Drag Coefficient Distribution and Wind Speed Dependence in Tropical Cyclones*

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OUTLINE

- Background
- Objectives
- Database
- Analysis Procedure
- Wind profiles
- Preliminary Results

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 5 times more sonde profiles

Surface layer wind profile:

Log Law for neutral stability

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

Surface stress:

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

Cd can be computed given the surface stress and wind speed, or roughness

Roughness length (Charnock):

$$Z_o = aU_*^2 / g$$

a range=0.01-0.03

- OBJECTIVES
  - Examine surface stress, Cd, roughness dependence on:
    - wind speed
    - storm relative azimuthal and radial location
    - water depth
  - Provide data to help develop new surface flux parameterizations for modeling

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

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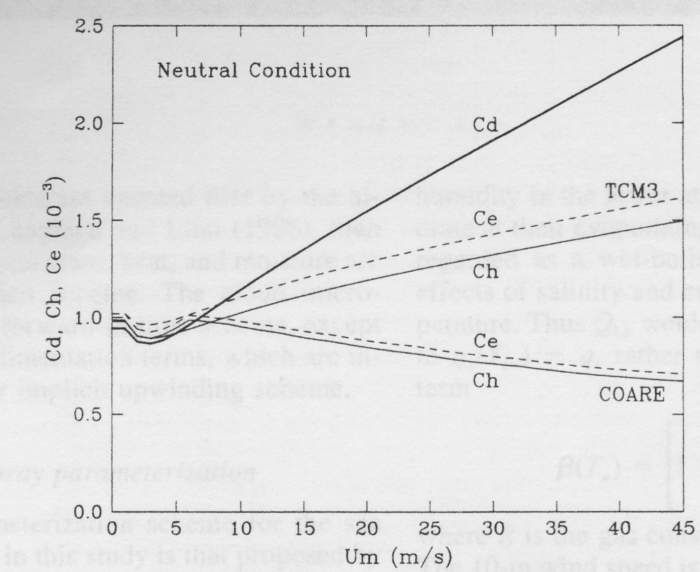
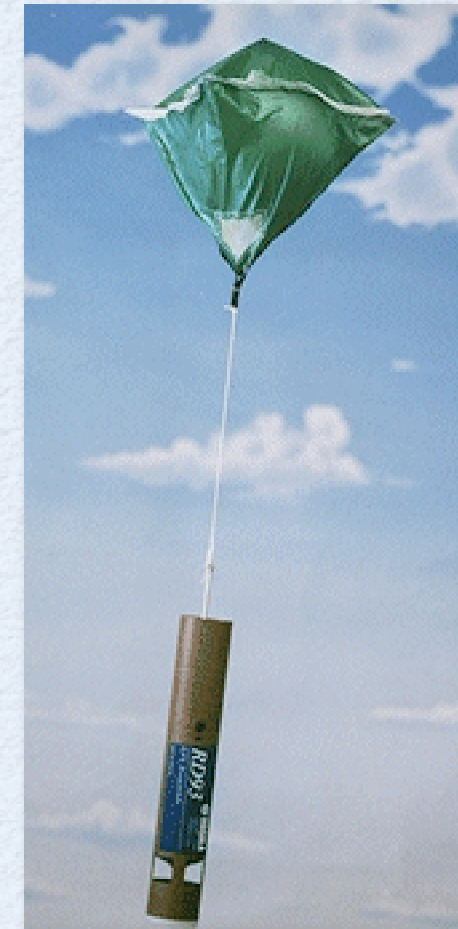


FIG. 1. Comparison of drag coefficient (Cd), exchange coefficients for heat (Ch), and moisture (Ce) as a function of wind speed at 26.5 m above the sea surface under neutral conditions, obtained by the standard TCM3 algorithm (Wang 1999) and by the COARE algorithm (Fairall et al. 1996).

