Tropical Cyclone Radar Archive of Doppler Analyses with Recentering (TC-RADAR)

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1. Introduction and motivation:

NOAA's Hurricane Research Division (HRD) routinely collects airborne radar observations of tropical cyclones (TCs) in the North Atlantic, and occasionally, the eastern and central North Pacific basins. Onboard NOAA's P3 aircraft are three radars, located on the nose, lower fuselage, and tail of the aircraft (for more information, see: https://www.aoml.noaa.gov/hrd/about_hrd/HRD-P3_radar.html). The tail Doppler radar (TDR) is an X-band radar that scans in both the fore and aft directions, allowing observations of the three-dimensional kinematic structure of a TC (Gamache et al. 1995). Typically, a given mission will have 3–4 passes through the center of the storm. For each center pass through the storm, a TDR analysis is created. In typical operating conditions, radar observations only extend outward ~50 km from the aircraft, limiting the azimuthal coverage of the storm. An example of the coverage the TDR provides for a set of passes is shown in Fig. 1 below.

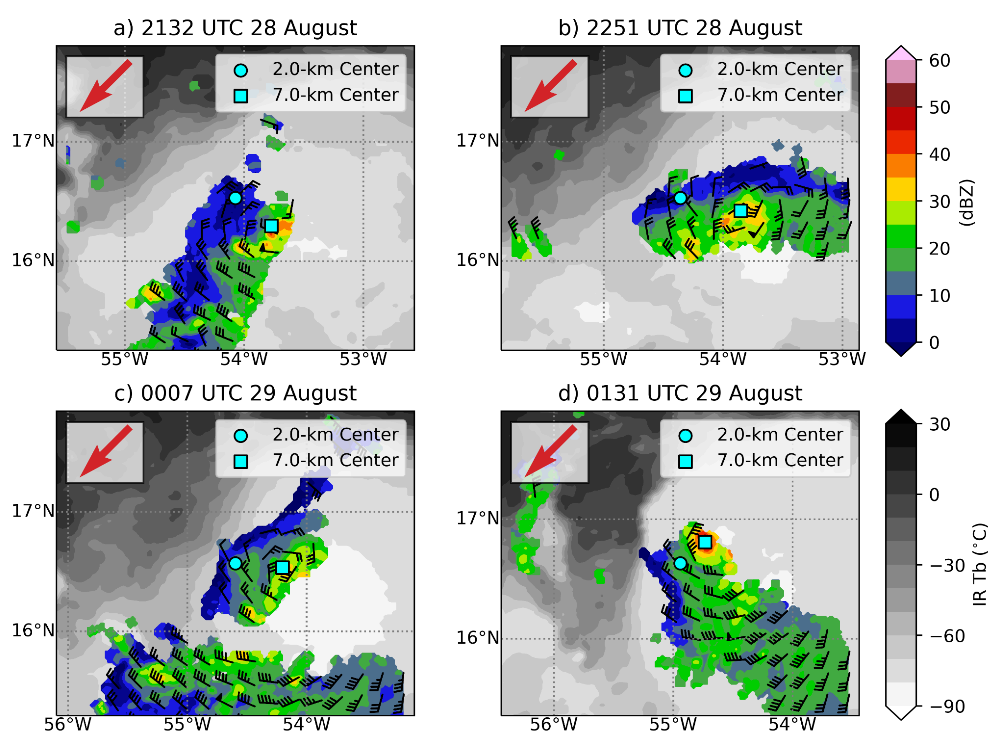

Fig. 1. *a) TDR analyses of reflectivity (shaded; dBZ) and storm-relative wind (barbs; kt) at a height of 7 km for the 100828I1 mission into Tropical Storm Earl. The 2-km and 7-km TC centers are denoted by the cyan circle and square, respectively. Analysis is valid at 2132 UTC 28 August 2010. Coincident satellite-derived infrared brightness temperatures (°C) are shown in the grayscale shading. The environmental vertical wind shear direction is shown by the red arrow in the top-left inset. b–d) As in a), but for analyses valid at 2251 UTC 28 August, 0007 UTC 29 August, and 0131 UTC 29 August, respectively.*

