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Evaluation of a New Observational Strategy for Monitoring the Tropical Cyclone Outflow Layer

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LONG-TERM GOALS

The long-term goal of this project is to improve our understanding of the role of the outflow layer in tropical cyclone intensity and structure change though dedicated field program design and execution, improved observation of outflow structure and state of the art instrument development. The outflow layer is hypothesized to play both an active and passive role in tropical cyclone intensification and structural changes. As part of an effort to bring additional observational capability to bear on this problem, a key goal is the development of a next-generation sounding system, which is initiated and tested for the Tropical Cyclone Intensity (TCI) experiment in 2014. The outflow layer is investigated during the Hurricane and Severe Storms Sentinel (HS3) field program in the Atlantic over three seasons from 2012 to 2014 using observations from three co-located data sources: 1) the NASA Global Hawk Unmanned Aerial Vehicle (UAV), 2) NOAA WP-3D, NOAA G-IV and Air Force WC-130J manned aircraft and 3) satellite-based microwave, infrared and visible imagers, radiometers and scatterometers.

OBJECTIVES

The objectives of this research are as follows:

1. Analyze existing hurricane outflow layer dropsonde observations from the HS3 Global Hawk and TCI WB-57 flights from 2012-2014.
2. Test a new-generation atmospheric sounding system for improved high-density observation of the TC outflow layer.

APPROACH

Our approach is to design and execute a comprehensive field program for TC outflow observations that employs high altitude observing platforms: the NASA Global Hawk AUV and high-altitude WB-57 manned aircraft using a new-generation, mini-dropsonde observing technology for atmospheric vertical profiling. Our approach involves designing test and evaluation strategies as well as experimental observational strategies in concert with existing in-situ and satellite remote sensing observations.

WORK COMPLETED

1. *Observations of tropical cyclone outflow layer*
   The design of flight patterns to sample the TC outflow layer, development of plans to execute and the execution of these plans has been completed for the final two years of HS3 and the first year of TCI. Negotiations to fit outflow layer sampling modules within the overall HS3 experiment plan was continuous during the field campaigns from 2012 through 2014. Outflow features were sampled for two cases in 2012, Leslie and Nadine. In 2013 only one outflow case was sampled over more than one day, i.e. Tropical Storm Gabrielle while in her depression stage. However, in 2014, Hurricane Edouard's outflow was sampled on four days, i.e. every other day. The first TCI case, Hurricane Gonzalo, had its outflow sampled for a short two-hour period on three successive days. Unfortunately, problems with the HDSS sonde system resulted in only a partial data set being obtained.

   Analysis of vertical and horizontal structure of outflow layer jets in Hurricane Nadine in 2012 and Pre-TC Gabrielle (depression AL07) in 2013 has been conducted using NCAR-EOL/Vaisala mini-dropsondes deployed from NASA AV-6 Global Hawk AUV in concert with U.Wisconsin CIMSS –derived Atmospheric Motion Vectors (AMVs), as well as microwave, visible and infrared outflow layer observations. Similar analysis of Global Hawk minisonde and satellite data are in the process of being synthesized for Hurricane Edouard from AVAPS minisonde data from the HS3 campaign and for Hurricane Gonzalo during TCI using a partial HDSS XDD minisonde data set.

2. *Testing and evaluation of High Definition Sounding System (HDSS) and eXpendable Digital Dropsonde (XDD) system*

   Tests of the dual dispenser, 12-sonde capacity HDSS/XDD dropsonde system were designed and conducted during 3 flights flown from 13-19 Nov, 2013 in which XDD's were deployed from the NASA WB-57 from 60,000 ft over a test range created off the Texas coast between Corpus Christi (CRP) and Brownsville (BRO). Several issues were identified on the first two flights, such as sondes jamming in the dispenser and other electrical issues. These issues were corrected leading to a more successful experiment on 19 Nov in which 26 sondes were deployed with about a 30% failure rate. In addition, most sondes suffered from data dropouts from 500 to 850 mb, a problem later traced to cold-soaking of the XDD batteries as they fell leading to loss of power on the sonde until they warmed up at lower levels. Sufficient sondes returned a data set from flight level to the surface that provided the capability to compare meteorological observations with the NWS radisonde data obtained from simultaneous launches at CRP and BRO during the flight. Ku-band SATCOM failed over water resulting in difficult communications via chat and satphone.

Additional XDD testing resumed on 23 and 24 Sept, 2014 on a new redesigned HDSS system with dual 42 sonde capacity dispensers. NASA had earlier made the decision to migrate their HIRAD remote surface wind sensor and IWRAP Doppler radar instrument from the failed AV-1 Global Hawk to the WB-57, on which both instruments had previously flown. These test flights became a check-out for these two sensors as well as a piggyback sensor referred to as OCS. This made the remainder of TCI flights on the WB-57 a joint campaign with HS3. However, during these flights, HDSS software problems resulted in no data being acquired on the 23rd, and jamming due to loss of pressure in dispenser units on the 24th which required the aircraft to return to base. Only 11 sondes were deployed on these two days. Pressure hose and software problems were fixed and a third test flight conducted on Oct 10, 2014. INMARSAT satcom system was not operating until the last minute making pre-flight system check-out and preparation difficult. Twelve sondes were launched on the 10th with dispenser continuing to jam and intermittent data being received by HDSS. HIRAD, HIWRAP and OCS instruments were successfully flown.

By Oct 10, the decision was made to deploy WB-57 assets to MacDill AFB in Tampa with the plan to begin a 3-day series of science flights into a new disturbance which subsequently became Hurricane Gonzalo. This was an extremely difficult logistical effort as it was undertaken over a holiday weekend (Columbus Day). However, it was successfully executed with all equipment, flight and maintenance crew and scientists making the transition to MacDill with help from NOAA colleagues at NOAA/AOC, with whom joint Gonzalo flights were also planned. This effort never materialized as NOAA aircraft were deployed to Hawaii for EPAC reconnaissance duty. However, WB-57 science flights began as scheduled on 15 Oct at extreme range from MacDill leaving only 1.5 hours on station. Flights continued on 16 and 17 Oct.

Only partial data were obtained from the HDSS with sondes falling at two different fall speeds. So what went right and what went wrong? The principal issue was that the noise floor on the instrument rose precipitously as the aircraft powered on and climbed to altitude. This resulted in a loss in signal strength reducing effective range from the aircraft to about 60 km (32 nm) or roughly 8.5 min of transmission time. This resulted in sonde loss of signal at approximately 11-12 km altitude for slow fall sondes and 8-9 km for fast-falls, which made up only 30% of the total. Subsequent analysis on the ground after the flights revealed an number of electrical problems with the two belly-mounted receivers. However, the two wing-mounted receivers, which seemed to work fine, we found to be disconnected due to wing wiring and connector faults. Thus the data was being received only through the air between wing antennas and belly-mounted receivers, a tribute to the sensitivity of the receivers, but insufficient to receive a complete signal as the aircraft range increased. An additional problem was found with wing tip preamplifiers likely suffering from reduced efficiency due to cold soaking. Heaters have since been designed, manufactured and installed to remedy this problem.

There were also issues with on board systems. INMARSAT did not function properly and the backup Blue Force Tracker malfunctioned at 40,000ft resulting in no real-time aircraft positions. Only the capability of HDSS to provide Iridium satcom link independent of aircraft systems made it possible to manually receive XDD sensor position prior to launch and thus providing real time position information from the aircraft. Coms with the aircraft was maintained only via satphone. Subsequent to the flight, aircraft navigational data was provided for the 15th and 17th, but not on the 16th when a major computer failure occurred.

Problems also occurred in the data recovery effort with system software failing to register XDD launch detect signals and no auxiliary checks being made for data availability. This made the conversion process from binary to working text file format somewhat random. Initially, only 75% of the sondes were reported. However, once this error was tracked down, data files for all but 6 sondes were reported. This meant that 97% of sondes successfully exited the aircraft and transmitted data until received power ran out, a very large improvement from the signal loss statistics on the test flights. Therefore, with wing wiring issues repaired and electrical issues identified and repaired, successful future test flights and science flights are anticipated. Additional issues requiring correction are the stabilization of the data conversion process from binary to useable ascii text files so that all data files from all releases are reported promptly.