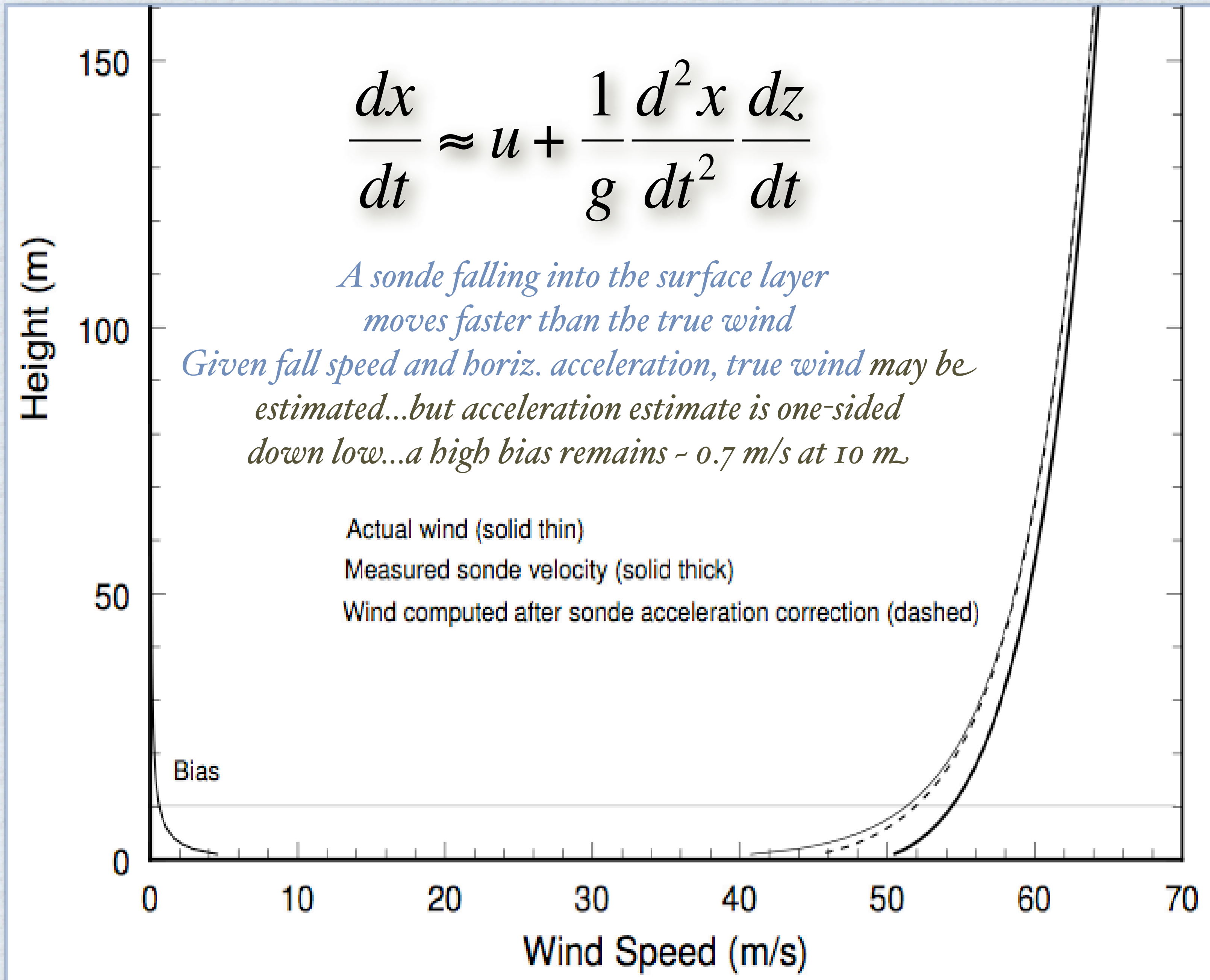
- TC Modeling
  - Charnock type roughness is used by most models
  - Some modelers also include a wave age or sea state dependence which can increase Charnock alpha by order of magnitude
  - Model parameterizations of momentum flux in the hurricane boundary layer are changing to limit or cap increase 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

