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Analysis of Sub-Grid Boundary Layer Processes Observed by TODWL in Support of the Western Pacific Tropical Cyclone DRI (TCS-08)

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LONG-TERM GOALS

The long-term goals of this research are to (1) demonstrate that a coherent Doppler wind lidar can provide useful wind profile and other data in the environment surrounding tropical cyclones; (2) analyze the quality of the lidar wind profiles; and (3) investigate typhoon boundary layer processes using the lidar wind profile.

OBJECTIVES

Our research objectives are to use the lidar data acquired during TCS-08 to produce vertical wind profiles in the boundary layers surrounding incipient and mature tropical cyclones. Once the boundary layer wind profiles have been produced, they must be evaluated against the available drop sonde profiles and Doppler radar winds from Eldora and finally used to understand boundary layer processes surrounding typhoons in conjunction with simple models (Foster 2005; Foster, 2009)

APPROACH

The Tropical Cyclone Structure, 2008 (TCS-08) was conducted August through September in the West Pacific Ocean. The goal was to study the wind structure in and around developing and mature tropical cyclones. TCS-08 was primarily funded by ONR and NSF and was conducted as part of the THORPEX Pacific Asian Regional Campaign experiment. Multiple aircraft were deployed, including Air Force C-130s, the NRL P-3, the Taiwanese Dotstar and the DLR Falcon, which deployed a separate Doppler wind lidar and flew at higher altitude than the P-3. The P-3 was equipped with the NCAR Eldora Doppler Radar and a Doppler wind lidar (P3DWL) and primarily operated out of Guam. The P3DWL was funded by the ONR with hardware provided by the ARL, NRL and NASA.

The P3DWL uses the latest version of a 1.6 micron coherent Doppler transceiver developed at Lockheed Martin Coherent Technologies coupled with a biaxial scanner mounted outside of the aircraft. The scanner has an azimuthal range of ±30° and an elevation range of ±120°. The P3DWL as installed on the NRL P-3 is shown in Figure 1. The scanner is computer-controlled with a number of pre-planned scanning strategies. The photons scatter off aerosols, which are assumed to move with the wind, and the resulting Doppler shift of the received photons provides the line-of-sight (LOS) velocity.

The most common scanning sequence used during TCS-08 was a twelve-point downward step-stare through 360° of azimuth (20° off nadir cone angle, each step lasting 1 sec with about a 5 second slew) followed by a 5 second nadir stare. This pattern was repeated throughout the flight unless a decision was made to use a special sampling strategy. The lidar operates at 100 Hz, so each dwell includes about 100 individual laser shots, which are processed into a single LOS velocity profile at this perspective. The sets of twelve off-nadir LOS wind profiles are processed into a single vertical wind vector profile with 50 m range gates from 200 to 300 m below flight level (which was typically about 3000 m) down to 200 m above the sea surface. The spacing between vertical wind profiles along the flight path is about 3.3 km for typical P-3 ground speeds. In the lowest layer adjacent to the surface (LAS, 0 to 200 m) special processing is required to separate the aerosol return from the reflection off the surface. It is crucial that accurate aircraft attitudes (latitude, longitude, altitude, roll, pitch, yaw) be provided to the lidar system in order to correctly navigate the LOS wind profiles.

WORK COMPLETED

During initial processing, it was determined that a hardware problem in the P-3 induced errors into the stream of aircraft attitude data that was fed into the lidar system. The errors were subtle and interacted in a non linear fashion. Because of this, not all vertical profiles were significantly affected and it took some time to detect the error. Once the source of the error was identified, a method for estimating the aircraft state had to be developed as well as a new methodology for extracting the vertical wind profiles. This was a time-consuming effort and a usable science product was only produced in late August, 2010. Previously, vertical wind profiles were calculated using a standard VAD technique. Currently, they are produced using an optimization method, which, in the long run, should prove more robust. Note that any given vertical profile might not be continuous. Some layers will produce no returns, usually due to rain absorption. However, LOS winds and horizontal wind vectors are often obtained from layers below the intervening absorbing layers. This is possible because a small number of individual photons can pass through the cloud and rain contamination without interaction.

