16D.6 USE OF SYNTHETIC PROFILES TO DIAGNOSE SIMULATED TROPICAL CYCLONES IN REGIONAL HURRICANE MODELS†

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1. INTRODUCTION

Forecasts from regional hurricane models may suffer significant degradation when the structure of the simulated storm departs markedly from the observed storm. To assess and identify the deficiencies that lead to structural errors, it is necessary to develop alternative verification and diagnostic approaches that go beyond the computation of errors and biases in track and intensity. The plethora of aircraft reconnaissance and research flights taken each year offer an opportunity to make direct comparisons between the kinematic and thermodynamic quantities in the observed storm and those in the modeled storm. To do so, the observations need to be compared within a framework that is consistent with the model's resolution and simulated storm location.

This abstract outlines the development and application of synthetic profiles to evaluate the intensity and structure of simulated tropical cyclones (TCs) in operational and retrospective runs of the Hurricane WRF model (HWRF).[1] To accomplish this goal, the various NOAA and Air Force Reserve flight level data for a given storm are first standardized into a common NetCDF data file. Because the simulated cyclone does not typically follow the actual path taken by the real cyclone, it is necessary to translate the observational data into coordinates relative to the moving storm center of the actual storm and then sample the model space along these transects in a frame moving with the center of the simulated storm. The resulting synthetic radial profiles of the model's simulated flight level and surface data can then be directly compared with the observed 1-Hz flight level once an appropriate spatial smoothing is applied. Likewise, the model's simulated surface wind field can be sampled and compared with observed surface wind data from Stepped Frequency Microwave Radiometer (SFMR). The end goal of the present work is a software module that can be used to apply the synthetic profile approach for verification of many forecast cases, thereby gaining useful information to diagnose model errors for storm size, inner core kinematic and thermodynamic structure, and surface wind field distribution.

2. PREPARATION OF FLIGHT LEVEL DATA

Extensive efforts have been exerted to prepare the observational flight level data for use in verification using the synthetic profiles approach. This section describes such efforts, which include standardizing the multitude of data formats, conducting quality control measures, translating the data into a frame moving with the storm center, and automatically parsing the radial legs to obtain high quality radial profiles.

2.1 *Characteristics of flight level data*

Flight level data are typically obtained from two sources: the Air Force Reserve (AFRES) and the National Oceanographic and Atmospheric Administration's Aircraft Operations Center (NOAA/AOC). AFRES flights are normally conducted in support of operational reconnaissance of storms that may pose a threat to land in the North Atlantic, Northeast Pacific, or Central Pacific basins. As such, these flights normally fol-

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[1] The data preparation tasks ended up taking longer than expected, so this extended abstract will mainly document the data processing methods used to prepare the flight level data.

low a typical figure-'4' pattern at standard pressure levels (1500 ft, 925 hPa, 850 hPa, or 700 hPa). Occasionally, AFRES planes may participate in field campaigns in other tropical cyclones basins around the world (e.g. the Western Pacific). Most AFRES data are provided at a temporal sampling rate of 10-seconds (during which time the plane flies approximately 1.2 km). Since 2010, AFRES data have been provided at a 1-second sampling rate. Prior to 2004, some flights are only provided at 30-seconds or occasionally 60-seconds. AFRES data are usually provided "as is" without substantial quality control measures. The data files are made available on the Hurricane Research Division's (HRD) web site. Especially in earlier years, it has been necessary to hand-edit some of the AFRES data files to remove erroneous blocks of data. AFRES data come in ASCII text format. Approximately six formats have been used over the period 1997 - 2013. On occasion, the original AFRES flight data are unavailable; in those cases, operational data files may be substituted [e.g. the older "Minob" or more recent 'High Density Obs' (HDOBS) formats]. On other occasions, somewhat complex measures have been required to handle certain formatting issues in the legacy data files.