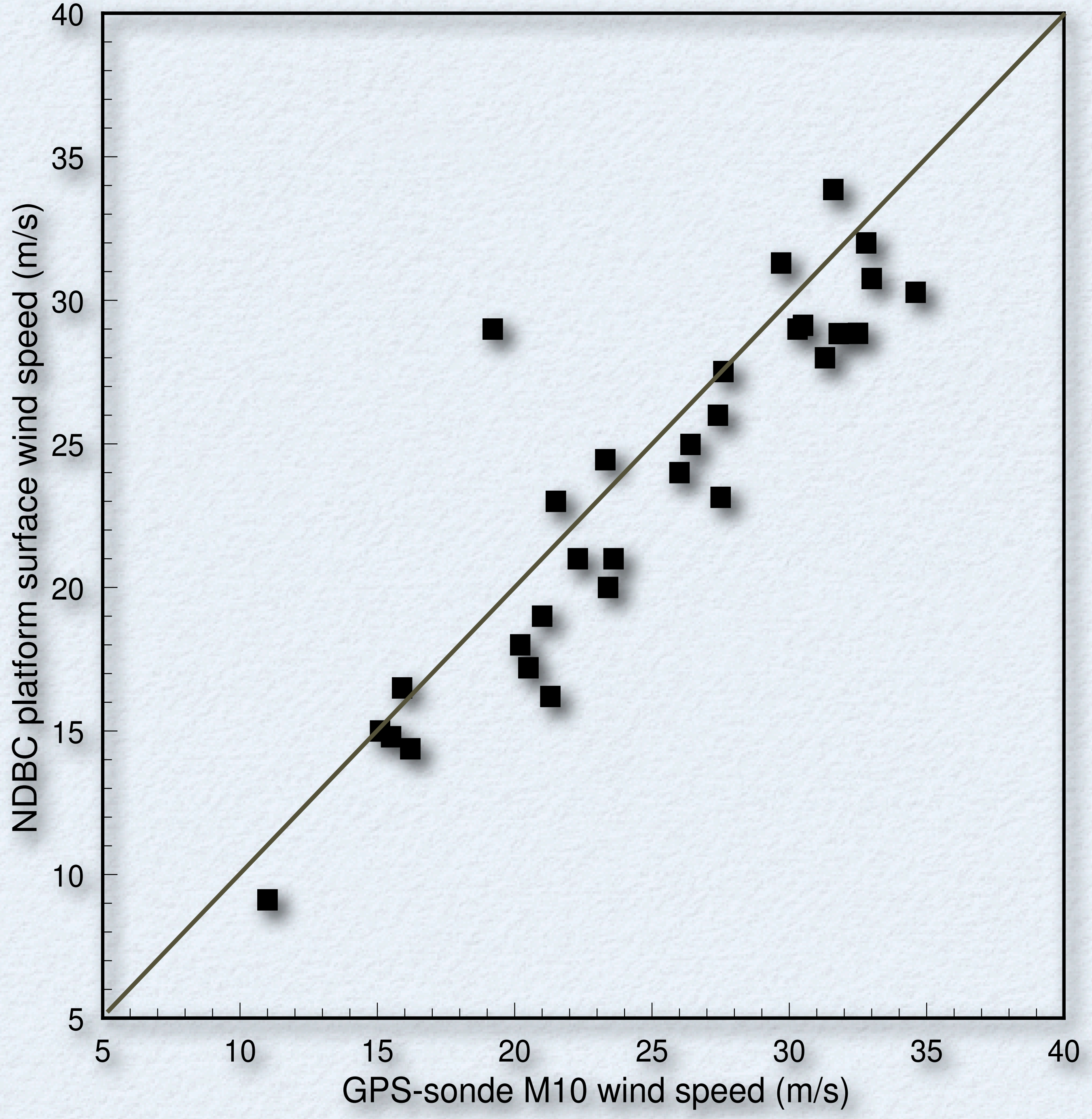
GPS Sonde wind measurement



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

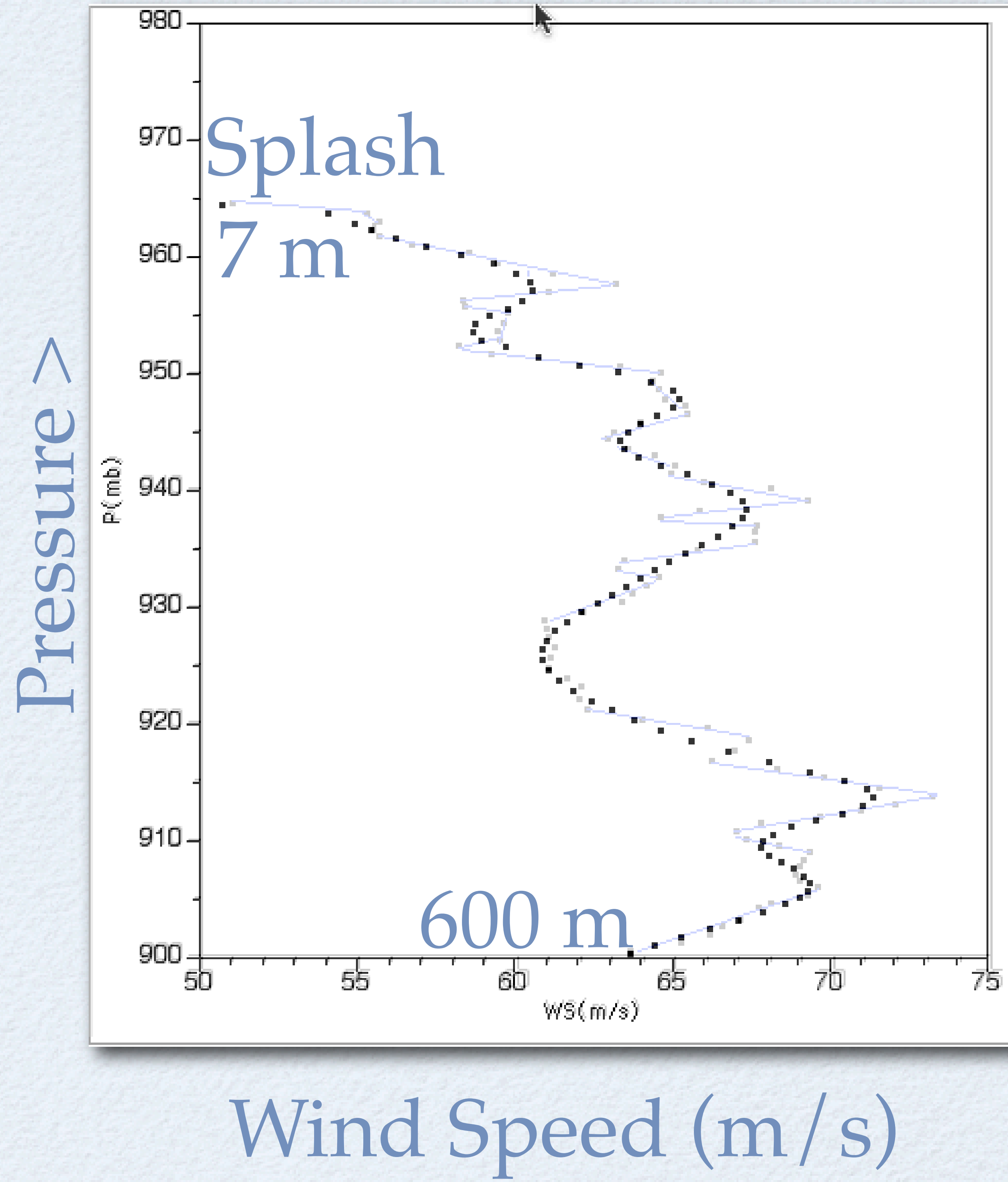
Sonde winds compared to NOAA platforms at 10 m

