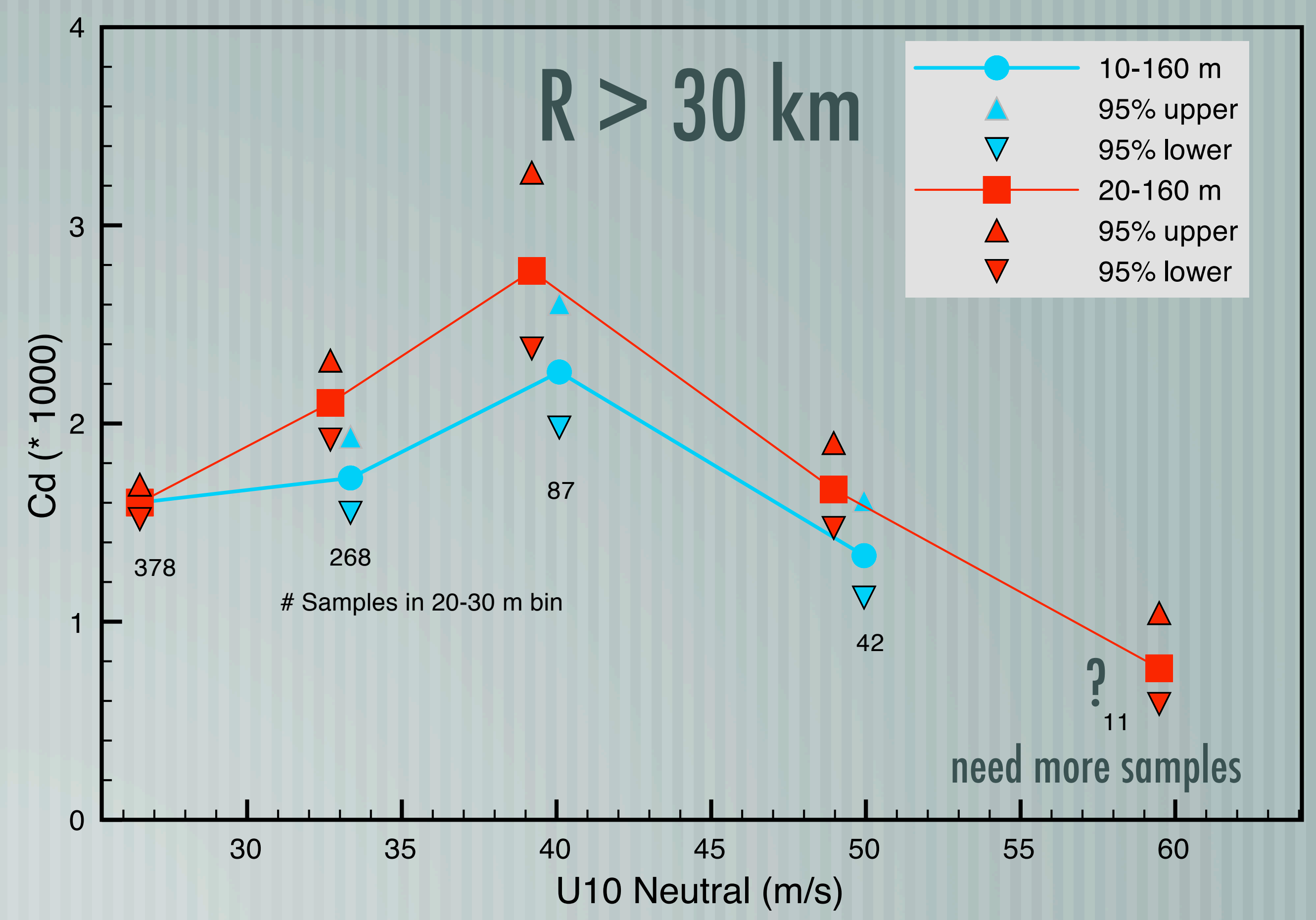
Database has capability of refining to 5 m/s MBL groups to refine where Cd first decreases



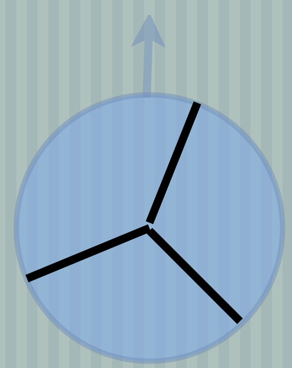
Cd dependence on R

Radii < 30 km show smaller Cd values
30 km is median for MBL wind groups > 50 m/s