As can be seen from Fig. 1, the azimuthal coverage of observations from these "swaths" of data is limited to regions near the flight track. To remedy this issue, the aircraft usually conducts multiple passes through the center of the storm at varying azimuthal angles. These swaths of data can then be combined, usually by averaging all swath analyses created from a single flight into a "merged" analysis. The greater azimuthal coverage of observations provided by merged analyses have been shown by previous studies to be useful for examinations of symmetric and asymmetric vortex characteristics. An example comparison of TDR swath analyses to merged analyses is provided in Fig. 2, for a flight into Hurricane Dorian (2019).

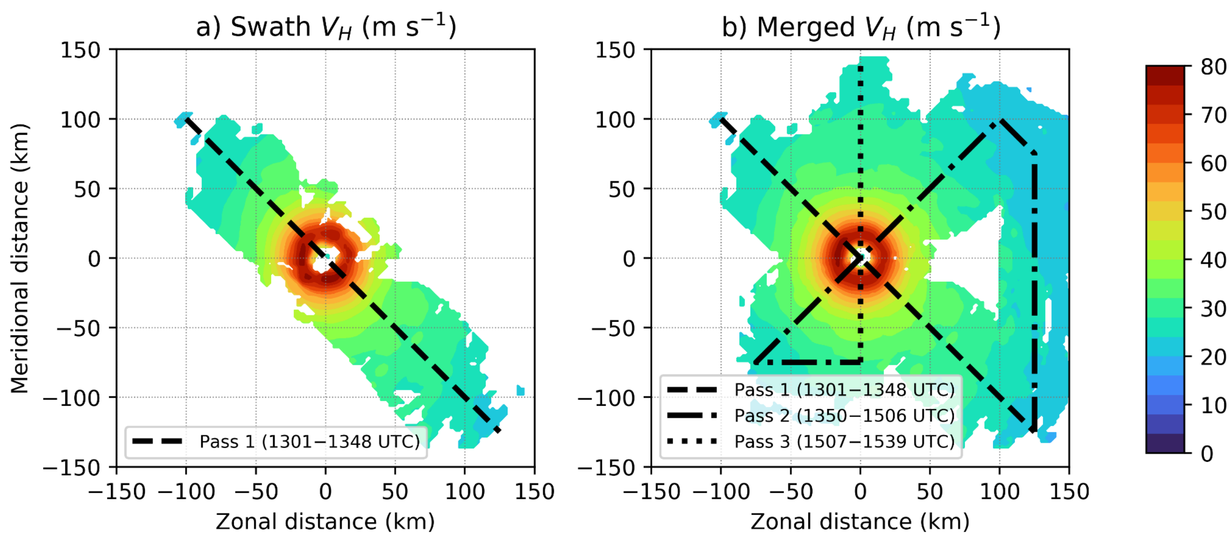

Fig. 2. *a) Storm-centered, motion-relative, TDR-derived horizontal wind speed (shaded;* $m\ s^{-1}$*) at a height of 2 km obtained from the 1324 UTC 1 September center pass into Hurricane Dorian (2019) as part of the 20190901H1 mission. The approximate flight track is shown by the black-dashed line, with the duration of the observing period shown in the legend. This pass serves as a representative example of swath data. b) As in a), but for the corresponding merged analysis using swath data from all three center passes in the 20190901H1 mission. The corresponding flight track for each TDR swath analysis is shown by a unique dash style, as denoted in the legend. Figure adapted from Fig. 1 of Fischer et al. (2022).*

To facilitate future research of TC vortex and convective characteristics, the TC-RADAR database provides a platform where post-processed swath and merged analyses are combined into two homogeneous data files, with relevant metadata pertaining to both the TC best-track information and the TC environment, as diagnosed by the operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) model. Such a format readily allows for storm-to-storm comparisons or climatological analyses. It is recommended that swath analyses are used to examine the convective characteristics of the storm, as the averaging process in the merged analyses will smooth features that are sampled by more than one pass.