Houston et al. 2000



GPSSonde filtering:

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



ORGANIZING / NORMALIZING

- *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

Surface stress and Cd:

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

Database

- Inventory: 4368 sondes dropped since 1997 (not yet completed)
- ~ 40% of the sondes have been post processed by several HRD scientists using the editsonde software developed by James Franklin
- Post processed sondes have been loaded into an Oracle database designed and implemented by Nirva Morisseau -Leroy and Russell St. Fleur
- 1729 Processed sondes have been loaded into the database (as of 3-20-2006)
- Preliminary results: based on 1017 post-processed profiles

Database

MBL group (m/s)	Sonde profiles in database (3-20-2006)
20-29	226
30-39	294
40-49	255
50-59	162
60-69	123
70-79	94
80-89	26

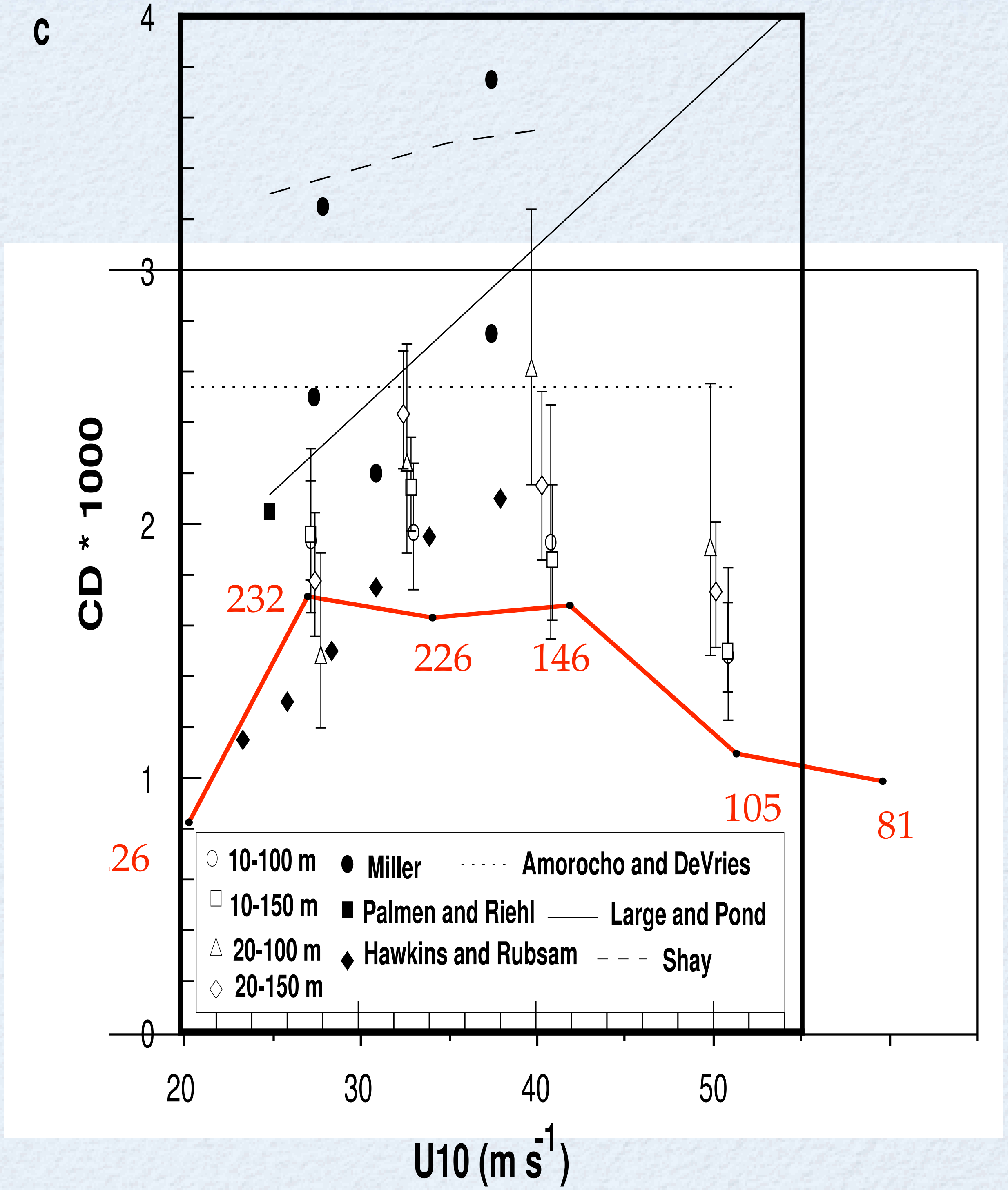
Preliminary Results

- Based on 1017/1729 profiles
- Incomplete criteria for including wind measurements and computing bin averages based on sample numbers, standard errors of the mean, # satellites, wind flags
- Profiles not corrected for bottom bias
- Error bars not computed
- Errors in storm relative positions, water depths
- Still to be linked to flight-level database to provide a scaled radial coordinate
- Lots of work remains!

Preliminary Results

Cd Dependence on 10 m neutral wind speed (red) with # profiles

Overlay: Powell et al 2003
Solid line: Large and Pond



Hurricane Waves : Profiles partitioned by S-R Azimuth

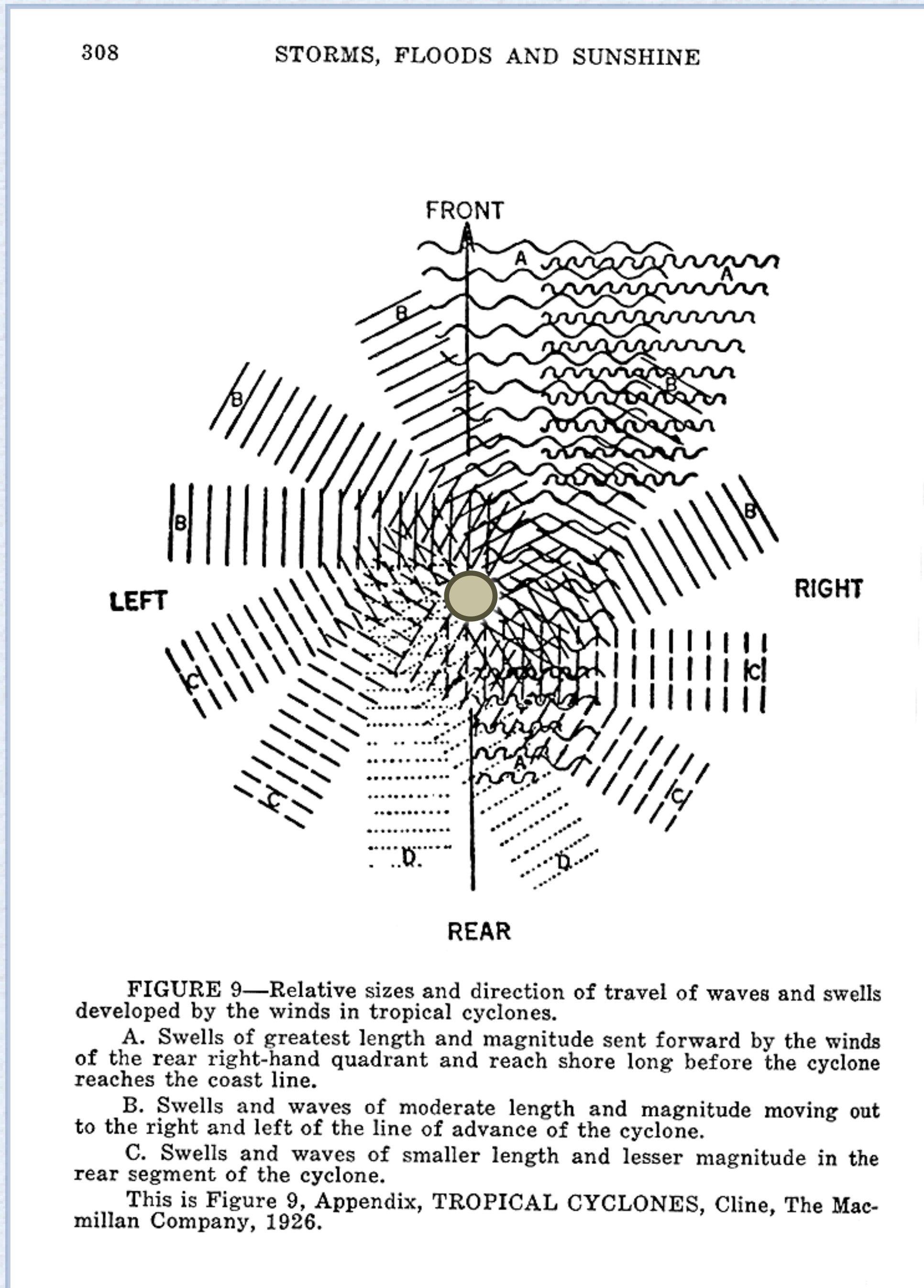

308 STORMS, FLOODS AND SUNSHINE

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.