Cd: right side of storm

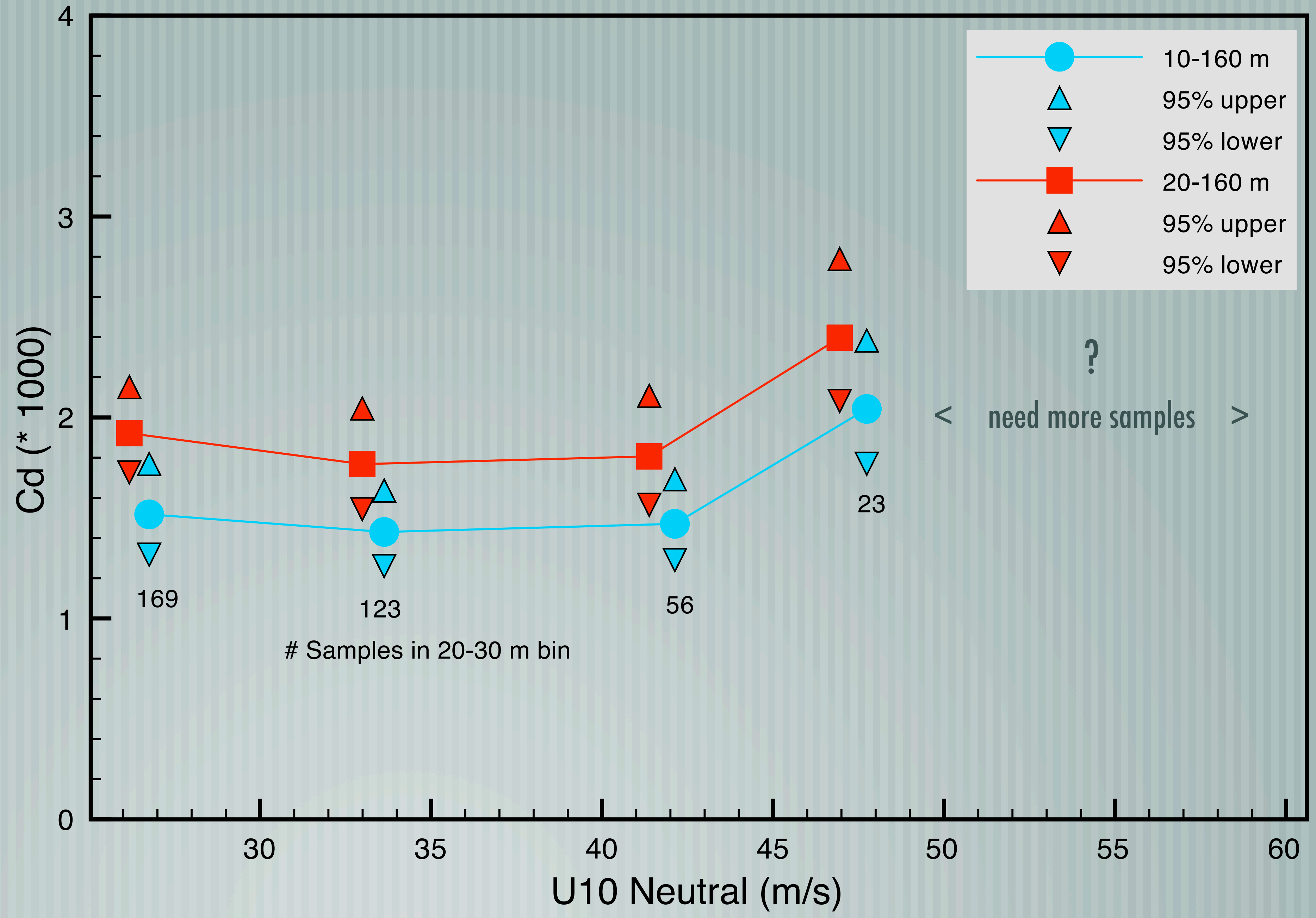


Right Side

R> 30 km

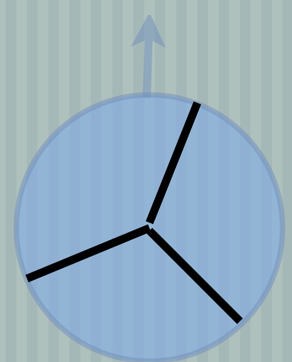