In total, TC-RADAR contains 1,193 swaths of TDR observations and 355 merged analyses for storms occurring in the North Atlantic, eastern North Pacific, and central North Pacific basins. Observations span all points of the TC lifecycle, ranging from pre-genesis disturbances, to mature hurricanes, to storms nearing extratropical transition.

2. Recentering process

One of the benefits of using TC-RADAR is that analyses are readily available on storm-centered grids. In this recentering process, the TC center is identified as the analysis grid point that best matches a perfectly symmetric vortex of purely cyclonic flow. The quality of the match is determined via a cost function that considers the radial distance of analysis grid points from the TC center and the wind speed. To summarize the center-finding process, the storm-relative wind direction at each grid point is compared to a flow that is purely tangential about a hypothetical TC center. This process is repeated for a series of hypothetical TC center locations. The best match is identified as the location that yields the lowest mean difference between the observed wind direction and the purely tangential flow. The "error" between the observed wind direction and the purely tangential flow are weighted by both distance from the TC center and the wind speed, where faster winds and points closer toward the TC center are weighted more strongly than grid points with relatively weak wind speeds and/or points farther from the TC center. This process is performed for all swath and merged analyses. In the construction of merged analyses, the TC center is determined at a height of 2 km for each swath analysis. Then, each swath analysis for a given flight is averaged about the respective 2-km TC center estimate to create the merged analysis.

3. Data formatting:

There are two main types of data files. Both are composed of netCDF (.nc) files. The first type contains all TDR swath analyses, while the second type contains all TDR merged analyses. Both data types use Cartesian grids with a horizontal grid spacing of 2.0 km and vertical grid spacing of 0.5 km. The vertical extent of the domain spans 0–18 km in height. Presently, there are two swath analysis and two merged analysis TC-RADAR .nc files, grouped by consecutive years (e.g., 1997–2019 and 2020–2022).

Swath data (e.g., v3l_1997_2019_xy_rel_swath_ships.nc):

Swath data is ideal for examining either processes evolving on short time scales (looking at pass-to-pass changes) or examining single snapshots in time, such as the convective characteristics of the storm. The following observed variables are available for the swath data:

- Eastward wind (m s^{-1})
- Northward wind (m s^{-1})
- Vertical velocity (m s^{-1})
- Reflectivity (dBZ)
- Wind speed (m s^{-1})

- Tangential velocity (m s^{-1})
- Radial velocity (m s^{-1})
- Earth-relative eastward wind (m s^{-1})
- Earth-relative northward wind (m s^{-1})
- Relative vorticity (s^{-1})
- Divergence (s^{-1})

Unless explicitly stated as “earth-relative”, all fields are storm motion-relative. These variables are available on grids relative three different types of TC center estimates:

- Relative to a TC center based on the real-time center fix (e.g., “swath_eastward_wind”)
- Relative to a TC center based on the recentered TC position (see section 2), using a reference height of 2 km (e.g., “recentered_eastward_wind”)
- Relative to a TC center based on the recentered TC position (see section 2), at every height (e.g., “total_recentered_eastward_wind”). In essence, this is a vortex tilt-relative framework.

These data are stored in four-dimensional arrays of the order: storm index, latitude/northward displacement, longitude/eastward displacement, and height.

Swath analyses also have certain vortex parameters stored. These include:

- Vertical profiles of the radius of maximum wind
- Vertical profiles of vortex tilt magnitude, including vector components

Merged analyses (e.g., v3l_1997_2019_xy_rel_merged_ships.nc):

Here, the merged analyses were constructed using the mean values of all swaths for a given mission. As a result, merged analyses are preferred for analyzing vortex-scale characteristics of the TC, as convective-scale features will be smoothed in the averaging.

Re-centered fields in the merged analyses are constructed in a two-step process. First, swaths are recentered, following the methods described above. Second, a revised center is estimated using the merged tangential wind field created from the recentered swath data. Theoretically, the greater azimuthal coverage of the merged analysis should give a more accurate center location than center estimates obtained from single swaths.