Although NOAA Hurricane Hunter aircraft can also be tasked for operational reconnaissance missions, NOAA flights are often conducted in support of the annual hurricane field program or other field campaigns. Because the aims of such research flights often involve a different set of priorities than those of operational missions, NOAA missions often fly at non-standard flight levels (e.g. near 650 hPa) to maximize the utility of the airborne Doppler radar systems. Flight patterns may be irregular or contain many loops and cross-legs to maximize radar coverage of the storm. NOAA aircraft data normally provided at a sampling rate of 1-second or 10-seconds, and are carefully quality controlled by a flight engineer at AOC before being made available on HRD's web site. Since 2005, much of the NOAA flight data has been been provided in Network Common Data Format (NetCDF) files. Changes in variable naming over the years pose challenges to reading these data files, however the variable naming has become increasingly standardized. Prior to 2005, NOAA flight data are provided in ASCII text files. Like the AFRES formats, the NOAA formats have also varied over the years: approximately eight main data formats have been used from 1997 - 2013.

2.2 *Standardization and quality control of flight level data*

In order to provide a high quality data set of flight level data suitable for comparing to model data, all available flight level data from 1997 to 2013 are standardized into a common data format. All of the AFRES and NOAA flight data from each storm are read and combined into one self-describing NetCDF file that uses a standardized set of variable names. When data were provided in English units, they are converted into metric units. This file is termed the Level 1 (L1) data product.

To ensure that each data file has been read correctly, the flight data for several key meteorological parameters are plotted in earth-relative coordinates. Fig. 1 shows an example of such a plot for flight level wind speed for the final flight before Hurricane Sandy made landfall in New Jersey. These parameters include the flight level pressure, flight level temperature, flight level wind speed, surface wind speed from the SFMR, and extrapolated surface pressure.[2] Particular attention has been taken to ensure that the wind speed data are not affected by artifacts that lead to erroneously high maximum values. When the sources of such artifacts are found, the source data files have been edited to remove the offending data points.

2.3 *Automatic parsing of radial legs*

The next step in the data processing is to translate the flight level data into storm-relative coordinates. In order to do this, a detailed track of the storm center locations is required. HRD accomplishes this by running the wind-center-finding method of Willoughby and Chelmow (1982). This method determines the wind center of the storm using lines normal to the wind at the aircraft's location. Through iteration, the method chooses the center that minimizes a cost function based on both wind and pressure information. The resulting wind centers are then fitted to a cubic spline under tension, resulting in a high quality track of the storm's wind centers in time. The end result is a file that contains the wind centers every two minutes for the times when aircraft were in the storm. This project downloads these wind center '.trak' files from HRD and uses those data to translate the flight level data into storm-relative coordinates by subtracting the geographical coordinates of the wind centers from those of the coordinates of the flight level trajectory. The motion of the storm center can also be subtracted from the wind speed, putting the wind data in a frame moving with the storm center. Then the wind data are decomposed into tangential and radial wind components.

Once the data are in storm-relative coordinates, an automated algorithm is used to determine which parts of the flight trajectory correspond to "good" radial legs (i. e.

[2] SFMR data have been routinely available on most flights since 2008. Flight level pressure is not available for many AFRES flights prior to 2005.