RESULTS

1. *Initial observations of tropical cyclone outflow layer*

The HS3 outflow observations were derived from flight modules flown during multi-mission, multi-objective Global Hawk flights in 2012, 2013 and 2014 hurricane seasons. Two regions of observation were identified:1) the far-field, upper-level outflow jets at the perimeter of the TC outflow layer and the outflow layer 'roots' adjacent to inner-core convective bursts. The Nadine case study for 14-15Sept, 2012, and the pre-Gabrielle study on 4-5 October, 2013 both exhibited examples of outflow perturbations associated with inner-core convective bursts. The later indicated how transient these features are. Hurricanes Edouard and Gonzalo were the first cases where TC outflow layers were observed at regular intervals over a sequence of several days: Edouard on 11-12, 14-15, 16-17 and 18-19 Sept, 2014 and Gonzalo on 15, 16, and 17 Oct, 2014. Although Nadine was observed over multiple days, the outflow layer was not routinely sampled. These cases were observed in both the outer outflow jet region and the inner core 'root' region. Both cases exhibited outflow changes that were related to environmental interactions and also to inner core convective bursts. Synthesis of outflow layer jet structure relative to inner-core supercell convection has been accomplished and is ongoing

By way of review, Fig. 1 illustrates the location of the first detailed observations of Nadine's outflow jet reported earlier. This was an example of a single poleward and eastward directed outflow jet developing during a slow intensification event previously reported. It illustrates the important of sampling the outflow jet roots near the TC inner core in an effort to assess its relationship to a developing convective burst shown in the left panel of Fig. 1. This is in contrast to less dynamic, but stronger outflow jets developing in the far field edge of the TC outflow layer in response to environmental forcing events. The outflow layer was subsequently shown to be very dynamic with outflow jets developing near convective bursts in the TC inner core and propagating outward. Dunion (personal communication) has suggested that this behavior may be associated with convective pulsing linked to the diurnal cycle that may generate outflow jets initially linked to convective bursts, but later take on a life of their own in controlling outflow layer dynamics. Such a process is illustrated by the minisondes deployed during the pre-Gabrielle Global Hawk flight on 4-5 Sept, 2013. A poleward-directed outflow jet is seen to propagate northward over a period of 6-12 hours following an intense convective pulse generated near the depression center. Resulting vertical wind profiles, indicated in Fig. 2 compared with the Nadine profiles, indicate an outflow layer dominated by small scale fluctuation whose thickness depends upon range downstream from outflow jet 'roots'. Fig. 3 illustrates the diurnal evolution of the outflow jet that develops in response to the convective burst from 3-hourly AMVs, showing the jet moving rapidly outward and intensifying with

time. The details of the convective pulse itself are shown in Fig. 4 based on NWS 88D land-based radar on Puerto Rico's El Yunque mountain. The top two rows of panels show the radar reflectivity and cloud top temperatures evolving with time as a mid-level meso-vortex develops and moves northeastward away from the low level center which continues to move westward preventing further TC development.

2. *Testing and evaluation of High Definition Sounding System (HDSS) and eXpendable Digital Dropsonde (XDD) system*

   The initial HDSS tests conducted as mentioned earlier revealed good comparison with NWS radisonde observations, taken simultaneously with HDSS XDDs deployed simultaneously form the WB-57 aircraft flying a racetrack pattern just offshore. Fig. 5 illustrates good wind and temperature comparisons and also humidity up to 8 km, above which cold temperatures limit the XDD hygrometer from functioning properly.

   Fig. 6 illustrates the infrared SST sensor observations showing excellent comparison with moored and drift-buoy 'ground truth'. This limited comparison suggests only a 0.5 to 1.0 C bias over a range of temperatures from 11-27 C.

   Fig 7 illustrates usefulness of HDSS camera system in monitoring ejection of sondes as well as overshooting cloud tops in the environment around which XDD sondes are deployed.

3. *Recent observations of tropical cyclone outflow layer*
   Results from AVAPS minisonde deployment in Hurricane Edouard and HDSS/ XDD observations in Hurricane Gonzalo offer promise for focused observation of time evolution of the TC outflow layer relative to TC intensity change in two key regions: 1) the outer region outflow jet with strong, narrow and vertically complex structures at the edge of the outflow layer forced mainly by environmental interactions and 2) the inner core outflow jet 'roots' associated with inner-core convective bursts. The upper level outflow jets seem to surge outward on a diurnal time scale while inner core rainbands and concentric eyewalls contract as part of eyewall replacement cycles on a multi-day time scale.

   Global Hawk flight times flown in Edouard relative to peak intensity estimated by CIMSS/NRL SATCON technique from satellite images and NHC's working best track is shown in Fig. 8. During the first flight on 11-12 Sept, depression AL06 became a named tropical storm (Edouard). The second flight on 14-15 Sept occurred near the end of a rapid intensification event with Edouard at CAT2 status. The third flight on 16-17 Sept was at Edouard's peak intensity as a CAT3 hurricane with Vmax of 108 kt just prior to initial weakening. The fourth flight on 18-19 Sept occurred during rapid weakening and initial stages of extra-tropical transition.

   Fig 9 shows the outflow jet location north of the cloud mass east of the newly named tropical storm center during the 11-12 Sept GH flight, where 10 sondes were deployed into the equatorward sector of the poleward-directed jet. On the 14-15 Sept flight, 8 sondes were deployed along a north-south line indicated by the dashed white line, which was just east of the outflow jet axis as shown in Fig 10 cross section. An additional 4 sondes were deployed equatorward of the jet axis near the end point of subsequent flight legs further east.

Fig 11 illustrates the development of a pair of mature outflow jets just prior to peak intensity during the 16-17 Sept flight, and just subsequent to rapid intensification. The combination of AMVs and sondes indicates the development of dual outflow jets, one equatorward and one poleward as hypothesized in project objectives, i.e. observe relation of development of dual outflow jets to TC intensity change. This case presents circumstantial evidence to support the idea that dual outflow jets and intensification occur in sequence. Flight timing was insufficient to establish which came first, however. The approaching mid-latitude trough undoubtedly played a role in the intensification process as well. A series of 6 sondes were deployed into the roots of the poleward outflow jet and 5 sondes deployed into the roots of the equatorward outflow jet. An additional 6 sondes were deployed into the equatorward sector of the approaching mid-latitude jet.

The flight on 18-19 Sept shows the equatorward and poleward outflow jets merging into a large broad outflow band as part of strong upper level westerlies overtaking Edouard and initiating ET. 8 sondes were deployed across and along the mid-latitude westerly jet impinging on the north edge of Edouard's outflow.

Gonzalo was the second storm of interest during the 2014 HS3 and TCI program. This storm developed into a CAT 4 Major Hurricane during the period when the 3 WB-57 flights were conducted. The decision was made on 10 Oct to deploy the WB-57 from Ellington Field (EFD), TX to MacDill AFB (MCF), Florida over the 2014 Columbus Day weekend, a very daunting logistical exercise carried out successfully by WB-57 Program Group at EFD. With assistance from NOAA Aircraft Operations Center, work space was set up and 3 flights were conducted on 15, 16 and 17 Oct with an average of 2 hours on-station time over the storm. Fig. 12 shows the timing of the flights relative to Gonzalo's intensity change as measured by the estimated maximum wind, Vmax. The flight on the 15 took place following a day of steady state conditions at CAT3, reached the day before during a rapid intensification event. The flight on the 16th followed an eyewall replacement cycle where the storm intensified to CAT4 Major Hurricane status and occurred during the absolute peak intensity of the storm. Gradual weakening ensued on the 17th as shear increased and the storm accelerated northeastward over Bermuda.

Fig. 13 shows the WB-57 flight tack and dropsonde locations for 15, 16 and 17 Oct relative to outflow jet feature each day. On the 15th, outflow was nearly uniform with a broad area of cyclonic outflow (area inside dashed circle) and several week outflow jets originating in the inner core region where the XDD drops were made. The sondes only partially functioned with sondes in the fast-fall mode providing profiles across the outflow layer. Besides sampling the area of the outflow 'roots' near the inner core, the WB-57 also overflew the boundary of the expanding outflow generated by the inner core convective bursts occurring during the flight, extending into the dry, subsiding air to the northwest of the center all the way to the developing outflow jet at the boundary of the outflow layer.

On the 14th, the flight was planned to cover the outflow roots region to the northeast and northwest of the center. It turns out that this was in the area of a weak, but developing outflow channel and in a region of peak divergence. Primary convective bursting on this day occurred in the southwest quadrant of the storm, having rotated from the northeast on the 15th. A mid-latitude jet was rapidly approaching Gonzalo from the west on the day, a fact that may have assisted in the further storm development to CAT4 status. On the 17th the shear increased,

likely cause by the mid-latitude jet impinging on the storm and forced a broad region of poleward-directed outflow to the northeast of the center as well as a very strong outflow jet along the periphery of the outflow region northwest of the center. A weak equatorward-directed outflow jet also developed southeast of the center. A continuation of the eyewall replacement continued on the 17th with the eye expanding and peak winds weakening.

Fig. 14 shows the WB-57 flight pattern and XDD sonde deployment locations relative to eyewall and rainband features depicted by microwave satellite imagery. These images show a relatively small eye (17 km in diameter) on the 15th being replaced by a larger outer eyewall on the 16th, with remnant inner tiny eyewall. This feature was further documented by HIRAD during the flight on the 15th as shown in Fig. 15. Despite lack of real-time aircraft position information, HDSS sonde position data was relayed via on-board Iridium satcom link to track the aircraft and adjust flight tracks to penetrate over the eye on every one of the 7 eye overflights during the 3-day period.