Including the ferry flights to and from Guam and between bases during TCS-08 and ground based testing, there are 171 hours of lidar data. There were 18 flights in and around tropical storms during TCS-08, for a total of 118 hours of lidar data. During the flights at ~3000 m altitude, approximately 82% of the LOS profiles detected a surface return (although not necessarily a horizontal wind vector at the 200 m level). This is much higher than might be expected in typhoon environments.

To get a sense of the P3DWL sampling, we can look at the distribution of retrieved wind vectors in the vertical profile during the second of three flights into TS Nuri. Excluding five profile files for which no vectors were retrieved, there were 443 P3DWL vertical wind profiles (vs. six usable drop sondes – eight dropped with two failures). Of these, 73% retrieved a horizontal wind vector at the lowest level of 200 m. Only about 10% of the profiles had a lowest vector above 1000 m. (Figure 2a). There are 37 possible ranges gates in the layer between 200 m and 2000 m. On average, the P3DWL profiles

retrieved vectors for about half of the possible heights (19 gates). About 16% of the profiles included 30 or more heights in this layer and about 18% had ten or fewer vectors in this layer (Figure 2b).

The vertical wind vector profiles were provided to Zhaoxia Pu of the University of Utah, who examined their impact on WRF mesoscale model runs of Nuri (Pu et al., 2010). She found a positive impact in terms of its formation, track and intensity. Including the DWL winds enhanced the low-level convergence and upper-level divergence during the transition from tropical disturbance to tropical depression. In a 48 hour simulation, including the DWL winds increased the surface winds from about 20 m s^{-1} in the control case to ~30 m s^{-1} (JTWC best track reached ~37 ms^{-1}). Figure 3, taken from Pu et al. (2010), shows the impact of the P3DWL winds on the WRF model runs using 3-D VAR and 4-D VAR. 4-D VAR produces the best results.

RESULTS

A subjective quality ranking was applied to the profiles. The highest quality (A) had no evident rain contaminations and few gaps. Lower quality (B and C) were still considered to have good data, but may have isolated rain contamination (B) and/or gaps (C). The lowest quality profiles (D) either had few or no vectors or severe rain contamination. Figure 4a shows the subjective quality rankings for the profiles obtained during the second flight into TS Nuri. Note that most of the profiles are in category C indicating gaps and possible residual rain contamination within the profiles.

We are presently assessing the quality of the retrievals by comparing the drop sondes with the nearest-in-time P3DWL profiles. Of particular interest is to validate the correction for the aircraft state. The comparison is difficult since the DWL and the sondes are fundamentally different measurements taken in conditions where there can be significant spatial variability. The same volumes of air are not sampled. Sondes follow a several-minute-long quasi-Lagrangian descent in which they are blown by the wind. The splash point can be eight or more km from the drop point. In TC conditions when the aircraft is circling the storm center, the splash point is usually closer to the storm center. In contrast, the DWL profiles are constructed from a cycloidal cone sampling of the air below the aircraft over a period of about one and a half minutes and an along-track distance of about 3.3 km. The locations of the six drop sondes and the near-in-time P3DWL profiles are shown in Figure 4b.

An objective scoring method for comparing vector profiles was described in Kundu (1976). This is a complex correlation coefficient defined as

$$\rho = \frac{\langle w^* w \rangle}{\langle w_1^* w_1 \rangle^{1/2} \langle w_2^* w_2 \rangle^{1/2}} \tag{1}$$

in which the vector profiles are converted into complex numbers, $w(z) = u(z) + iv(z)$. The absolute value of ρ gives the overall correlation and the phase angle is a speed-weighted overall veering angle between the profiles. Ideally $|\rho| = 1$ and the phase angle is zero. The speed-weighted phase angles, around 10° to 15°, for the second Nuri flight are shown in Figure 4b.

We compare the P3DWL profiles to the sondes for the layer between 200 m to 2000 m. The sonde winds were vector averaged within the DWL range bins before comparison. Results are shown in

Figure 5 for all of the drop sondes from *all* flights during TCS-08. As expected, the magnitudes of the correlation coefficients are much higher when only category A profiles are compared. The correlation decreases overall as profiles of lesser quality are included, however, 90% of the profiles have correlation coefficients over 0.95 for all classes A-C (Figure 5a). The phase angles are of greatest interest. Overall the mean phase angles are near zero. The width of the phase angle distribution increases when classes B and C are included (Figure 5bcd) and the distributions do not appear to be normal. The tails of the phase angle distributions are heavy and there is a relatively high frequency of non-zero phase angles.