Storm Rel. Azimuth

20-150 deg



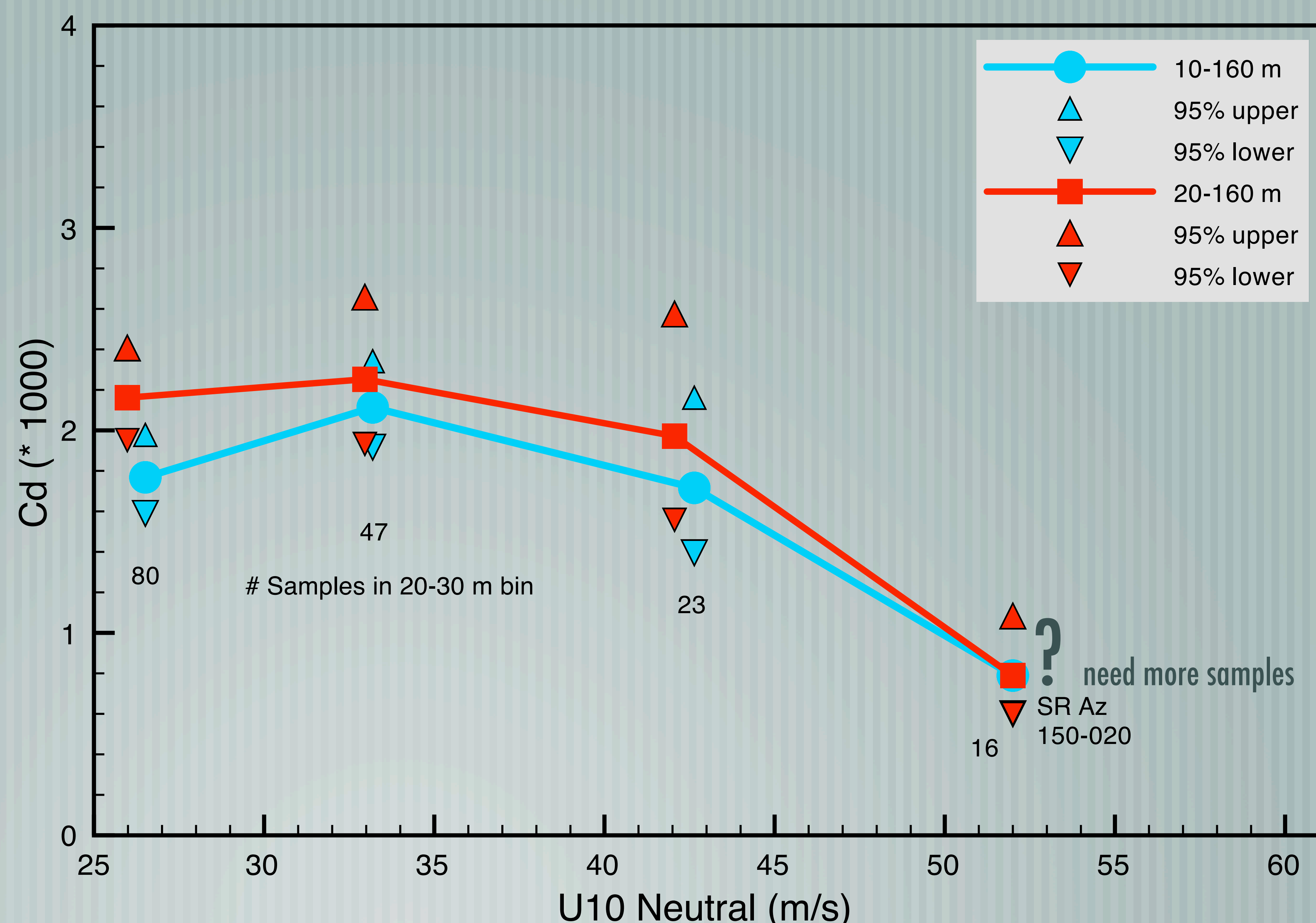
Cd ~ constant on right side for R> 30 km