Fig. 16 further shows the relation of the flight track and sonde deployment locations to Gonzalo structure as depicted by GOES visible and infrared imagery for 15, 15 and 17 Oct.

Figs 17 and 18 provide some insight into the nature of the HDSS/XDD data obtained in Gonzalo. Due aircraft wiring problems and HDSS electronic problems, the noise floor on the instrument was way higher than expected, causing signal strength to be way lower than expected. The result was the XDD data was only received up to a range of 60 km from the aircraft, which translated into about 8 minutes of data time. With sondes falling in both slow-fall, spiral-dive mode and fast-fall, ballistic mode, 8 minutes of data time translated into signal reception for slow-fall XDDs only from flight level at 18 km to11-12 km and for fast-fall XDDs only to 8-10 km, as shown in Fig. 17 from sondes deployed on 17 Oct. This characteristic allowed for detailed sonde measurements of outflow structures mainly from fast-fall sondes. For example detailed measurements of outflow jet characteristics on the 17th was resolved quite well for winds that observed the outflow jet max at the periphery of the outflow region. In addition temperature observations well resolved details of the tropopause height and stable layer above.

RELATED PROJECTS

This project provides valuable observational input to COAMPS-TC project N0001414WX20042 entitled: Improvement of High-Resolution Tropical Cyclone Structure and Intensity Forecasts using COAMPS-TC and to satellite studies project 75-4838-0-3-5, entitled Defense Weather Satellite follow-on Analysis of Alternatives (AoA), sponsored by the U. S. Air Force.

PUBLICATIONS

Refereed Publications: Submitted or appeared.

1. Lin, I-I, P. Black, J. F. Price, C-Y Yang, S/. S. Chen, C-C Lien, P. Harr, N-H Chi, C-C Wu and E. A. D'Asaro, 2013: An ocean cooling potential intensity index for tropical cyclones, ***Geophys. Res. Letters***, *Geophys. Res. Letters*, **40**, 1878-1882.

2. D'Asaro, E.A., P.G. Black, L.R. Centurioni, Y.-T. Chang, S.S. Chen, H.C. Graber, P. Harr, Verena Hormann, R.-C. Lien, I.-I. Lin, T.B. Sanford, T.Y. Tang, and C.-C. Wu, 2014: Impact of typhoons on the ocean in the Pacific, ***Bull. Amer. Meteorol. Soc***., **95**, 1405-1418.

3. Wang, J-H., K. Young, T. Hock, D. Lauritsen, D. Beringer, M. Black, P. G. Black, J. Franklin, J. Halverson, J. Molinari, L. Nyguyen, T. Reale, J. Smith, B. Sun, Q. Wang and J. A. Zhang, 2014: A long-term, high-quality, high vertical resolution GPS dropsonde data set for hurricane and other studies, ***Bull. Amer. Meteorol. Soc***., accepted.

4. Black, P.G., L. Harrison, M. Beaubien, R. Bluth, H. Jonsson, A. B. Penny, R. W. Smith and J. D. Doyle, 2014: High Definition Sounding System (HDSS) for atmospheric profiling, ***J. Atmos. Oceanic Technol.***, submitted- in review.

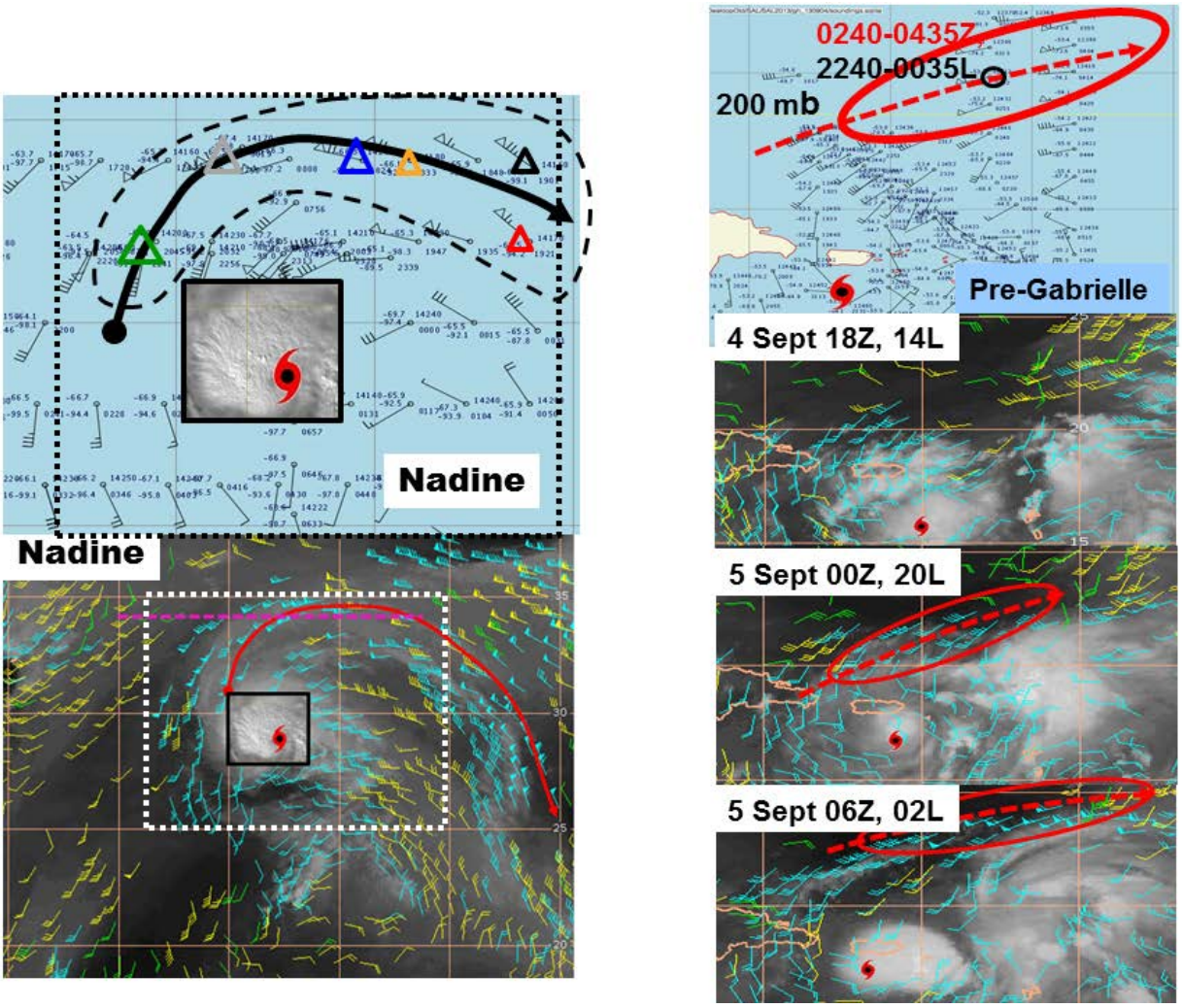

Figure 1. Overview of Hurricane Nadine AVAPS minisonde wind observations at 200 mb (upper left) from NASA Global Hawk during HS3 flight on 14-15 Sept, 2012. Outflow jet boundary indicated by dashed line and jet axis by solid black line (peak winds of 75 kt). Lower left shows larger scale AMV's for 15Sept, 00GMT with jet axis on large scale indicated by solid red line. Boundary of 200 mb mini-sonde observations is indicated by dotted white line. Inner region bounded by black box indicates MODIS visible image of supercell convective burst at the time. Upper-right indicates mini-sonde wind vector observation for pre-Gabrielle on 4-5 Oct, 2013 showing outflow jet boundary by the solid red oval and its axis by the solid black line. Panels in lower-right indicate the rapid onset, northward motion and evolution of the outflow jet from the upper-level AMVs at 6-hour intervals from 4 Oct, 18GMT to 5 Oct, 06 GMT. The red hurricane symbol indicates the position of the low-level center from WC-130J reconnaissance observations.