One set of P3DWL wind profiles compared to a drop sonde from the second Nuri flight is shown in Figure 6. Visual inspection of many such comparisons suggested that an overall rotation of the DWL profiles might improve the agreement with the sondes. The magenta curves in Figures 6 show the P3DWL wind profiles rotated by phase angle defined by (1). This rotation usually improves the agreement between the sondes and the P3DWL.

Understanding the sonde/P3DWL profile comparison is the current focus of our research. It is important to understand if the apparent rotation indicates an error in the reprocessed P3DWL profiles requiring an improved aircraft state correction methodology or if it reflects the differences in the measurements in tropical storm and/or cyclone conditions. The Kundu correlation coefficient will be used to objectively remove likely rain contaminated vectors within the profiles. Once this issue is better understood, we can pursue our goal of using these wind profiles to better understand how the TC boundary layer interacts with the airflow in the interior and with the sea surface.

IMPACT/APPLICATIONS

The P3DWL data acquired during TCS-08 represents first-time data from a first-time instrument in tropical cyclone research. These early data products revealed mostly good results and comparisons with dropsondes and flight level observations. Measurements to the surface from 3km were much more numerous than would have been expected for Typhoon environments. About half of the DWL wind vector profiles contained about half of the possible wind vectors within the layer between 200 m and 2000 m. However, wind profiles were obtained almost continuously during the P-3 flights with a typical along-track spacing of 3.3 km. Thus, once validated, this system represents an enormous potential impact on the number and quality of boundary layer wind profiles in and around tropical cyclones.

PUBLICATIONS

Pu, Z, L Zhang and G.D. Emmitt 2010: Impact of airborne Doppler wind lidar profiles on numerical simulations of a tropical cyclone. *Geophys. Res. Lett*. **37**, L05801, doi:10.1029/2009GL041765.

Foster, R.C. and G.D. Emmitt 2010: Doppler Lidar wind profiles in TCS-08, *17th Conference on Air–Sea Interaction*, 27-30 Sep, 2010, Annapolis MD.

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Foster RC 2009: Boundary-layer similarity under an axi-symmetric, gradient wind vortex. *Bound.-Lay Meteorol*. **131** 321-344.

Pu, Z, L Zhang and G.D. Emmitt 2010: Impact of airborne Doppler wind lidar profiles on numerical simulations of a tropical cyclone. *Geophys. Res. Lett*. **37**, L05801, doi:10.1029/2009GL041765.

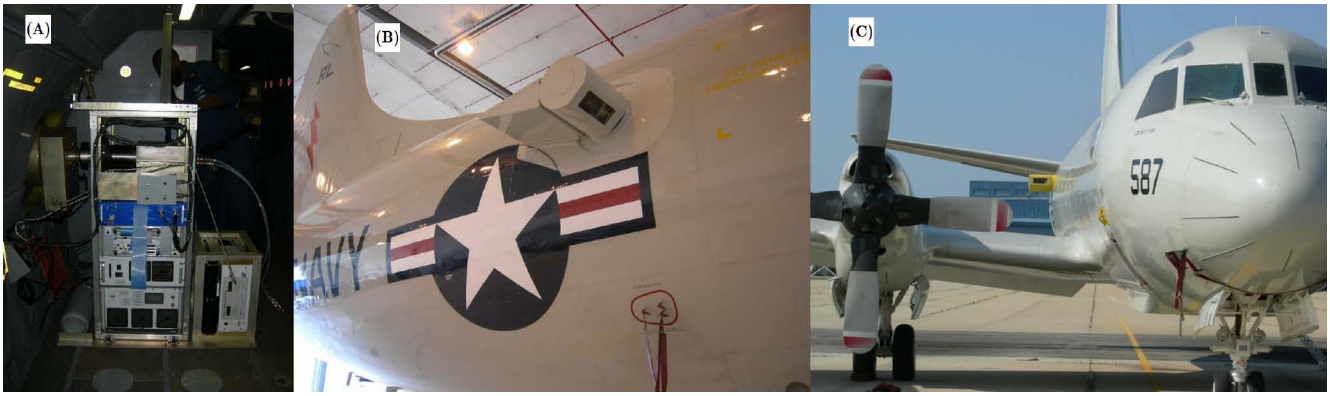

Figure 1 P3DWL system on the NRL P-3. (a) 1.6 µm Lidar transceiver and computer control. (b) 10 cm bi-axial scanner mounted on right side of NRL P-3. (c) Front view of P-3 showing scanner.