Cd: rear of storm



Rear

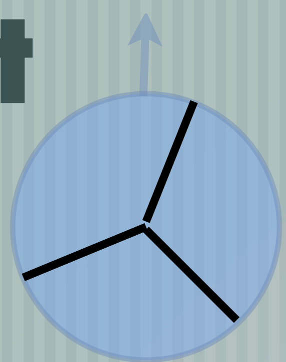
R> 30 km
Storm Rel. Azimuth
150-240 deg



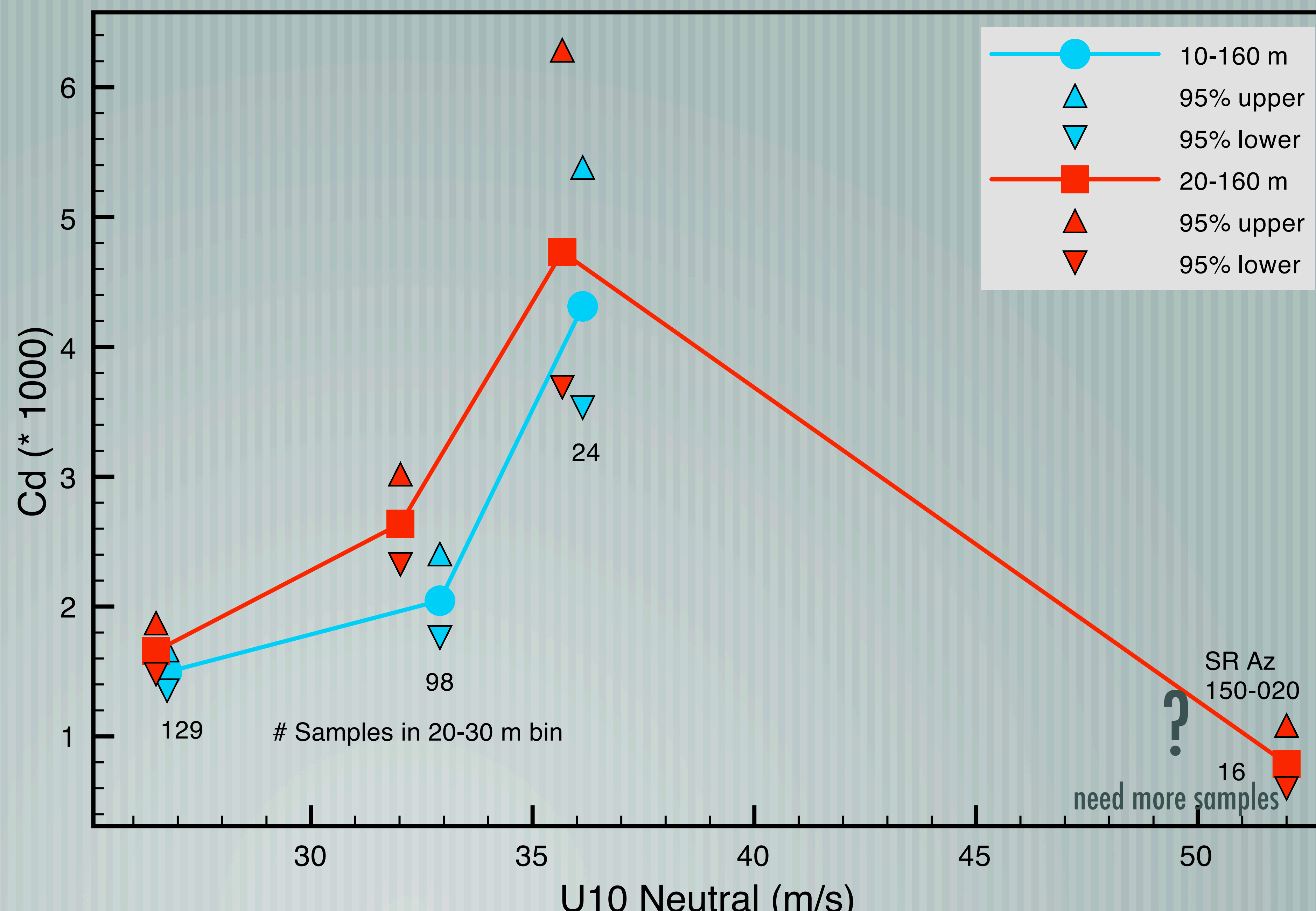
Cd ~ constant to rear for R> 30 km