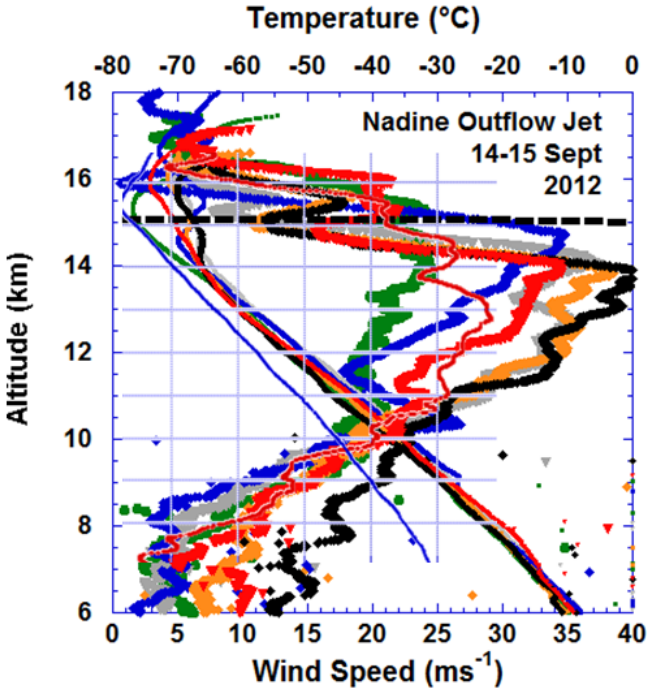

Figure 2. Wind speed and temperature profiles for Hurricane Nadine on 14-15 Sept, 2012 along the jet axis indicated by colors in Fig. 1 compared with sample 4-5 Oct, 2013 pre-Gabrielle wind profile on jet axis shown by thin red line.

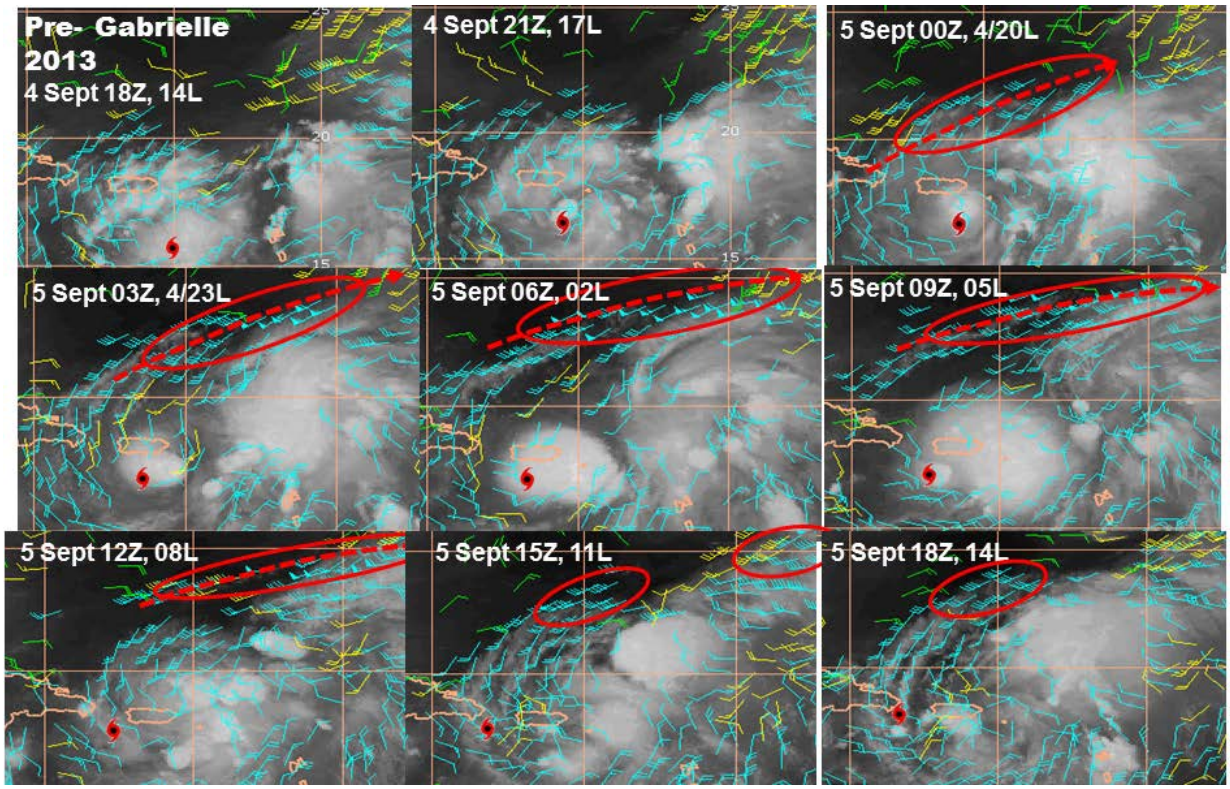

Figure 3. Diurnal cycle of pre-Gabrielle outflow associated with convective pulsations shown for a 24-hours period every 3 hours from 18 GMT 4 Oct, 2013 until 18 GMT 5 Oct, 2013. Red ovals indicate out flow jet boundaries and dashed red line indicates the axis. Red hurricane symbol indicates disturbance center at low level from WC-130J reconnaissance.

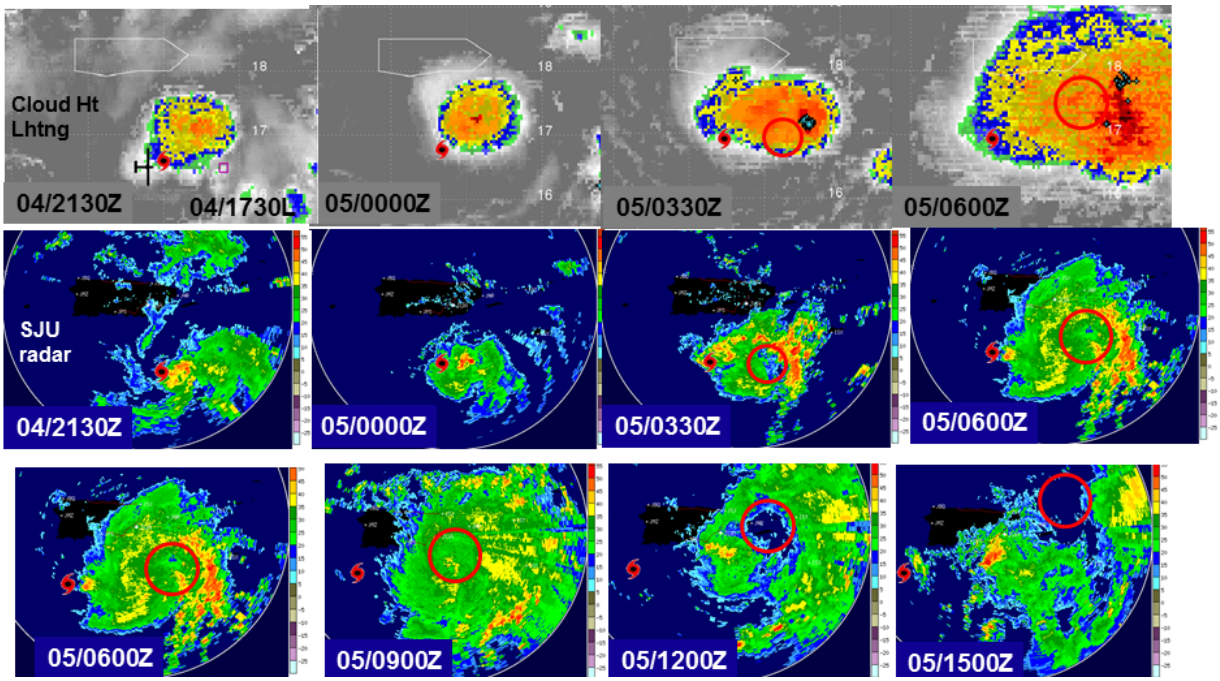

Figure 4. Time evolution of convective burst in pre-Gabrielle from 2130 GMT 4 Sept to 0660GMT 5 Sept from enhanced GOES satellite IR imagery and San Juan radar, as well as extending to 1500 GMT 5 Sept from the radar where formation of a mid-level meso-vortex and its movement to the northeast is evident from echo motions and Doppler velocities (not shown).