The following observed variables are available for the merged data:

- Eastward wind (m s^{-1})
- Northward wind (m s^{-1})
- Vertical velocity (m s^{-1})
- Reflectivity (dBZ)
- Wind speed (m s^{-1})
- Tangential velocity (m s^{-1})
- Radial velocity (m s^{-1})
- Earth-relative eastward wind (m s^{-1})
- Earth-relative northward wind (m s^{-1})
- Relative vorticity (s^{-1})

- Divergence (s^{-1})

Unless explicitly stated as "earth-relative", all fields are storm motion-relative. These variables are available on grids relative three different types of TC center estimates:

- Relative to a TC center based on the real-time center fix (e.g., "merged_eastward_wind")
- Relative to a TC center based on the recentered TC position (see section 2), using a reference height of 2 km (e.g., "recentered_eastward_wind")
- Relative to a TC center based on the recentered TC position (see section 2), at every height (e.g., "total_recentered_eastward_wind"). In essence, this is a vortex tilt-relative framework.

These data are stored in four-dimensional arrays of the order: storm index, latitude/northward displacement, longitude/eastward displacement, and height.

Merged analyses also have certain vortex parameters stored. These include:

- Vertical profiles of the radius of maximum wind
- Vertical profiles of vortex tilt magnitude, including vector components
- Vertical profiles of local shear, including vector components (use with great caution)

The profiles of local shear are three-dimensional arrays of the order: storm index, averaging radius, and height. Here the averaging radius ("local_radii") spans 25–100 km in 5-km increments. In order for the local shear to be computed, at least 50% of all data points in each geographic quadrant (i.e., northwest, southwest, southeast, northeast) must have valid data. Otherwise, an estimate of the local shear is not computed. Consequently, it is possible that for certain local_radii an estimate of the local shear exists, while it does not for other local_radii. Since azimuthal coverage generally decreases at larger radii, smaller values of local_radii more frequently have estimates of the local shear. For reference, the mean quadrant coverage and minimum quadrant coverage are stored in the variables of the corresponding names.

4. SHIPS metadata:

Select SHIPS metadata are included within both the swath and merged datasets. All variables are obtained from SHIPS developmental data. The following variables are currently available:

- Tropical cyclone identification code ("tcid_ships")
- Best-track TC center latitude ("lat_ships"; degrees)
- Best-track TC center longitude ("lon_ships"; degrees)
- Best-track maximum sustained 10-m wind speed ("vmax_ships"; m s^{-1})
- Best-track minimum central pressure ("pres_ships"; hPa)
- Eastward component of storm motion ("motion_x_ships"; m s^{-1})
- Northward component of storm motion ("motion_y_ships"; m s^{-1})
- Deep-layer (850–200-hPa) vertical wind shear magnitude ("shdc_ships"; kt)
- Deep-layer (850–200-hPa) vertical wind shear direction ("sddc_ships"; degrees)
- Deep-layer (850–200-hPa) generalized vertical wind shear magnitude ("shrg_ships"; kt)
- Deep-layer (850–200-hPa) generalized vertical wind shear magnitude ("shgc_ships"; kt)
- Deep-layer (850–200-hPa) vertical wind shear magnitude in 200–800-km ann. ("shrd_ships"; kt)

- Deep-layer (850–200-hPa) vertical wind shear direction in 200–800-km ann. ("shtd_ships"; deg.)
- Mid-layer (850–500-hPa) vertical wind shear magnitude ("shrs_ships"; kt)
- Mid-layer (850–500-hPa) vertical wind shear direction ("shts_ships"; degrees)
- Lower-tropospheric (850–700-hPa) environmental relative humidity ("rhlo_ships"; %)
- Mid-tropospheric (700–500-hPa) environmental relative humidity ("rhmd_ships"; %)
- Upper-tropospheric (500–300-hPa) environmental relative humidity ("rhhi_ships"; %)
- Distance to nearest major landmass ("dtl_ships"; km)
- Maximum potential intensity ("mpi_ships"; kt)
- Reynolds sea surface temperature ("sst_ships"; °C)
- Oceanic heat content from the NCODA analysis ("ohc_ships"; J kg^{-1} $°C^{-1}$)
- Mean total precipitable water within 200 km of the TC ("pw2m_ships"; mm)
- Standard deviation of total precipitable water within 200 km of the TC ("pw2s_ships"; mm)
- Mean total precipitable water within 500 km of upshear quadrant ("pw5u_ships"; mm)
- Mean total precipitable water within 500 km of the TC ("pw5m_ships"; mm)