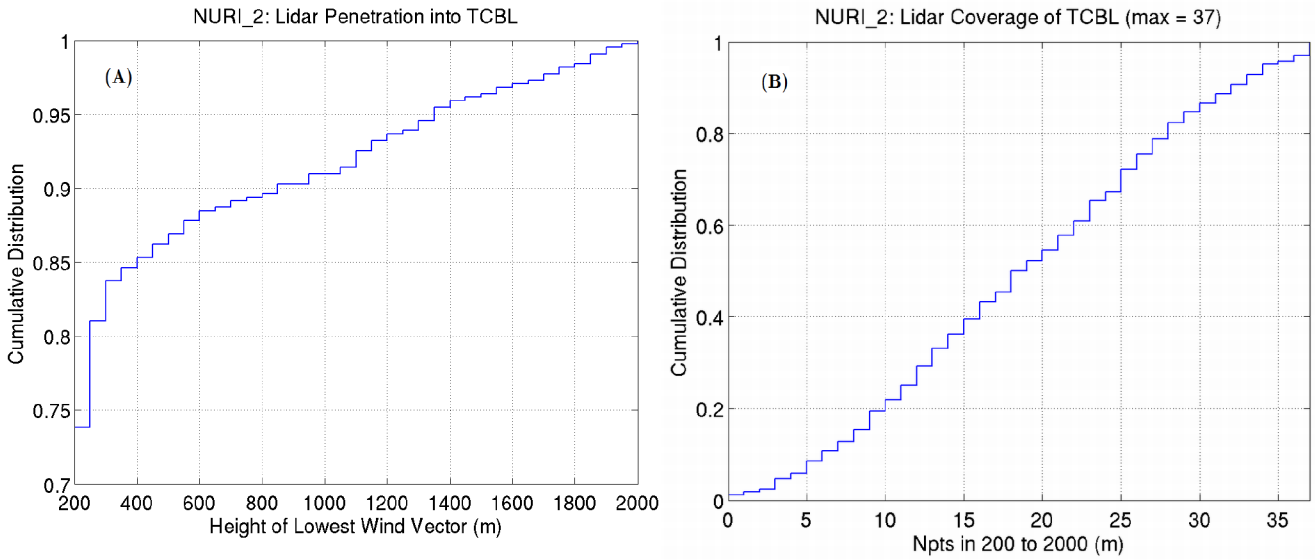

Figure 2 P3DWL sampling of boundary layer during the second flight into pre-Typhoon Nuri, 16-17 August, 2008, 22:14 to 03:19 UTC. (a) Cumulative distribution function of height of lowest retrieved wind vector in the layer between 200 m and 2000 m. (b) Cumulative distribution function of number of levels at which wind vectors were retrieved in the layer between 200 m and 2000 m (maximum possible is 37).