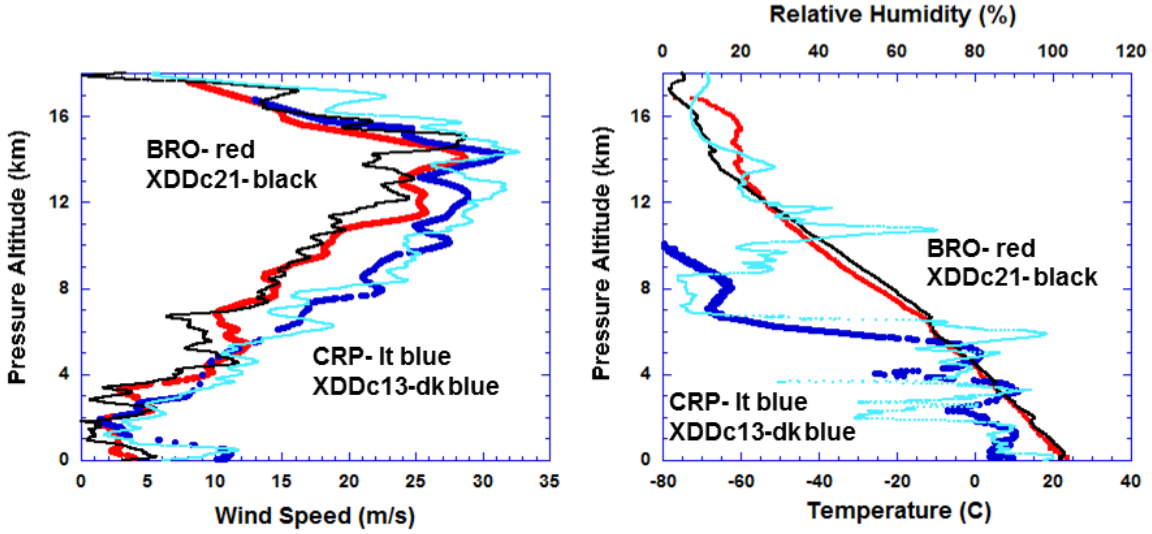

Figure 5. Comparison of wind speed (left) from HDSS eXpendable Digital Dropsonde (XDD) in dark blue and black deployed from a NASA WB-57 at 60,000 ft. offshore from Corpus Christi (CRP) and Brownsville (BRO) Texas with speeds from 12 GMT NWS radiosonde ascents on 19 Nov, 2013 (light blue and red, respectively). Humidity and temperature measurements are compared in the right panel.

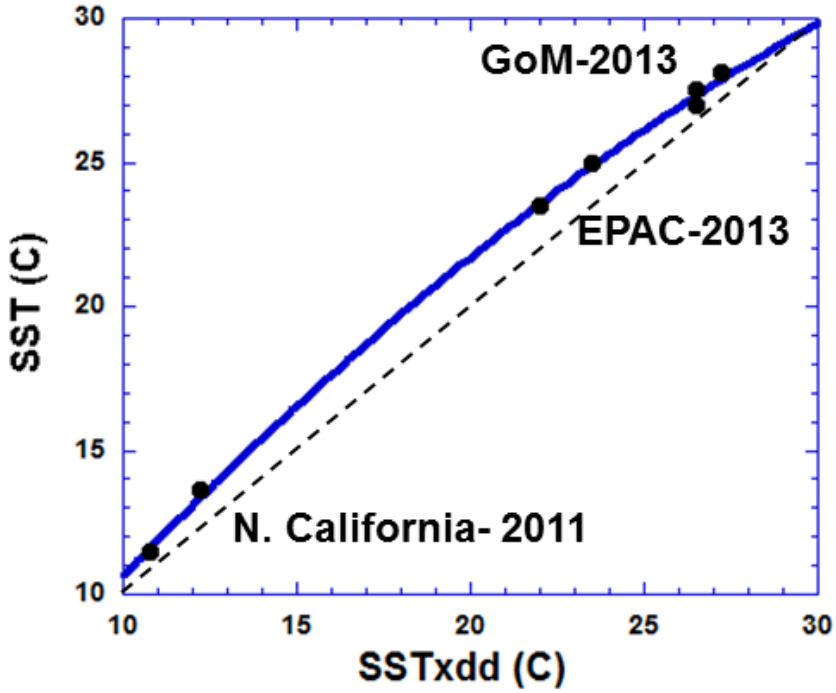

Figure 6. XDD infrared-derived SST observations compared with moored and drifting buoy observations in three regions: 1) northern California coast offshore from San Francisco Bay and Monterey Bay, 2) East Pacific offshore from Baja California and 3) Gulf of Mexico offshore from the Texas coast. Dashed line is line of perfect agreement that shows a small bias of 0.5 to 1.0 °C

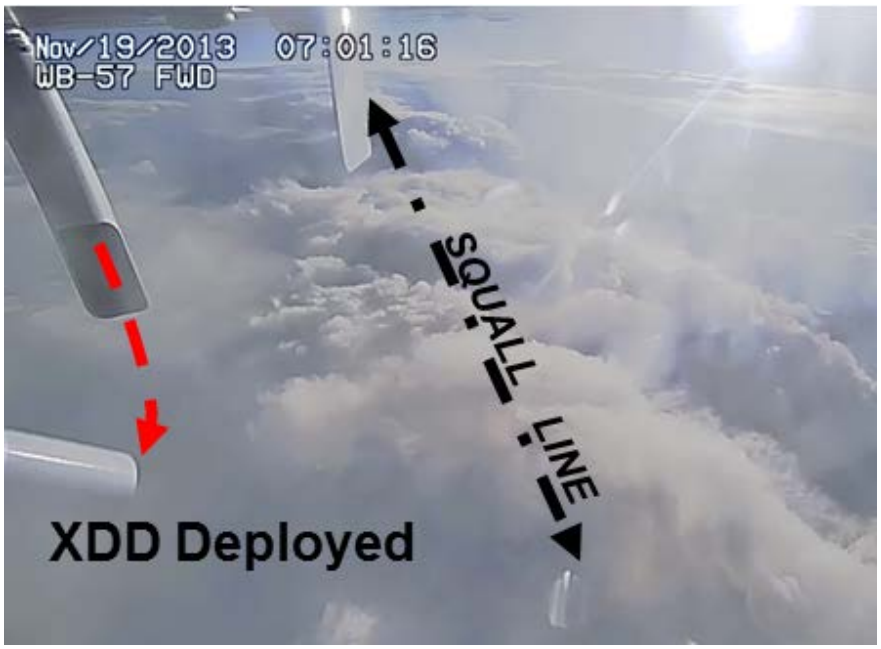

Figure 7. Image from camera system on HDSS that shows sonde being deployed from drop tube on the WB-57 instrument pallet. Also shown is the overshooting cloud tops associated with a squall line system overflown by theWB-57 during test deployments on 19 Nov., 2013.

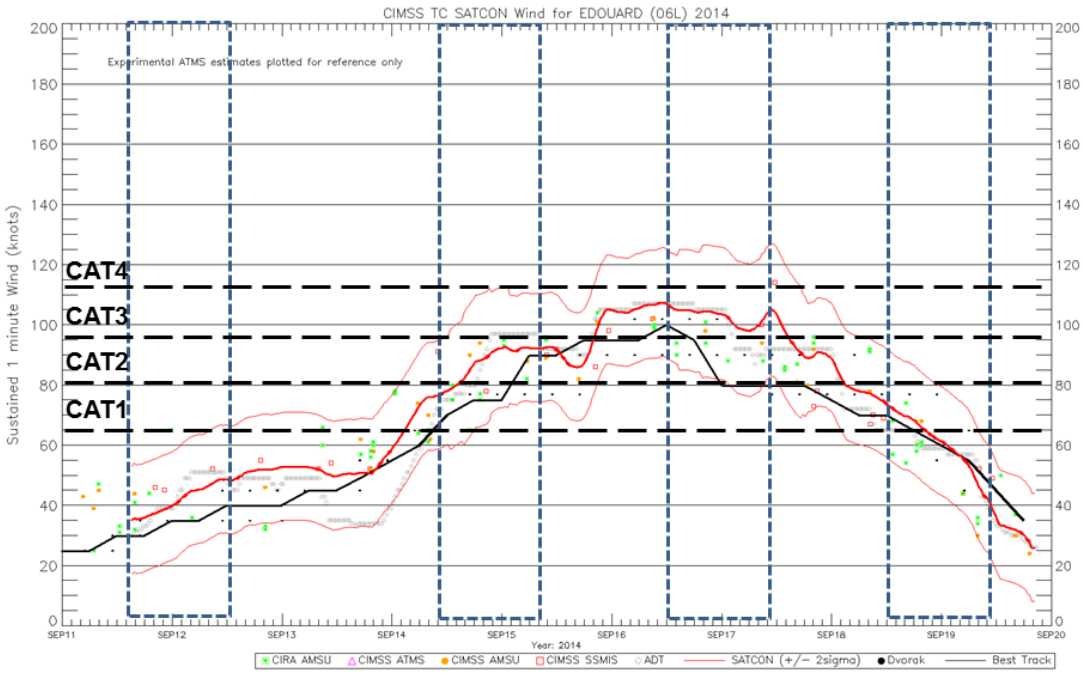

Figure 8. Time evolution of maximum wind, Vmax, during the four Global Hawk flights over Hurricane Edouard, indicated by dashed rectangles. The thick red line indicates SATCON Vmax estimate with thin lines indicating 2 sigma deviations. Black line is working best track Vmax estimate, which averages about one sigma less than SATCON. Horizontal long dashed lines are boundaries of the Saffir-Simpson storm category scale.