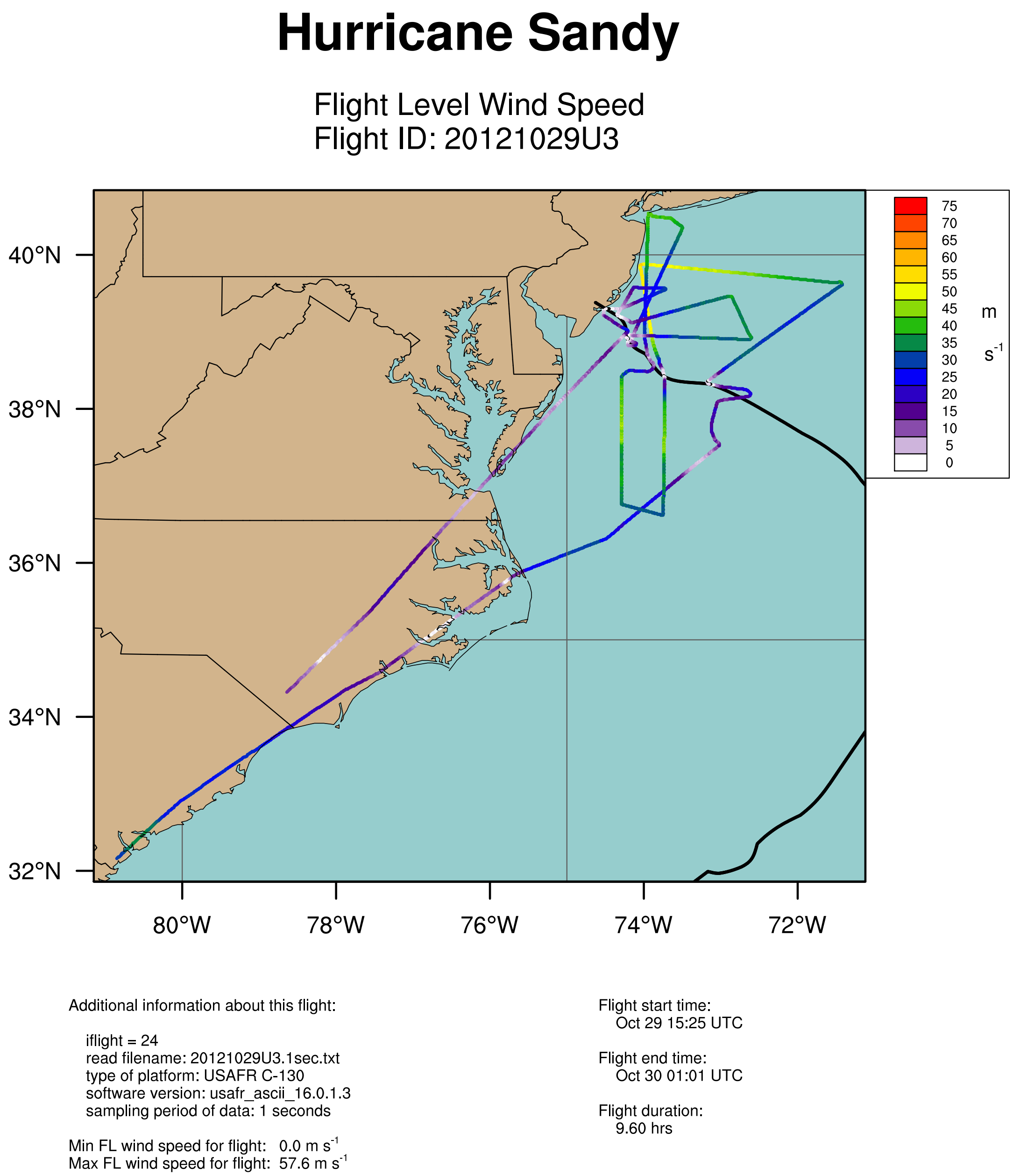

Figure 1: Flight level wind speed plotted in earth-relative coordinates for the final flight before Hurricane Sandy made landfall in New Jersey. The flight began at 15:25 UTC on 29 Oct 2012 and ended at 01:01 UTC on 30 Oct 2012 – near the time that Sandy made landfall. Flight level wind speed along the flight trajectory is indicated by the color of the line; the black line shows the path taken by the center the storm as determined by the wind-center-finding method of Willoughby and Chelmow (1982).

subsets of data that represent a relatively direct transact through the storm center). The algorithm accomplishes this task by means of a filtering operation, in which all points that do not correspond to inbound or outbound points of a radial leg are masked out by setting accompanying data flags to 'missing'. In brief, three criteria are applied in this masking operation: (a) the distance from the storm center, (b) the radial motion of the plane, (c) and the direction that the plane is heading. First, all points that are more than 400 km from the storm center are first eliminated from consideration to reduce the scope of the search (normally, radial legs begin and terminate approximately 200 km from the storm center). Then, a radial motion criterion is applied by examining whether the aircraft's distance to the center is increasing or decreasing in time. Points along the flight trajectory where the aircraft's distance to the center is decreasing in time are marked as potential starting points for an inbound leg. Similarly, points at which the platform's distance to the center are increasing in time are marked as potential starting points for an outbound leg. All other points are eliminated from consideration for the starting points of inbound or outbound radial legs. Then, a directional criterion is applied by using the angle difference between the plane's track (the direction in which the plane is moving) and the radial that passes through the storm center. All points at which the plane is tracking in a direction that is within $+/-35\,°$ of the storm center are included as potential starting or stopping points for the radial legs; all other points are eliminated. Because the plane does not always pass through the direct center, some leeway is given in applying the radial motion and directional criteria. These are not applied when the plane is closer than 30 km (for the radial motion criterion) or 25 km (for the directional criterion) of the storm center.