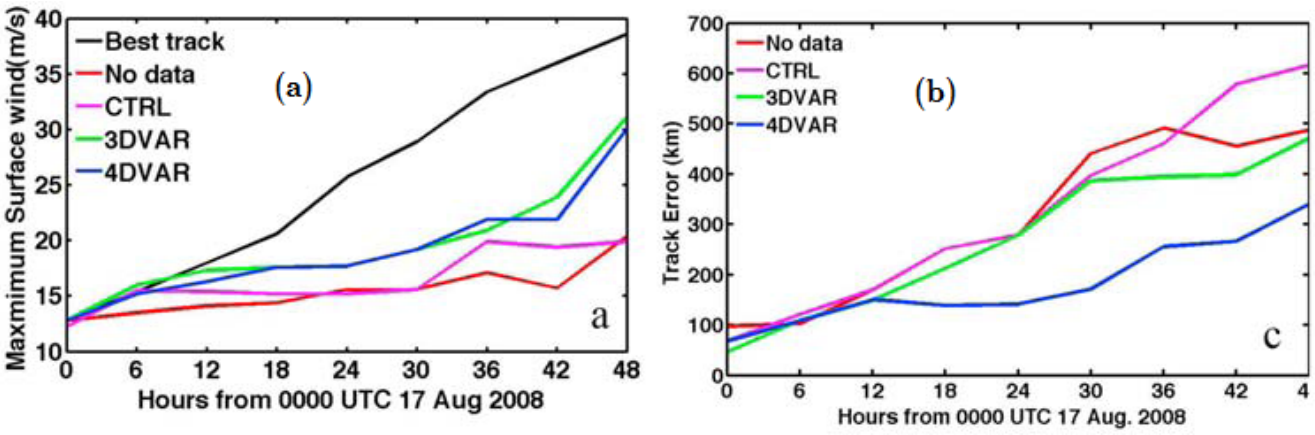

Figure 3: Impact of P3DWL winds on simulation of Typhoon Nuri. (a) intensity, (b) track. The blue and green curves show the effect of including P3DWL winds using 3-D VAR and 4-D VAR respectively.

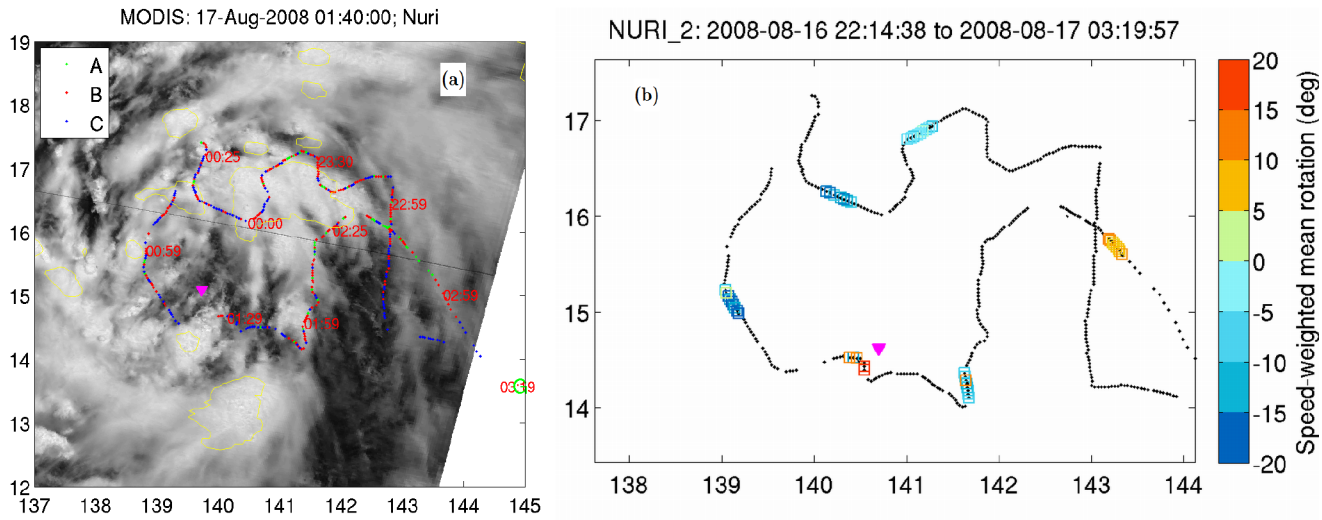

Figure 4 NRL P-3 flight track for 2nd flight into TS Nuri. The latitude and longitudes have been approximately adjusted using the JTWC best track. (a) P-3 flight track superposed onto MODIS visible imagery from 17 August, 2010 01:40 UTC. Yellow contours are the 200 K cloud top temperatures. Times along the flight track are indicated. Each dot represents a single P3DWL wind vector profile. The color indicates the subjective quality rating. Magenta triangle is approximate storm center. (b) As in (a), except the flight track is adjusted to the mid-flight time. Each black dot represents a single P3DWL wind profile. The colored boxes mark the P3DWL profiles that were within a few minutes of the six drop sondes. The box colors represent the speed-weighted mean rotation angle between the drop sonde profile and the P3DWL profile.