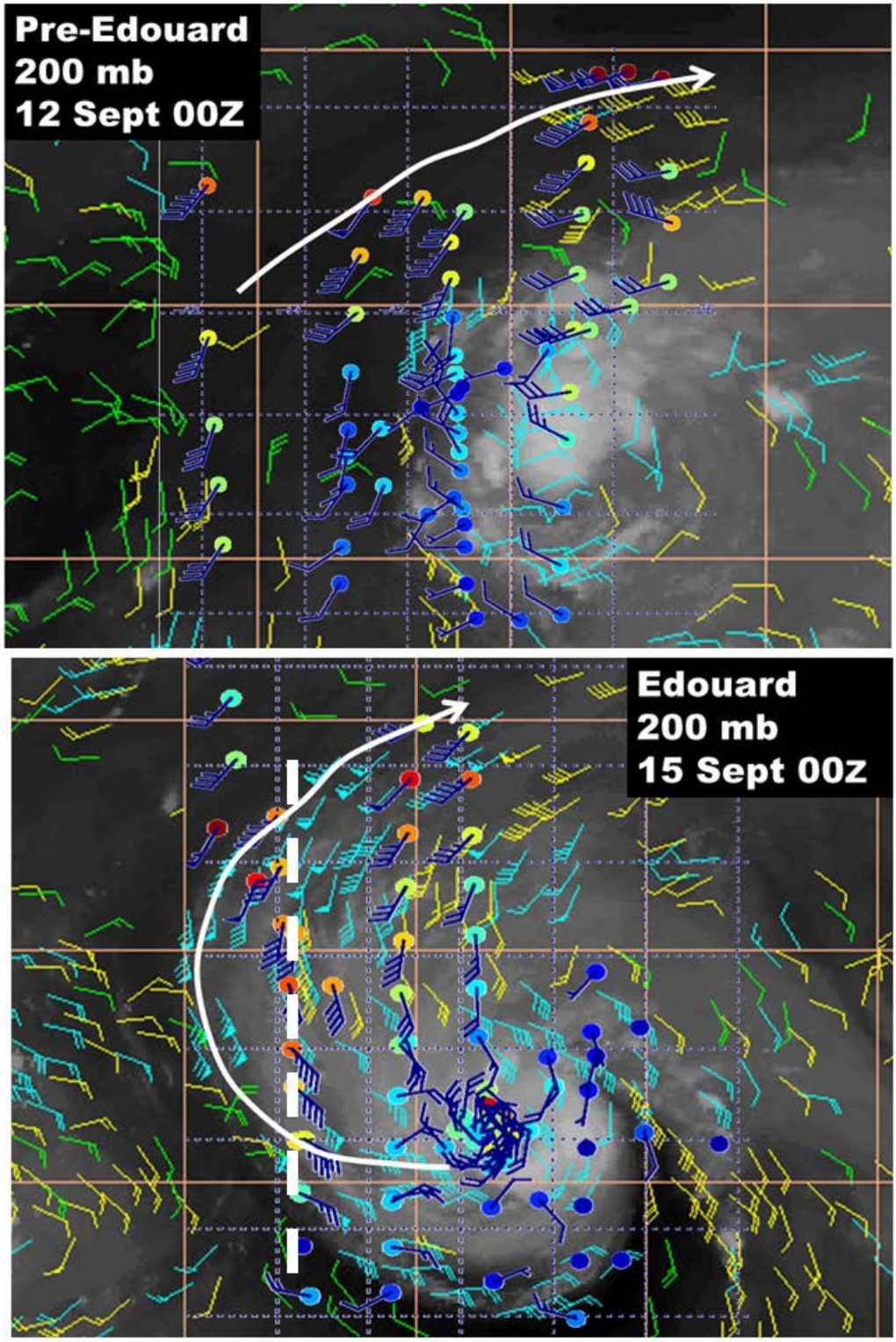

Figure 9. Distribution of mini-sonde wind observations at 200 mb (indicated by colored mini-sonde locations superimposed on upper level AMVs for 12 GMT each day, about half way through the flight. White solid curves indicates outflow jet axis. Dashed white line indicates location of cross section to follow.

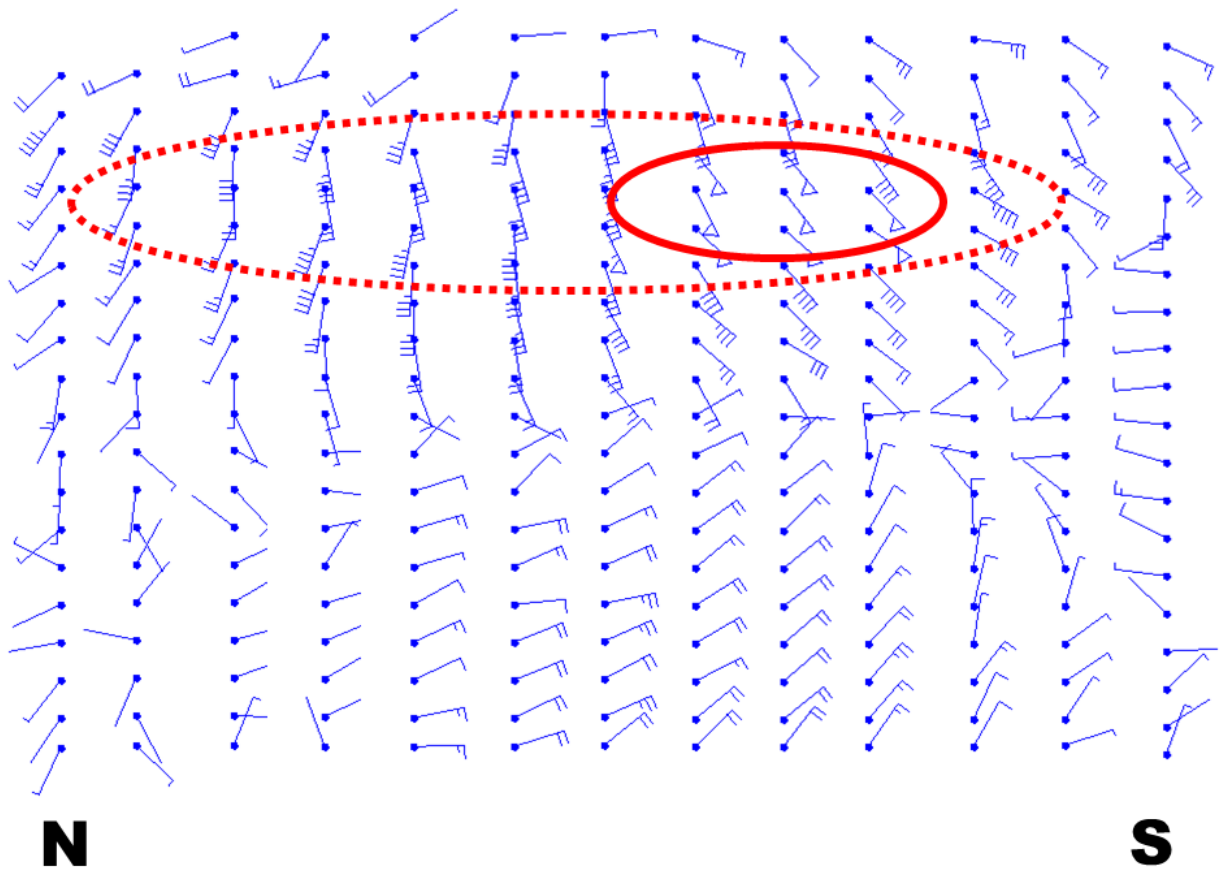

Figure 10. Cross section along dashed line in Fig 9 (lower) across outflow jet from 1000 mb near the surface to 100 mb. Jet maximum of 50 kt is centered at 200 mb.Two distinct layers are evident: lower layer with cyclonic northeasterly flow around the storm below 500 mb and the upper outflow layer above that with anticyclonic southerly flow.