CD: left front

Left
Front



R> 30 km
Storm Rel. Azimuth
240-020 deg



Cd increase with U10 to front for R> 30 km

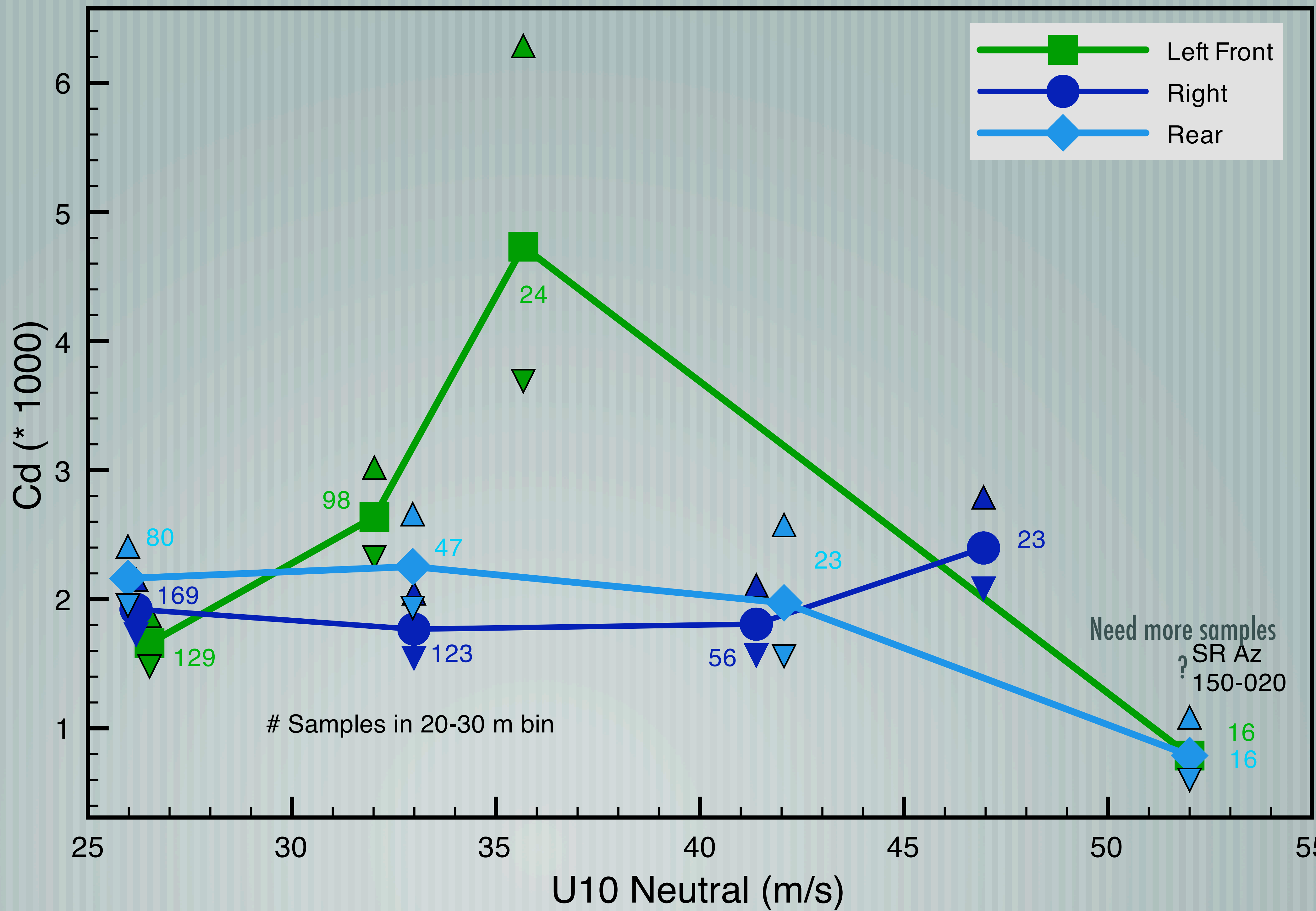
Cd: Storm rel. azimuth

20-160 m layer:

Cd increase with U10 left front

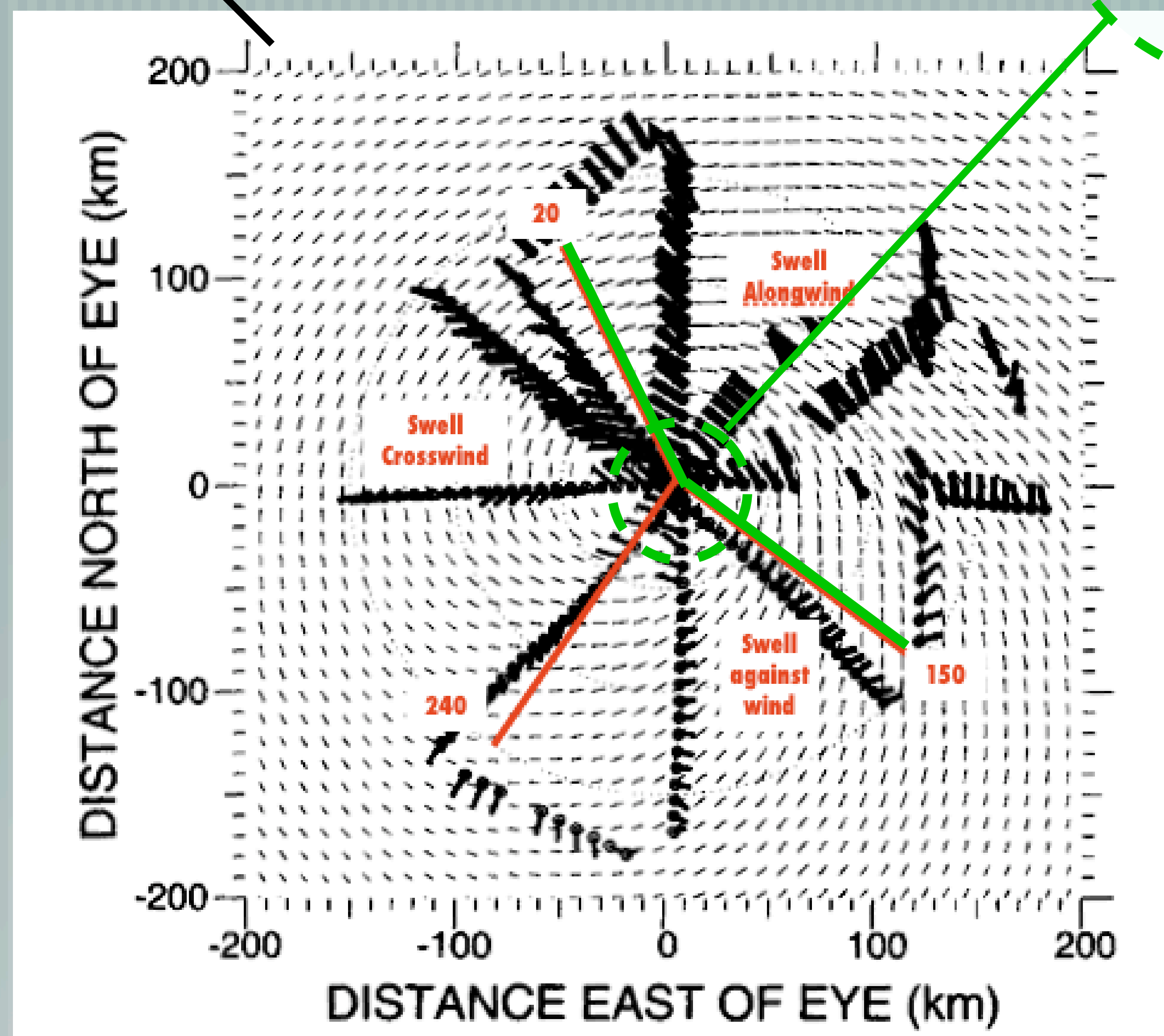
Cd right < Cd rear but both stay constant with U10