"Tropical Cyclones"
Isaac Cline (1926)

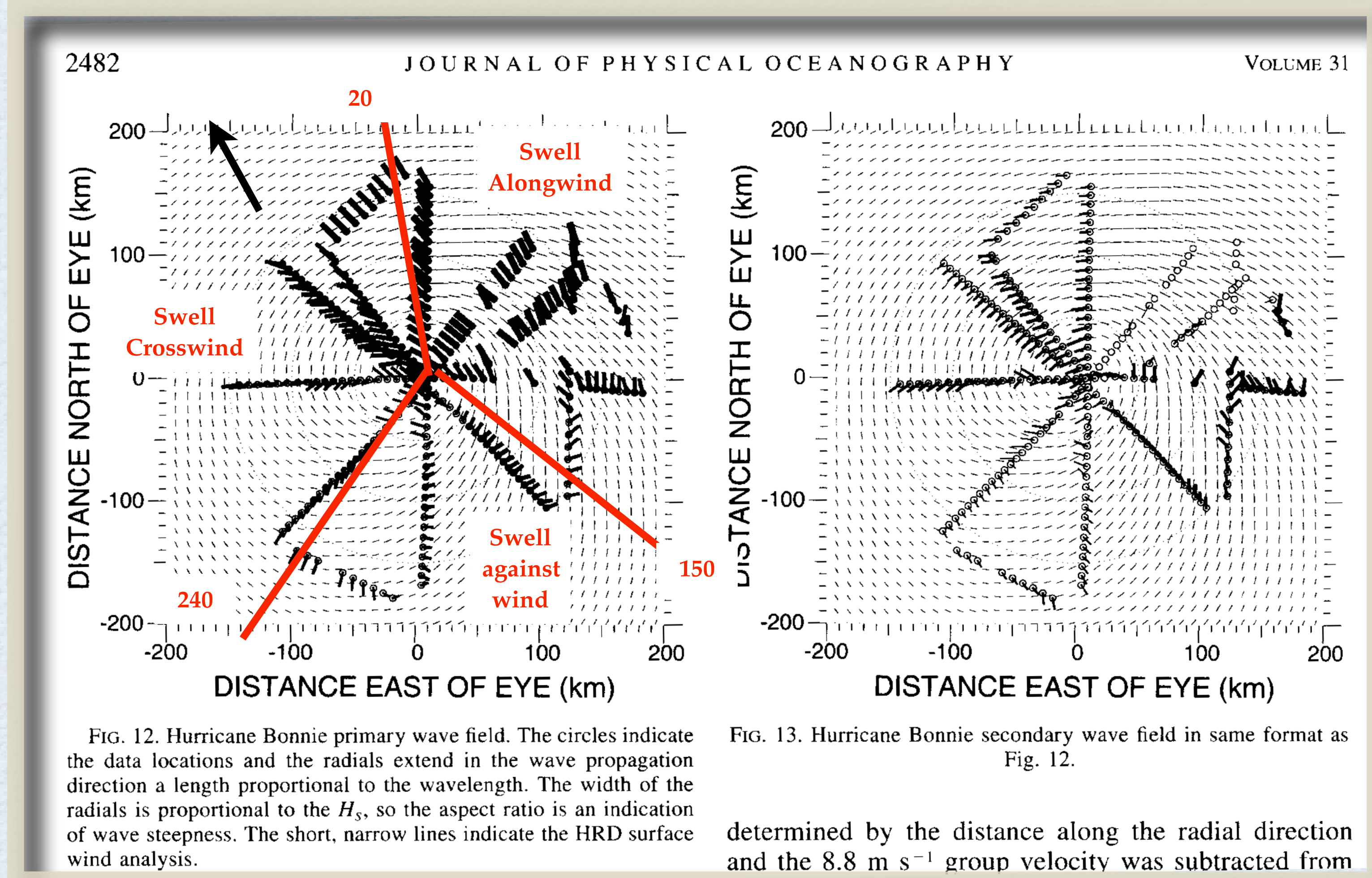

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FIG. 12. Hurricane Bonnie primary wave field. The circles indicate the data locations and the radials extend in the wave propagation direction a length proportional to the wavelength. The width of the radials is proportional to the H_s, so the aspect 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

Hurricane Bonnie: Wright et al 2001
Primary (L) and Secondary (R) wave field
Length ~ propagation direction
Width ~ H_s