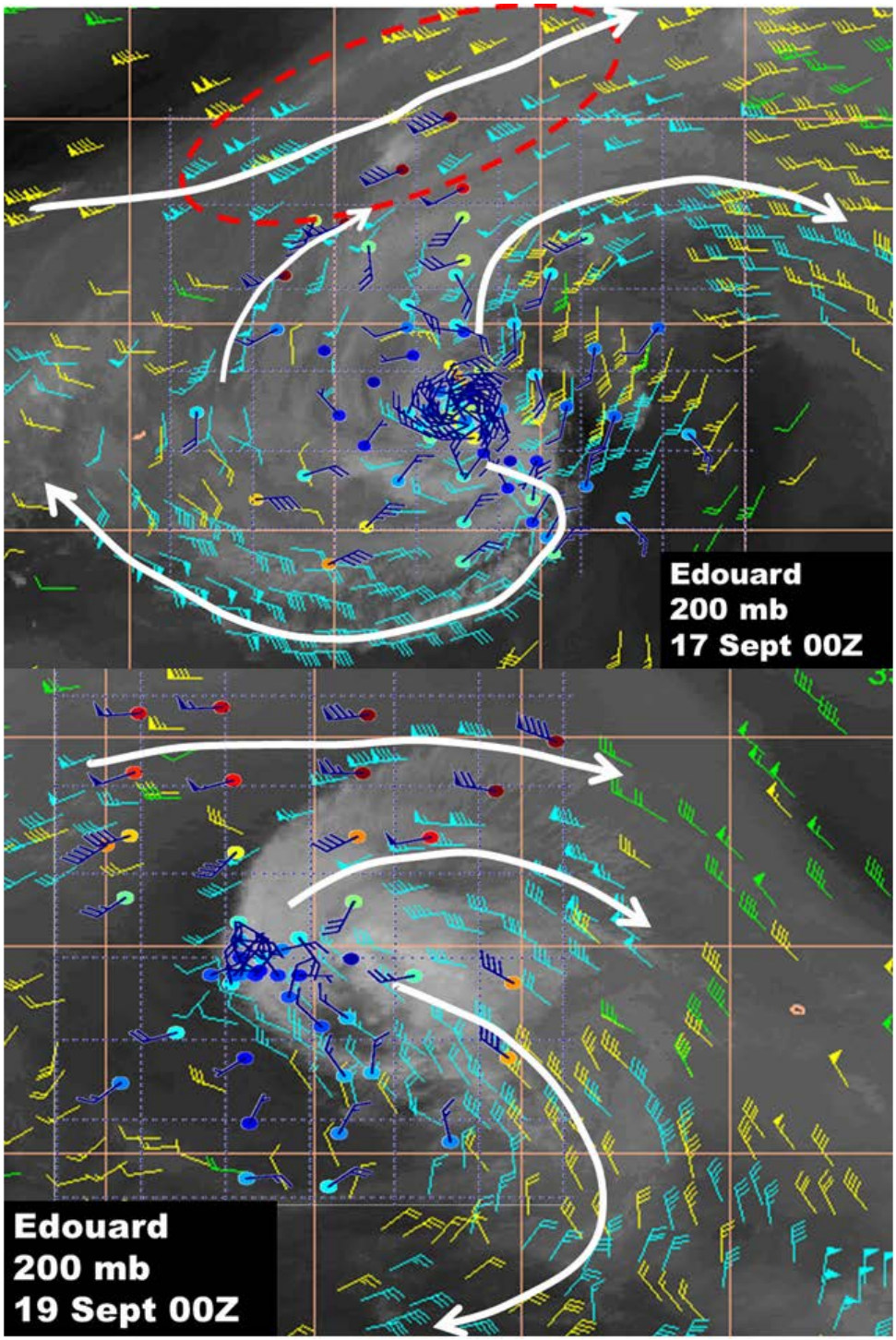

Figure 11. Evolution of outflow layer on the 17th and 19th as it transforms from a single northward directed outflow jet on the 15th to dual outflow jets directed easterly poleward of the center and westerly equatorward of the center. A remnant poleward jet remains as a major mid-latitude jet approaches from the west on the 17th and merges with the storm-related outflow jet while maintaining the equatorward out flow jet.

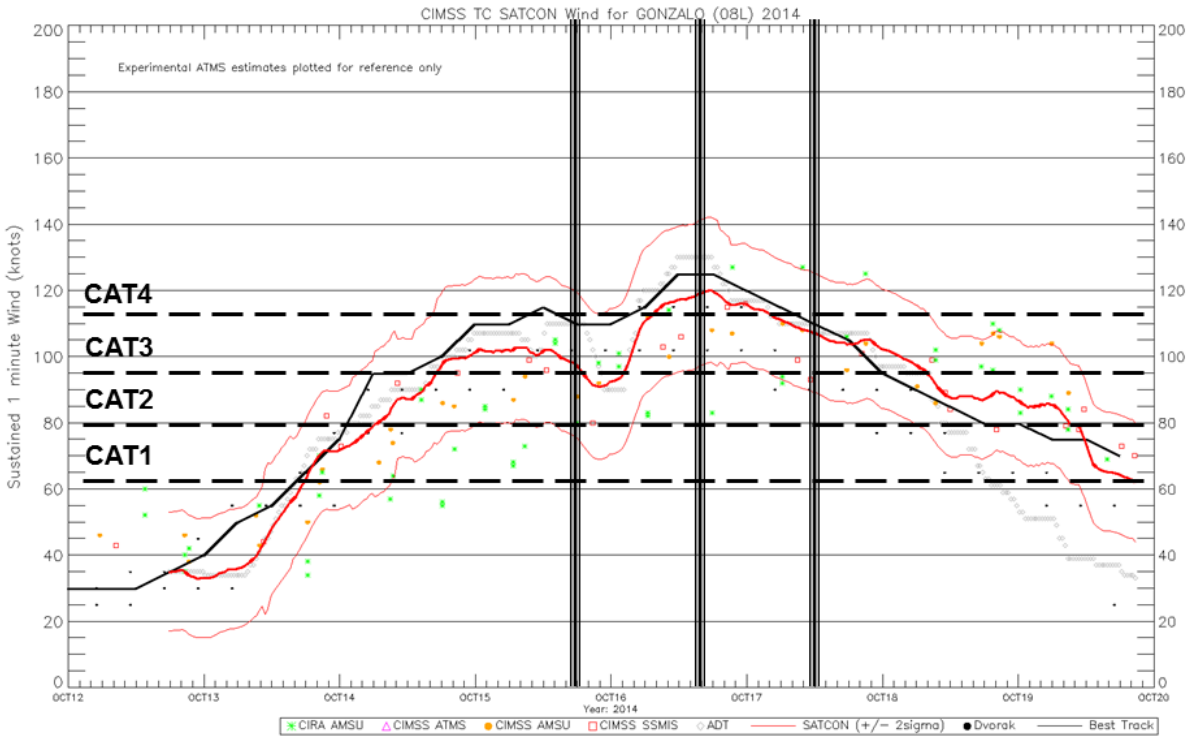

Figure 12. Time evolution of maximum wind, Vmax, during three sequential WB-57 flights over Hurricane Gonzalo on 15, 16 and 17 Oct, 2014, indicated by vertical lines. On-station time for each flight was about 2 hours. The thick red line indicates SATCON Vmax estimate with thin lines indicating 2 sigma deviations. Black line is working best track Vmax estimate, which averages about one sigma less than SATCON.

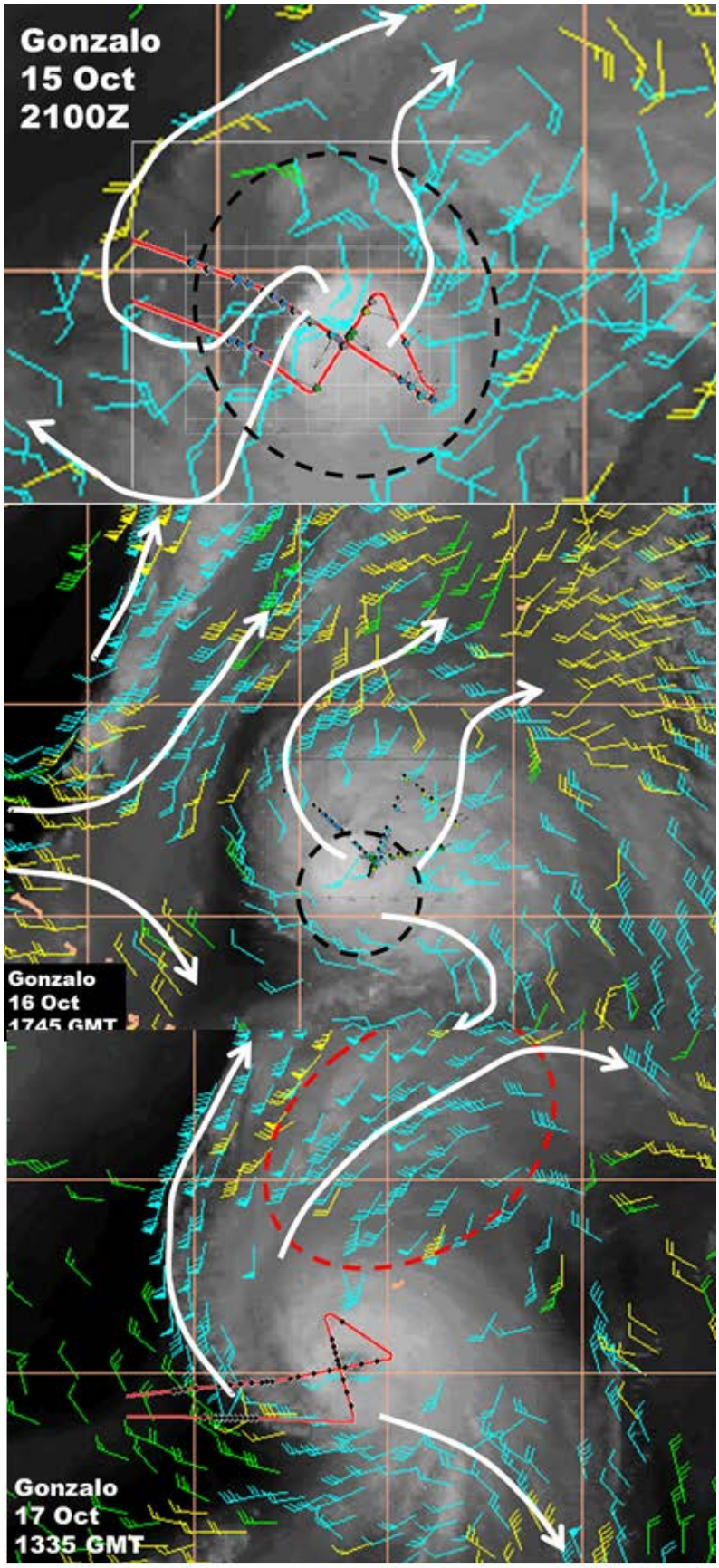
Gonzalo
15 Oct
2100Z
Gonzalo
16 Oct
1745 GMT
Gonzalo
17 Oct
1335 GMT