All of the above parameters are available in six-hour increments, spanning 48 h prior to the time of the observation, to 48 h following the observation ("ships_times"), whenever analyses were available. Please refer to SHIPS developmental data for more information on variable descriptions:

http://rammb.cira.colostate.edu/research/tropical_cyclones/ships/developmental_data.asp

5. Version updates:

v3a: Implemented a beta version of the new center-finding method

v3b: Fixed some bugs associated with center-finding technique

v3c: Adjusted tuning parameters associated with center-finding algorithm and improved code efficiency

v3d: Fixed a bug that affected the best-track entries for storms with an analysis hour between 21–00 UTC. Replaced older Earl (2010) analyses with an updated QC version. Vertical velocity analyses for storms prior to 2010 should still be used with extreme caution (or avoided altogether).

v3e: Added the capability to compute vortex tilt from swath data. Imposed stricter coverage criteria to recenter TC. If criteria are not met, values are set to "NaN".

v3f: Added 2020 cases and implemented a revised center-finding algorithm, which is no longer dependent on swath RMWs. This change was determined to provide center estimates that better agreed with subjective analyses.

v3g: Added the beginning and end times for swath analyses. Also fixed a bug related to the date stamp (datetime objects) with flights that spanned both the last day of one month and the first day of the next month (e.g., evening/overnight flights on August 31). Although this bug only affected a few cases, the corresponding merged analyses were incorrectly unable to be paired with best-track and SHIPS metadata.

v3h: Corrected a bug in the latitudes and longitudes of each TDR swath and merged analysis. The main modification was to correctly account for the curvature of the Earth. There was also an adjustment to account for the fact that the original TDR analysis grid origin falls between grid points, rather than at the middle grid point. Due to these changes, the location of some TC centers/tilts were changed in this version.

v3i (Used in TC-RADAR paper): Corrected a bug in the "get_bearing" routine that computes the angle of each grid point. This correction affected the center-finding algorithm. Centers seem largely similar to the previous version (v3h), but this method is more accurate.

v3j (5/25/2022): Added 2021 cases. Also implemented a revised center-finding algorithm designed to more accurately estimate TC center estimates from swath data, especially in the mid-levels of weak TCs. This included an additional coverage constraint, which is more strict than the previous version (v3i). Version v3j also includes a bug fix for the calculation of divergence.

v3k (6/22/2023): Added 2022 cases. Slightly modified the center-finding method to use a larger "core radius" parameter to improve the consistency of the method on swath analyses. As new analyses have been added to the database, the size of the .nc files have also grown. To mitigate memory issues, the TC-RADAR files have been separated into two swath analysis files and two merged analysis files, grouped by consecutive years (e.g., 1997–2019 and 2020–2022). Some coordinate name list parameters were revised to be more user friendly.

v3l (10/10/2024): Added 2023 cases. Revised names of variables to be more consistent with netCDF CF conventions. Also added "long names" to variables. Lastly, four precipitable water variables were added from the SHIPS developmental data.

6. Data access/Usage policy:

Each TC-RADAR netCDF file can be downloaded from the following location: https://www.aoml.noaa.gov/ftp/pub/hrd/data/radar/level3/. Users are free to download TC-RADAR, however, we request users notify the HRD radar team lead, Dr. Paul Reasor (email: paul.reasor@noaa.gov), of the nature of the research project to ensure proper usage. The nature of the quality control (QC) process is a delicate balancing act between retaining as much meteorological data as possible, while removing non-meteorological artifacts. More specifically, while the QC of raw radar data (Level 1a) attempts to identify and remove non-meteorological data, some meteorological data is invariably removed in the process. We have determined that for many research applications maximizing coverage is essential. Therefore, the QC settings employed here do not aim to remove *all* non-meteorological data in the production of the Level 2 radar analyses contained within TC-RADAR. Details on the production of specific Level 2 analyses since 2020 are provided in the following radar data README: https://www.aoml.noaa.gov/wp-content/uploads/2023/04/README_radar_dataset.pdf. It is incumbent on the user to carefully examine the wind and reflectivity analyses and employ an additional level of QC to the gridded fields consistent with their objectives. Users also should be aware of the known issues documented in Section 7. Any follow-up questions can be directed to the HRD radar team.