Preliminary Results

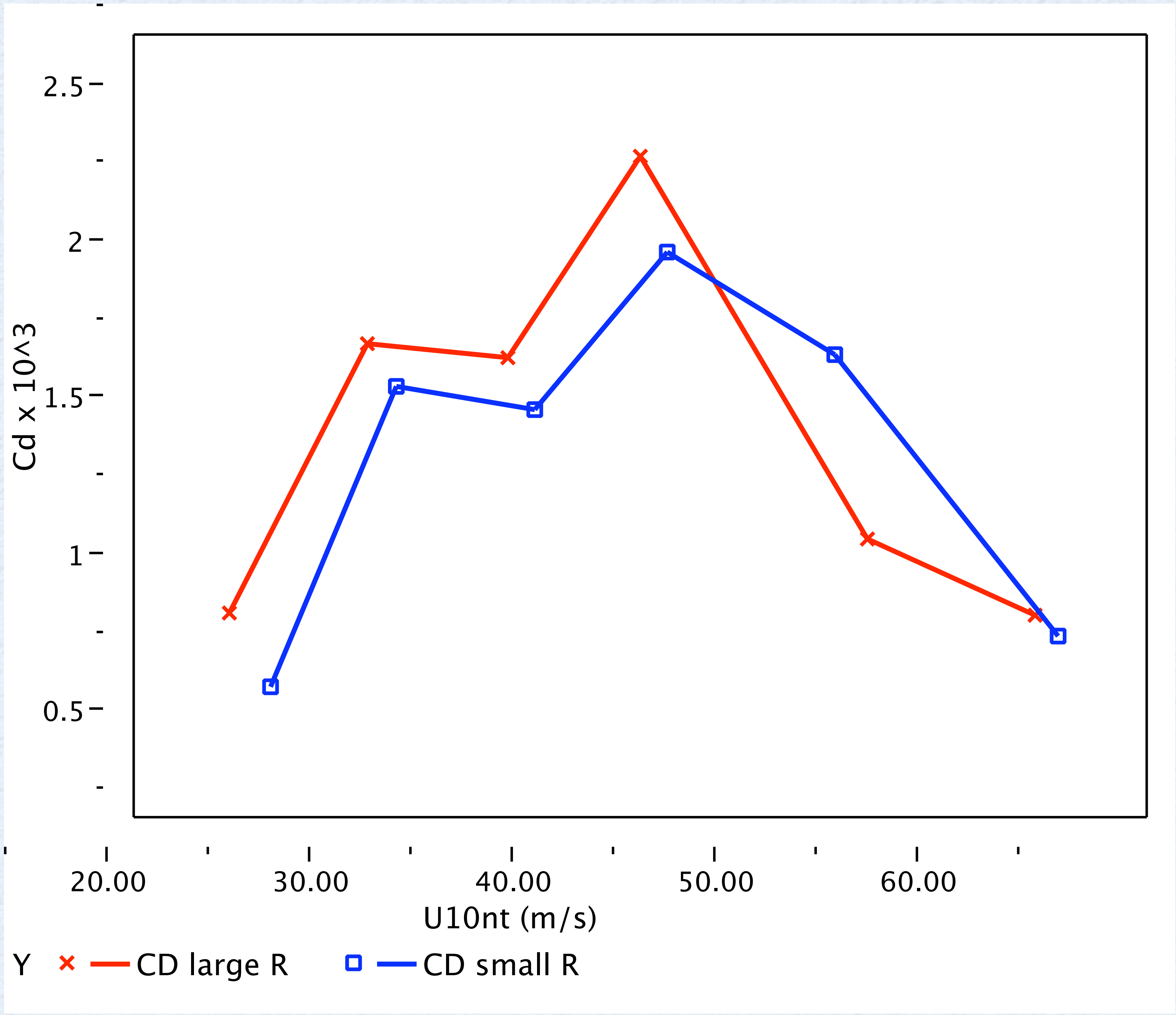
Cd Dependence on radial distance (~32 km if MBL > 40)

Radial distance errors in about 10% of sondes

Unexpected increase above 40 m/s

Profiles closer to the center show smaller Cd

Possibly related to profile scaling with inertial stability (Kepert 2001)