Once all points that do not correspond to inbound or outbound radial legs have been screened out, the beginning and ending times of candidate radial legs are recorded. Then each leg is screened using additional criteria to see if it should be included as a 'good' radial leg. These additional criteria are: (i) that the continuous leg be at least 45 km in length, (ii) that the plane pass within 25 K of the storm center, and that (iii) that the flight level pressure not deviate more than 10 hPa from the average pressure of the first 25 km of the leg (starting from the center). If criteria (i) and (ii) are not satisfied, the leg is not included as a 'good' radial leg. If criteria (iii) is violated, the leg will be terminated at the radius at which the pressure deviation exceeded the threshold. This final criterion assures that changes in the flight parameters are not due to large altitude changes of the measuring platform. Fig. 2 shows the result of the automatic parsing for the final flight before landfall in Hurricane Sandy. For this case, the algorithm correctly identifies the legs that are relatively straight and which pass near the storm center. Legs that are too short, that have too many directional changes, or which are not headed toward or away from the storm enter are correctly screened out. Overall, the algorithm correctly identifies good radial legs with an accuracy rate of about 99%. The parsing metadata is stored in a file for internal use, termed the Level 2 NetCDF file.

2.4 *Radial binning*

Once the 'good' radial legs have been identified, it is a rather simple exercise to take the parsing metadata from the Level 2 NetCDF file for each storm, translate all the earth-relative data into storm relative data, and then store the data into logical blocks that correspond to each radial leg. To allow further applications, such as use in synthetic profiles, the data are then linearly interpolated into radius space using a common radial grid that starts at the storm enter and extends outward to 700 km at a 100 m grid increment. Given an assumed ground speed of $115\,\mathrm{m\,s^{-1}}$, this results in a little less than one time point per radial point for 1-second data. For lower sampling rates, the linear interpolation will offer a very faithful radial representation of the data in the time domain. At 1-second, the linear interpolation may underestimate the maximum wind speeds of the most peaked wind profiles by a very small amount that should be less than the inherent uncertainty of the observations. Fig. 3 shows the radial profiles that result for the final flight before Sandy's landfall in New Jersey.

2.5 *Extended Flight Level Data Set*

The resulting *Extended Flight Level Data Set* (or FLIGHT+) covers nearly all tropical cyclones that have been flown in the North Atlantic, Eastern Pacific, Central Pacific, and Western Pacific basins from 1997 to 2013. The data set format has been designed to enable a wide range of industry and research uses. The data set will be publicly released to the research community in January 2015. Please check the FLIGHT+ page on the Tropical Cyclone Data Project (TCDP) to register to receive e-mail updates on the data set: http://verif.rap.ucar.edu/tcdata/flight/. Detailed graphical plots of the flight level data for each storm are already available at: http://verif.rap.ucar.edu/tcdata/flight/applications/. These plots include the earth-relative data, graphical summaries of the storm-relative parsing, and plots of the radial profiles. The data set files will include all typical navigational and meteorological information that is commonly available in both the AFRES and NOAA source data files.