Suggestion of smaller Cd at highest U10 in rear/left front



Conclusions

Storm motion



From Wright et al., 2001

Within 30 km

Cd smaller

Left Front> 30km:

waves propagate to right of wind, move faster than storm, Cd increase with U10

higher Cd than rear, right

Need more data for MBL > 60 m/s

Right side > 30 km:

waves / wind coincident

High ratio of wind to wave phase speed

Cd ~ constant with U10

Cd < left front

slightly < than rear

Need more data for MBL > 60 m/s

Rear > 30 km:

waves / wind can oppose

Cd ~ constant with U10

Cd slightly > right

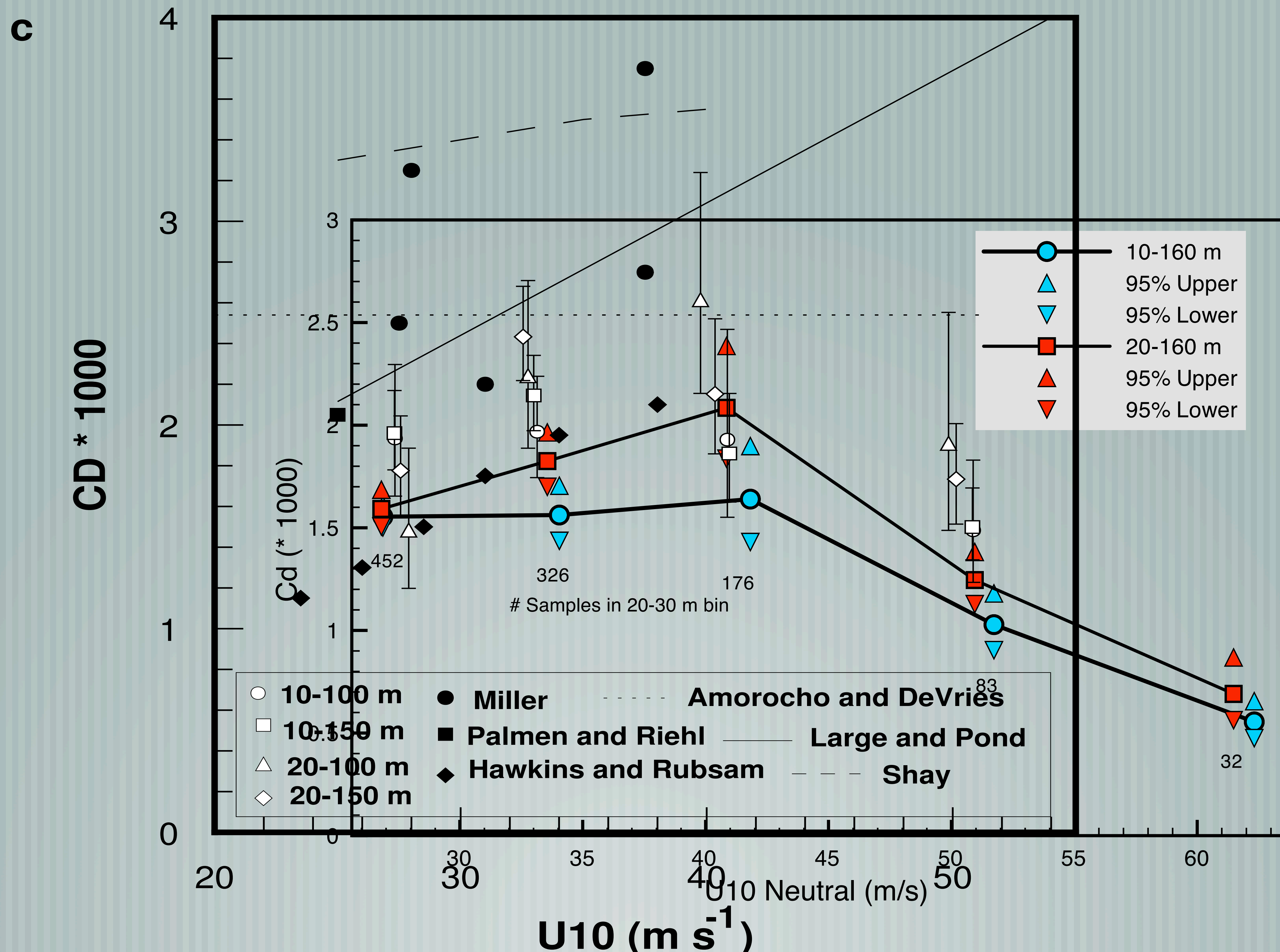
< left front

Future work:

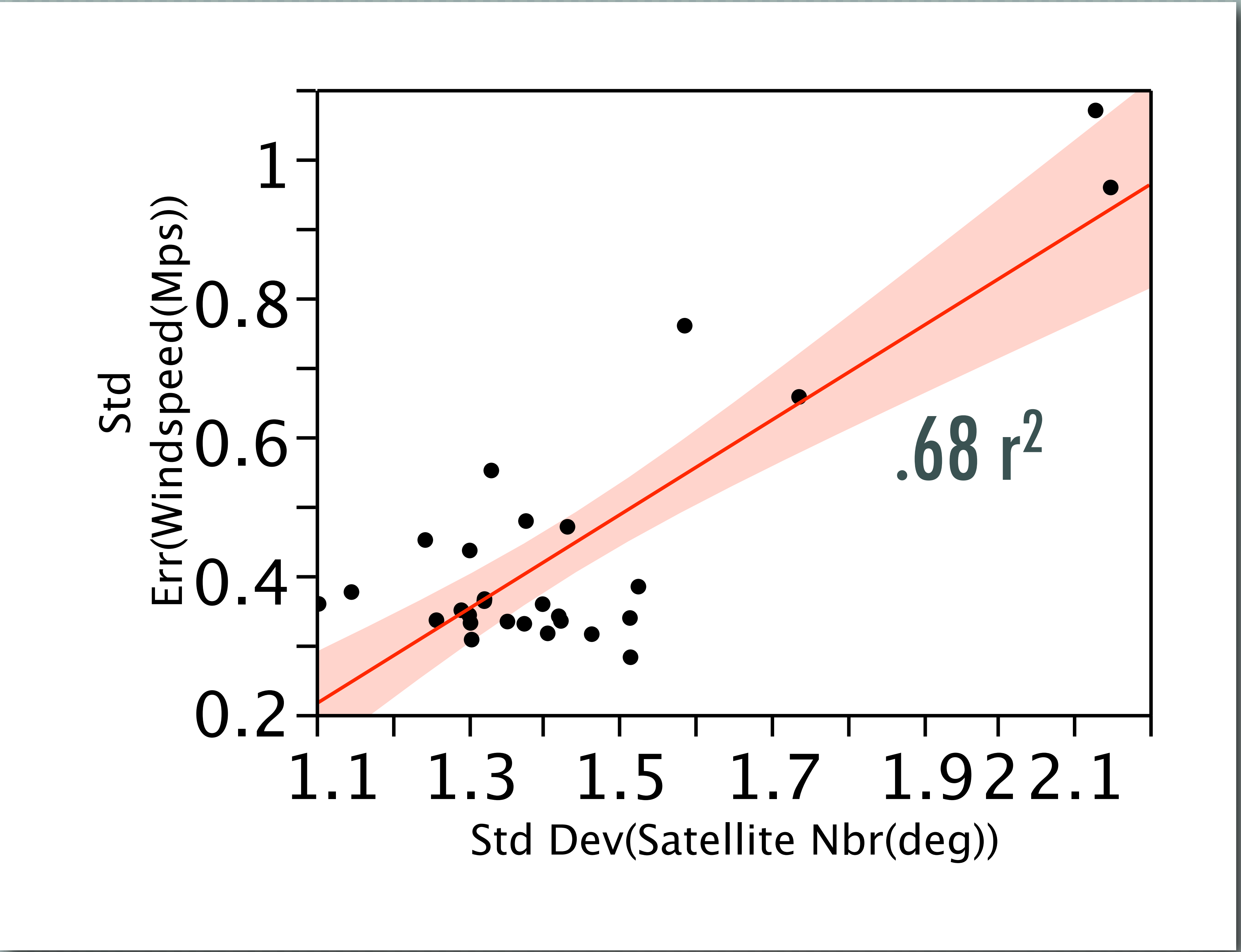
- Left front Cd increase, dependence on R/Rmax
  - Radial, azimuthal organization based on Rmax (requires a “join” with flight level data)
- Discuss with modelers at EMC
- Water depth dependence (proposed JHT)

The End

Comparison of Nature and 2007 results



Below 250 m, wind speed standard error is related to variability in satellite number, but not satellite number itself



Bias in shear correction

- One sided (upward) finite difference underestimates shear and overestimates wind
  - 1) Mean profile from 8-160 m for each MBL group
  - 2) Bias estimated from sonde “launched” into mean profile
  - 3) Bias removed from mean profile
  - 4) New profile fit to estimate slope (U*) and intercept (Zo)