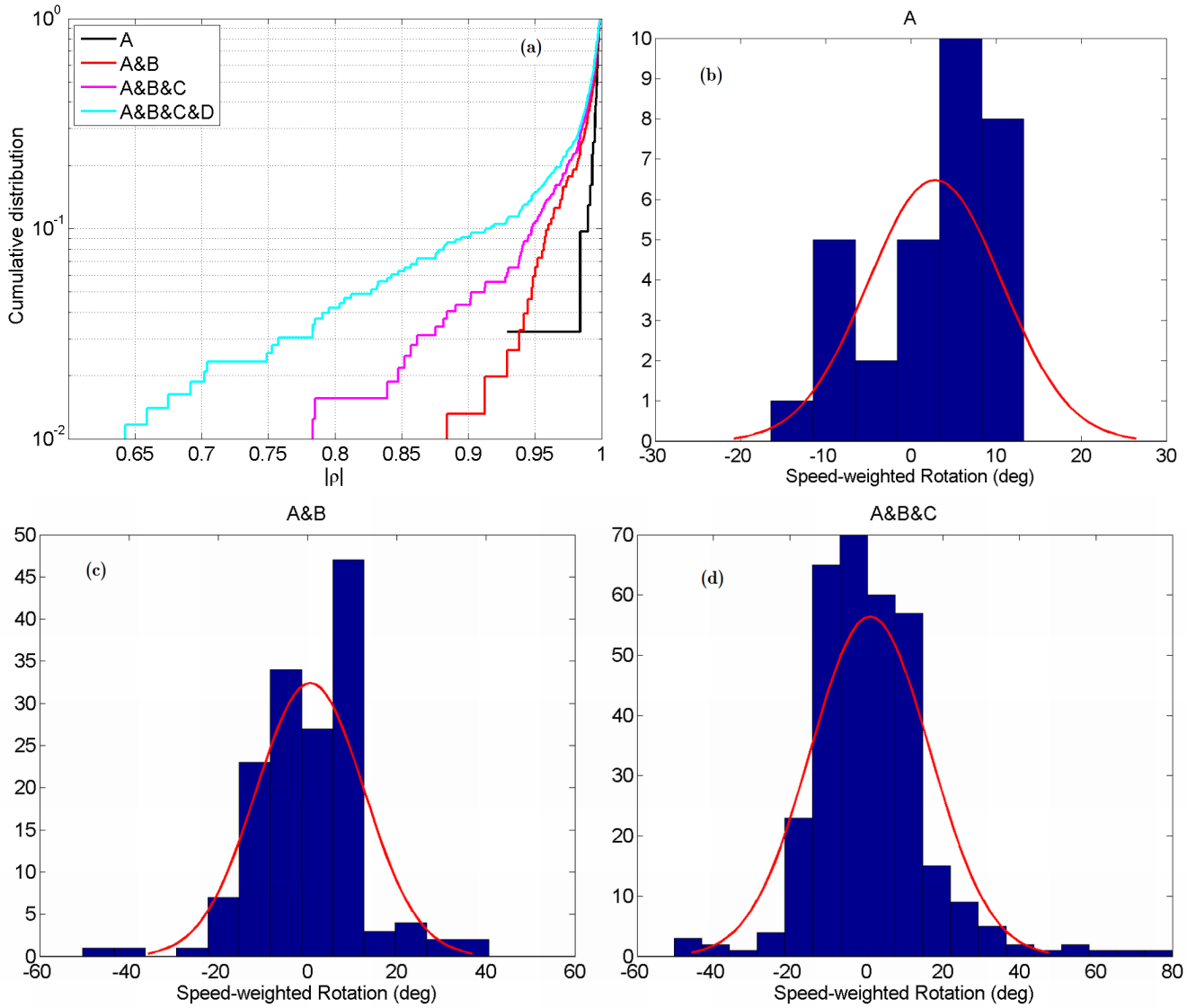

Figure 5 Kundu correlation coefficient applied to P3DWL profiles with near-in-time drop sondes from all flights during TCS-08. (a) Cumulative distribution functions for IρI for the different subjective quality rankings. In (b-d) the phase angle (speed-weighted mean rotation) is plotted. For reference, the best fit normal distribution is plotted in red. (b) Quality A only. (c) qualities A&B. (d) qualities A,B&C.