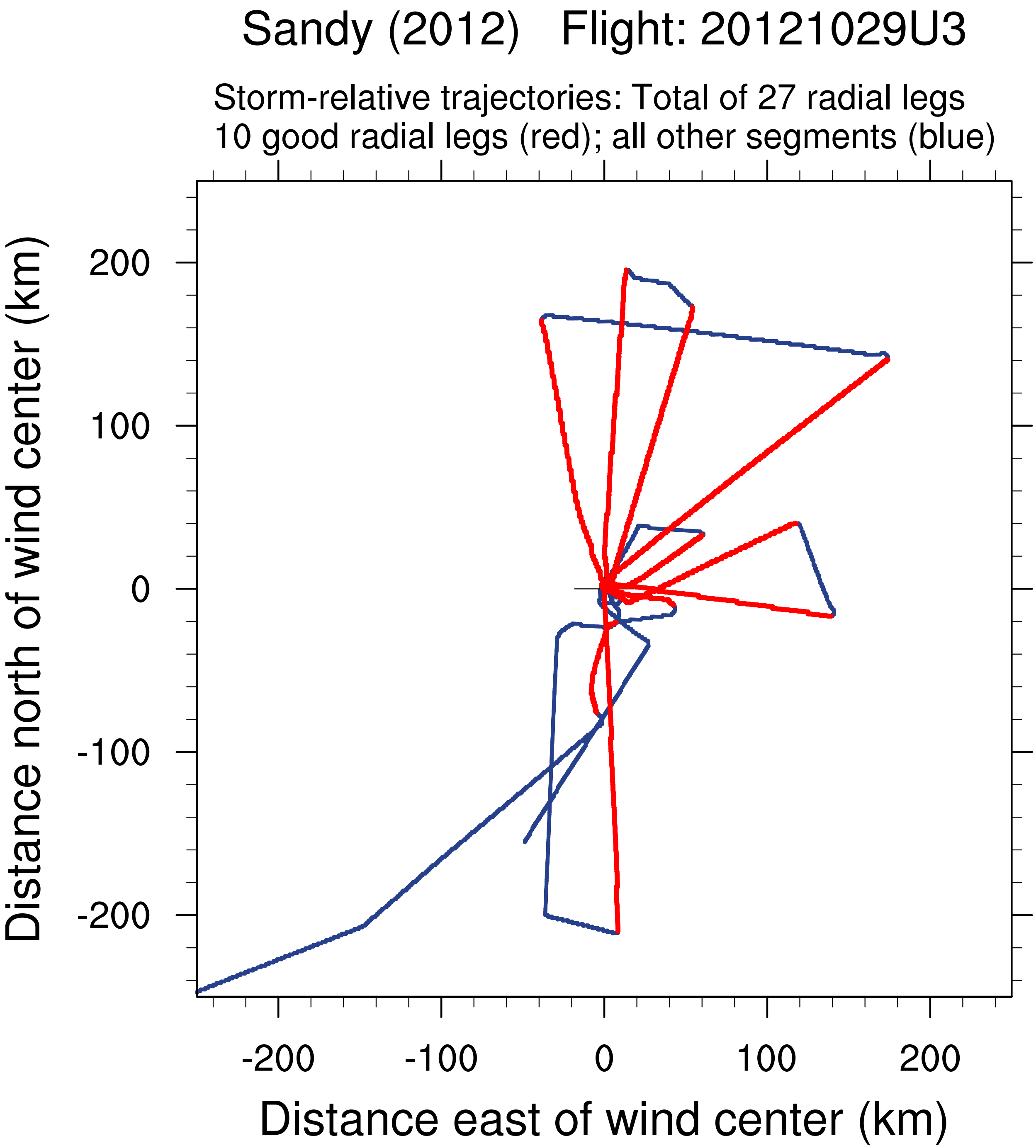

Figure 2: Flight trajectories in storm-relative coordinates for the final flight before Hurricane Sandy made landfall in New Jersey. Portions of the flight trajectory identified as 'good' radial legs are shown in red. All other flight portions are shown in blue.