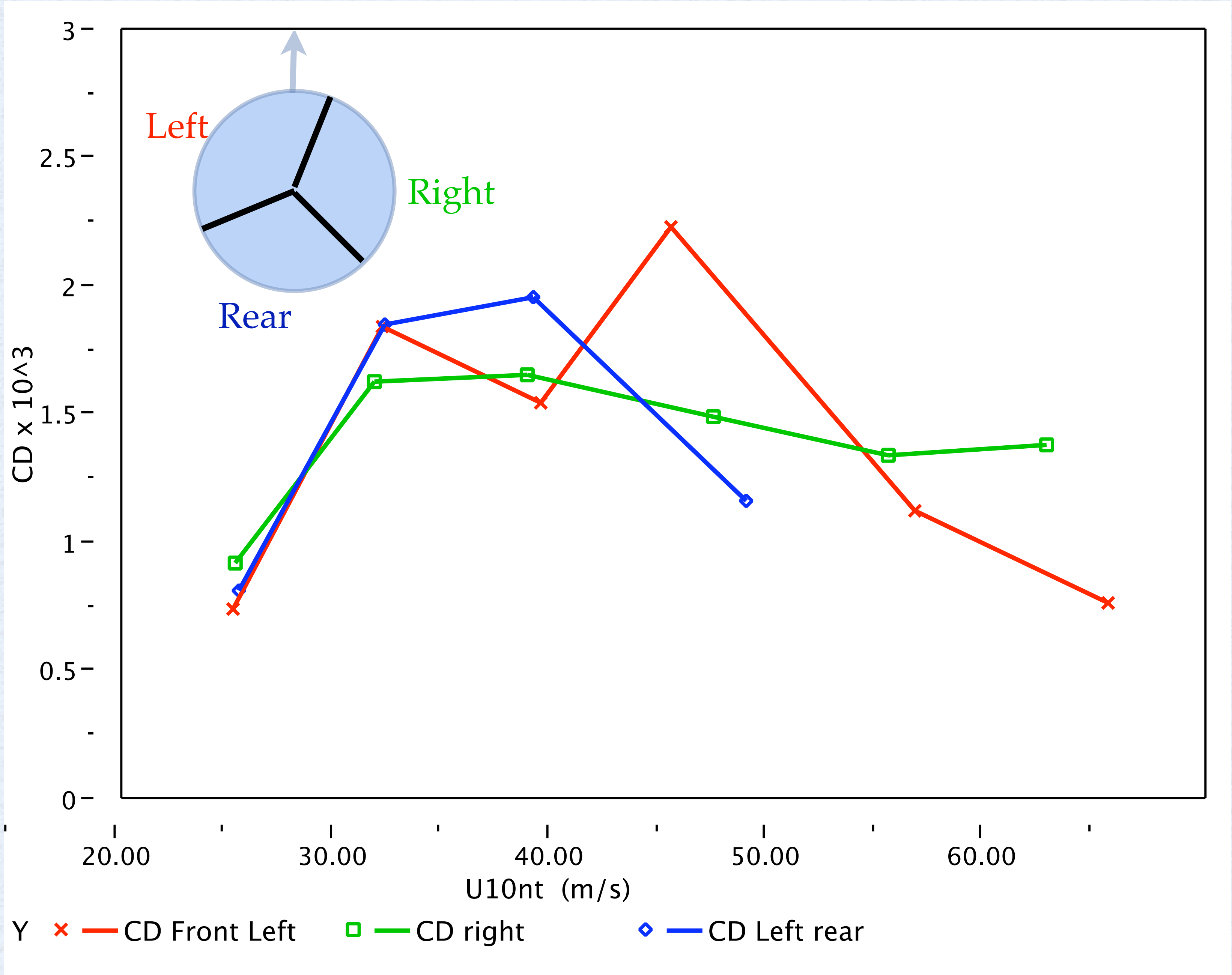
Preliminary Results

Cd Dependence on storm relative azimuth

Not as pronounced as expected

Need to add profiles and apply QC criteria for bin averages

May also need to account for radial position



Remaining Work

- Complete loading processed sondes to database through 2005
- Detailed analysis of profiles for dependence on location, wind speed, and water depth
- Share results with modeling community

- Drag coefficient behavior
  - Wind speed dependence: Numerous studies show Cd increase with wind speed but lots of scatter, no measurements above 25 m/s, decrease with fetch
  - Wave age dependence (Donelan, Janssen) : Fetch limited conditions, developing waves extract more momentum than fully developed waves. Much of stress is wave induced vs. atmospheric turbulence. Older waves have less influence on stress than younger waves. Opposite and cross-wind swell produce larger Cd.
  - Shoaling/Breaking waves: suggestion of larger Charnock alpha in shallow water

Speculation on why stress levels off (shear ~ constant) and roughness decreases (high near-surface winds)

Sampling Issues

Sondes caught in convergent portion of “roll vortices” ?
Sondes move horizontally towards sfc wind max while falling ?

Supporting Evidence

Sea state catalogs suggest > 90% foam coverage in > 50 m/s winds

Foam layers create a “slip” layer that impedes momentum transfer
Bubble annulus studies at Woods Hole (Alamaro 2002, Lundquist 1999)

C and Ku band Scatterometer measurements of normalized radar cross-section show saturation/decrease at winds > 40 m/s (Donnelly 1999, Carswell 2002). Capillary waves not relevant to wave-induced stress at > 40 m/s but small scale ocean roughness may be decreasing.

Flume experiments suggest wave separation zones cause wind to “see” a smoother surface (Donelan 2002)

- Other recent studies:

  - Moon et al. Moon et al >30 m/s young waves yield lower Cd...young waves have much smaller effect on stress when winds are strong. Larger Cd ahead and to right of storm where waves are high, long, more developed; Lower Cd behind and to left where waves are lower, shorter, and younger.

  - Emanuel (JAS, in press) Dimensional analysis for an emulsion layer. Cd scales with U* or Vg, i.e. independent of wind speed in high > 50 m/s winds, capping Cd and Ck when U~ 33 m/s or linear increases give accurate hindcasts ...(doesn't account for a decrease in Cd for const. U*)

  - Fairall, Frank: Water loading stabilizes the sfc layer and increases Cd