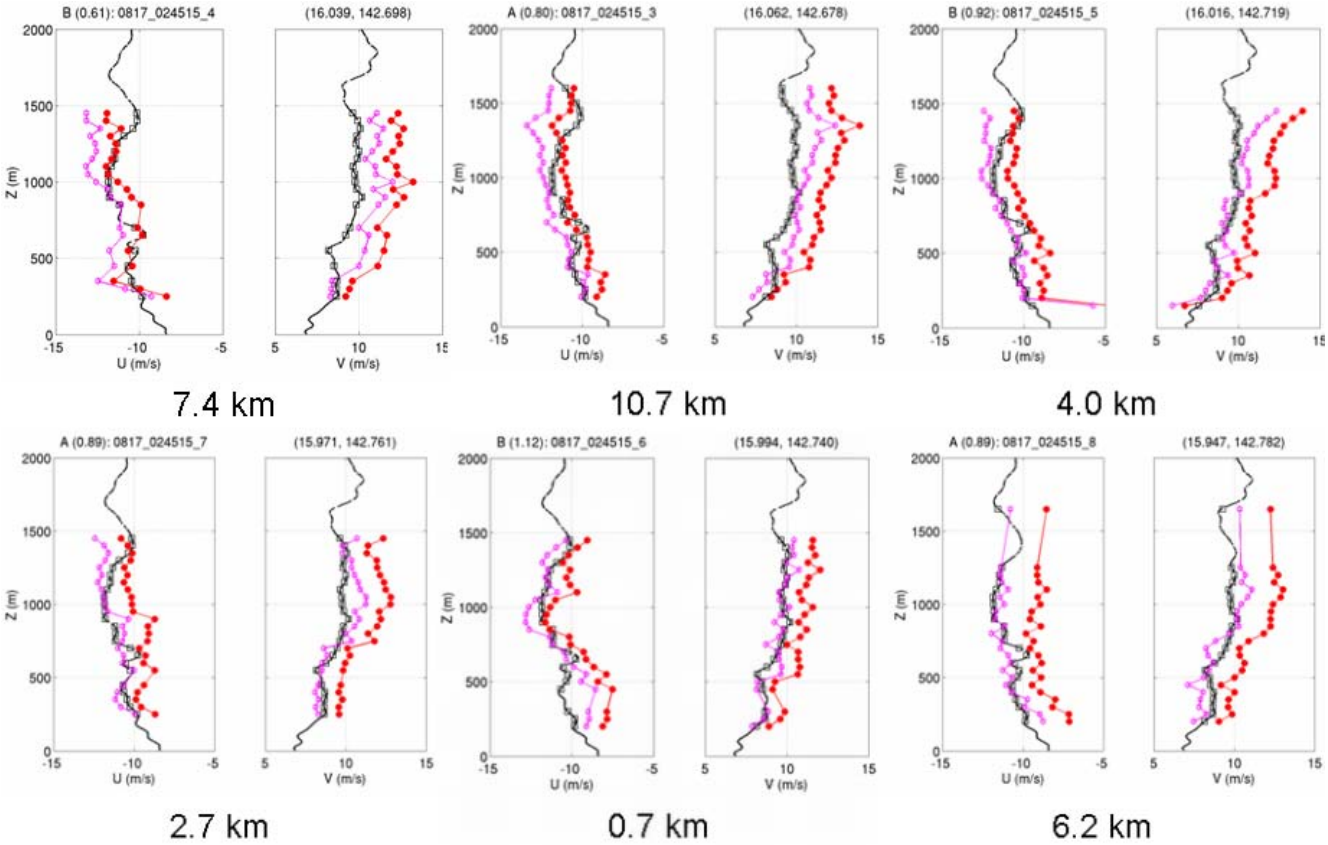

Figure 6 Comparison of six P3DWL wind profiles with drop sonde (17 Aug 2010 02:45 UTC) during 2nd TS Nuri flight. The distance from the location of the sonde drop is shown for each P3DWL profile. Drop sonde U,V profiles are in black. The uncorrected P3DWL profiles are plotted in red. Profiles rotated by the Kundu phase angle are plotted in magenta.