7. Known issues:

The following are known issues with the database that users need be aware of:

- TDR analyses for storms prior to the 2010 hurricane season were created with an error in the synthesis software that resulted in vertical velocities that were too deep and too strong in some instances. As such, **quantitative analyses of the TDR-derived vertical velocity field should not be made for analyses prior to 2010.** Analyses since 2010 (inclusive) have addressed this error and are considered more accurate. This issue is documented in more detail in Fischer et al. (2022).
- TDR-derived radar reflectivity has not yet been properly calibrated. Reflectivities can vary significantly (sometimes up to 7–10 dB) between the radar systems onboard each NOAA P3 (e.g., N42 vs. N43) in some seasons. There are also differences in reflectivity across seasons as the radar systems onboard each aircraft changed over time. **Until a proper calibration is performed, reflectivity should not be used for quantitative analyses outside of individual case studies.** Because the TDR is an X-band radar, attenuation also affects the analyzed reflectivities, particularly along the edges of swaths in regions of heavy precipitation. The effects of attenuation have also not been accounted for in TC-RADAR.

8. How to cite:

Any publications and/or presentations using TC-RADAR should cite the following publication:

Fischer, M. S., R. F. Rogers, P. D. Reasor, and J. F. Gamache, 2022: An analysis of tropical cyclone vortex and convective characteristics in relation to storm intensity using a novel airborne Doppler radar database. *Mon. Wea. Rev.*, **150**, 2255–2278, https://doi.org/10.1175/MWR-D-21-0223.1.

Any reference to the center-finding and/or vortex tilt should also reference:

Fischer, M. S., P. D. Reasor, J. P. Dunion, and R. F. Rogers, 2024: An Observational Analysis of the Relationship between Tropical Cyclone Vortex Tilt, Precipitation Structure, and Intensity Change. *Mon. Wea. Rev.*, **152**, 203–225, https://doi.org/10.1175/MWR-D-23-0089.1.

9. References:

Gamache, J.F., F.D. Marks, and F. Roux, 1995: Comparison of Three Airborne Doppler Sampling Techniques with Airborne In Situ Wind Observations in Hurricane Gustav (1990). *J. Atmos. Oceanic Technol.,* **12**, 171–181, https://doi.org/10.1175/1520-0426(1995)012<0171:COTADS>2.0.CO;2

Lorsolo, S., J.A. Zhang, F. Marks, and J. Gamache, 2010: Estimation and Mapping of Hurricane Turbulent Energy Using Airborne Doppler Measurements. *Mon. Wea. Rev.,* **138**, 3656–3670, https://doi.org/10.1175/2010MWR3183.1

Reasor, P.D., M.D. Eastin, and J.F. Gamache, 2009: Rapidly Intensifying Hurricane Guillermo (1997). Part I: Low-Wavenumber Structure and Evolution. *Mon. Wea. Rev.,* **137**, 603–631, https://doi.org/10.1175/2008MWR2487.1

Reasor, P.D. and M.D. Eastin, 2012: Rapidly Intensifying Hurricane Guillermo (1997). Part II: Resilience in Shear. *Mon. Wea. Rev.,* **140**, 425–444, https://doi.org/10.1175/MWR-D-11-00080.1

Rogers, R., S. Lorsolo, P. Reasor, J. Gamache, and F. Marks, 2012: Multiscale Analysis of Tropical Cyclone Kinematic Structure from Airborne Doppler Radar Composites. *Mon. Wea. Rev.,* **140**, 77–99, https://doi.org/10.1175/MWR-D-10-05075.1