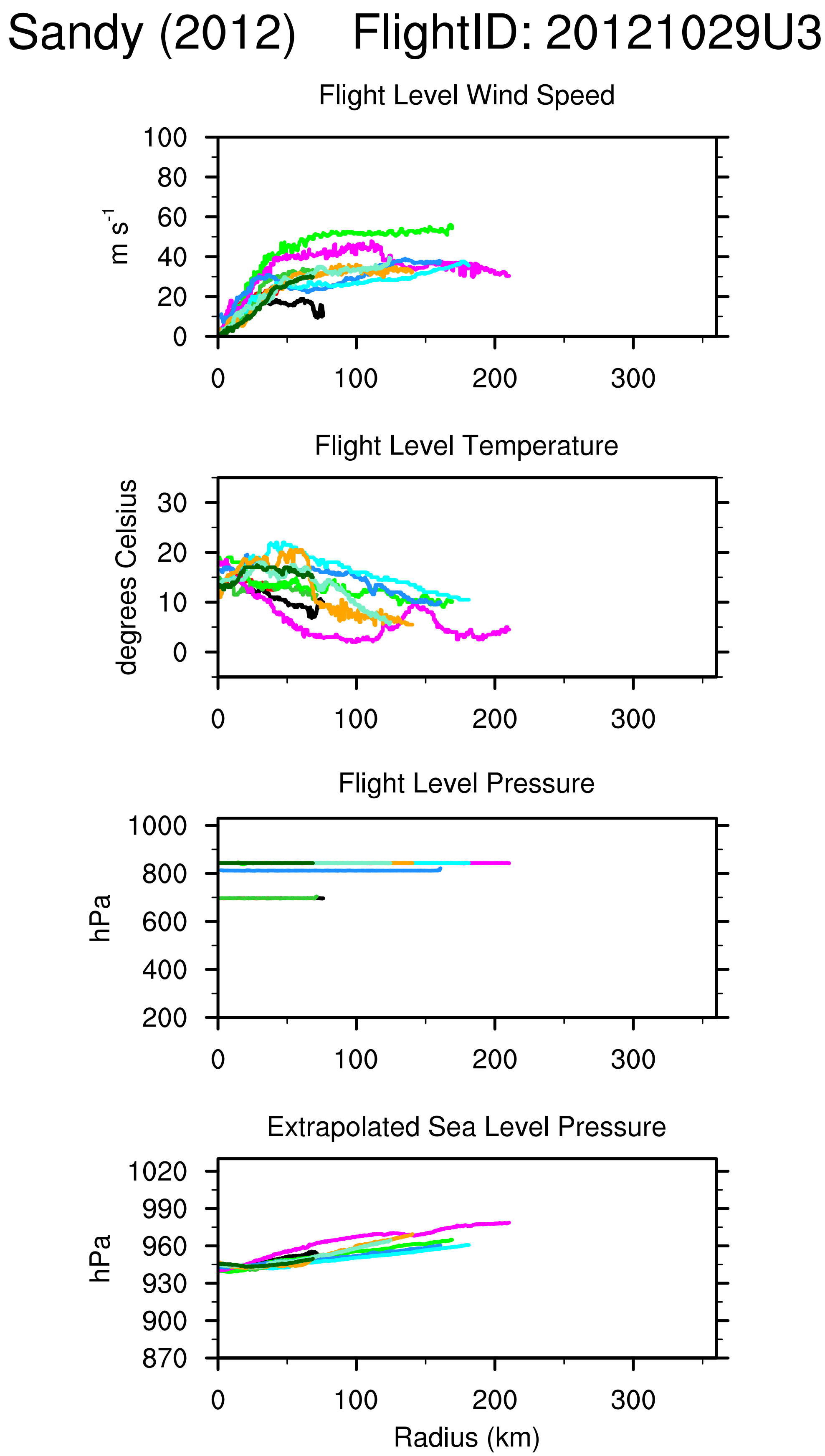

Figure 3: 'Good' radial profiles for the final flight before Hurricane Sandy made landfall in New Jersey. Panels from top to bottom: (a) flight level wind speed, (b) flight level temperature, (c) flight level pressure, and (d) extrapolated sea level pressure. Each radial profile is represented using the same color in each panel.

3. APPLICATION OF SYNTHETIC PROFILES

Work continues on the application of the synthetic profile technique to the operational Hurricane WRF (HWRF) model. The approach will closely follow after the work of Uhlhorn and Nolan (2012), except some modifications will be needed to account for the fact that the operational HWRF model runs are not available at the very high temporal frequency that was available in that study's nature run. Different spatial smoothing methods will be examined to determine the optimal amount to smooth the aircraft observations so as to match the spatial resolution of the model simulation. Also, instead of sampling the model space through linear interpolation to the time of each point in the radial leg, we will likely start by making a stationarity assumption as if the entire flight trajectory was flown instantaneously. We plan to examine the sensitivity of the results to these various assumptions and methodology options.

4. CONCLUSION

The aim of this initial work is to determine the efficacy and usefulness of the synthetic profile methodology for verification and diagnostics. In the future, we plan to apply the synthetic profile approach to the curving trajectories of dropsondes. As the resolution of regional and global hurricane models increases to ever finer scales, this approach may provide a more useful and direct way to examine the low-level vertical structure in simulated storms. We also hope to explore potential real-time applications.

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