Figure 13. Outflow jet evolution for 15, 16 and 17 Oct based upon upper level AMV's and 150-150 mb wind vectors from HDSS XDD sondes. Outflow jet locations are indicated by white curved arrows. Red lines indicate aircraft flight track based on WB-57 navigation data while black diamonds indicate XDD sonde locations. There was no nav data on the 16th due to on-board computer hard drive failure. Dashed circles indicates outer limit of cyclonic outflow. Outflow layer transitioned from weak dual polward and equatorward jets on the 15th as Gonzalo was slowly developing to dual poleward-directed outflow jet on the 16th near maximum intensity, with mid-latitude jet approaching from the west to dual poleward directed and a weak equatorward jet on the 17th as gonzalo weakens and undergoes extra-tropical transition.

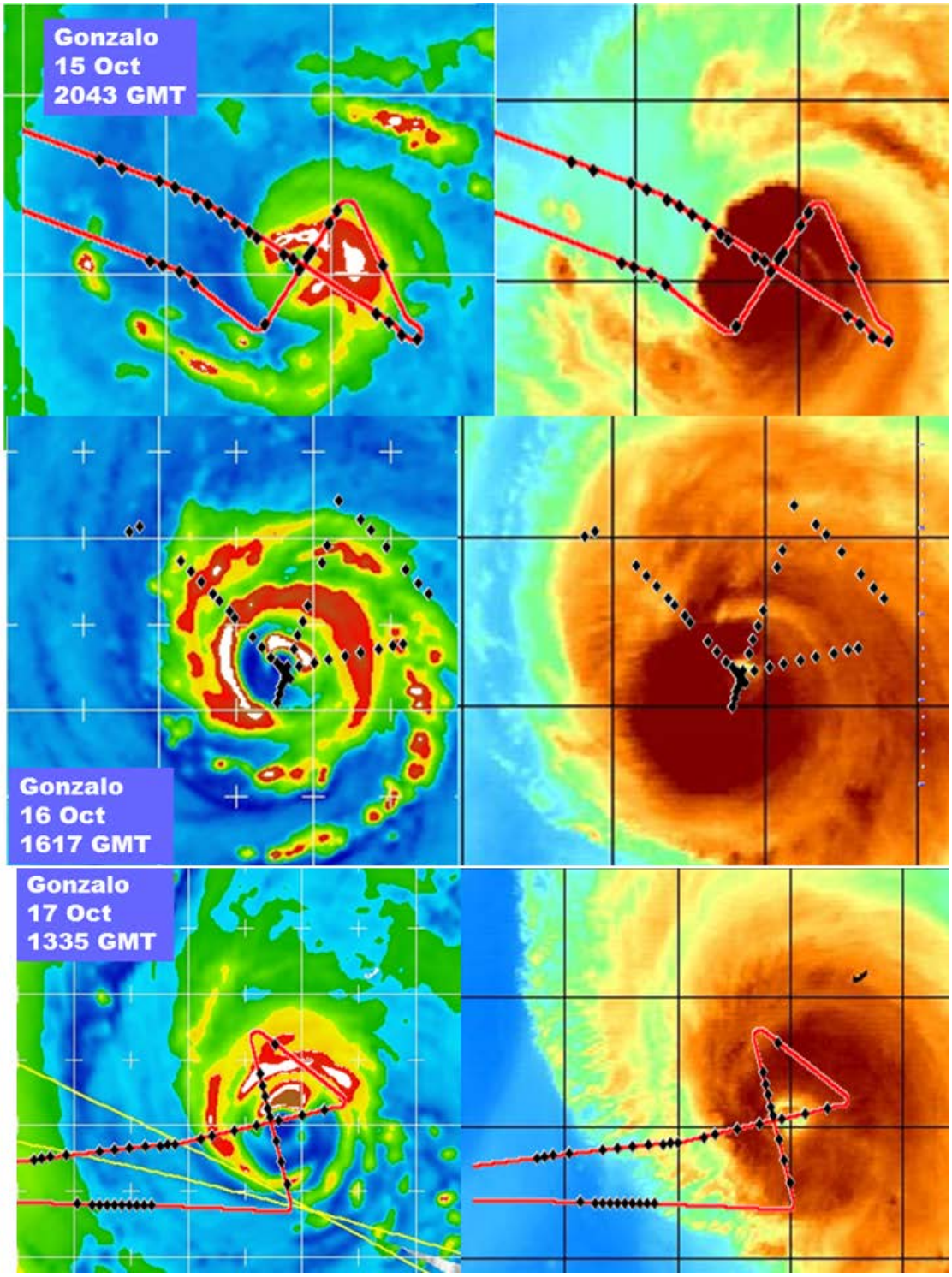

Figure 14. XDD sonde locations and aircraft track relative to eyewall and rainband features of Gonzalo on 15, 16 and 17 Oct, represented by microwave imagery (left column). This is compared to upper water vapor features from GOES IR water vapor channels (right column). Leading edge of large water vapor gradients tends to be co-located with outflow jet axes. Note the focus on rapid sonde deployment across outflow boundary on the 17th.

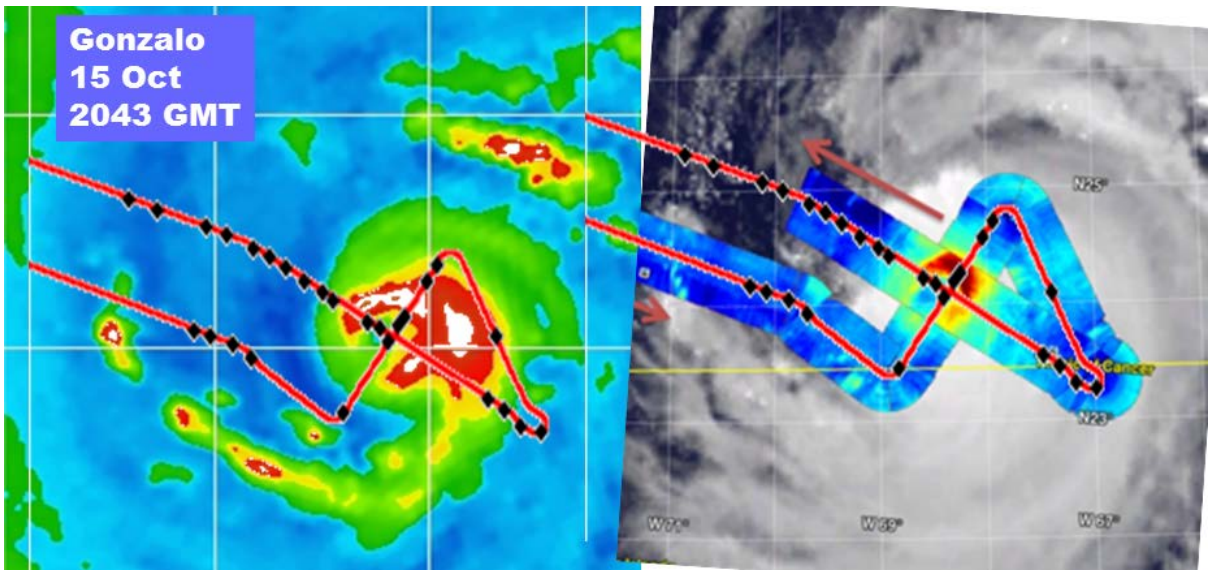

Figure 15. WB-57 track and XDD sonde locations compared with HIRAD brightness temperature retrievals during the WB-57 flight over Gonzalo

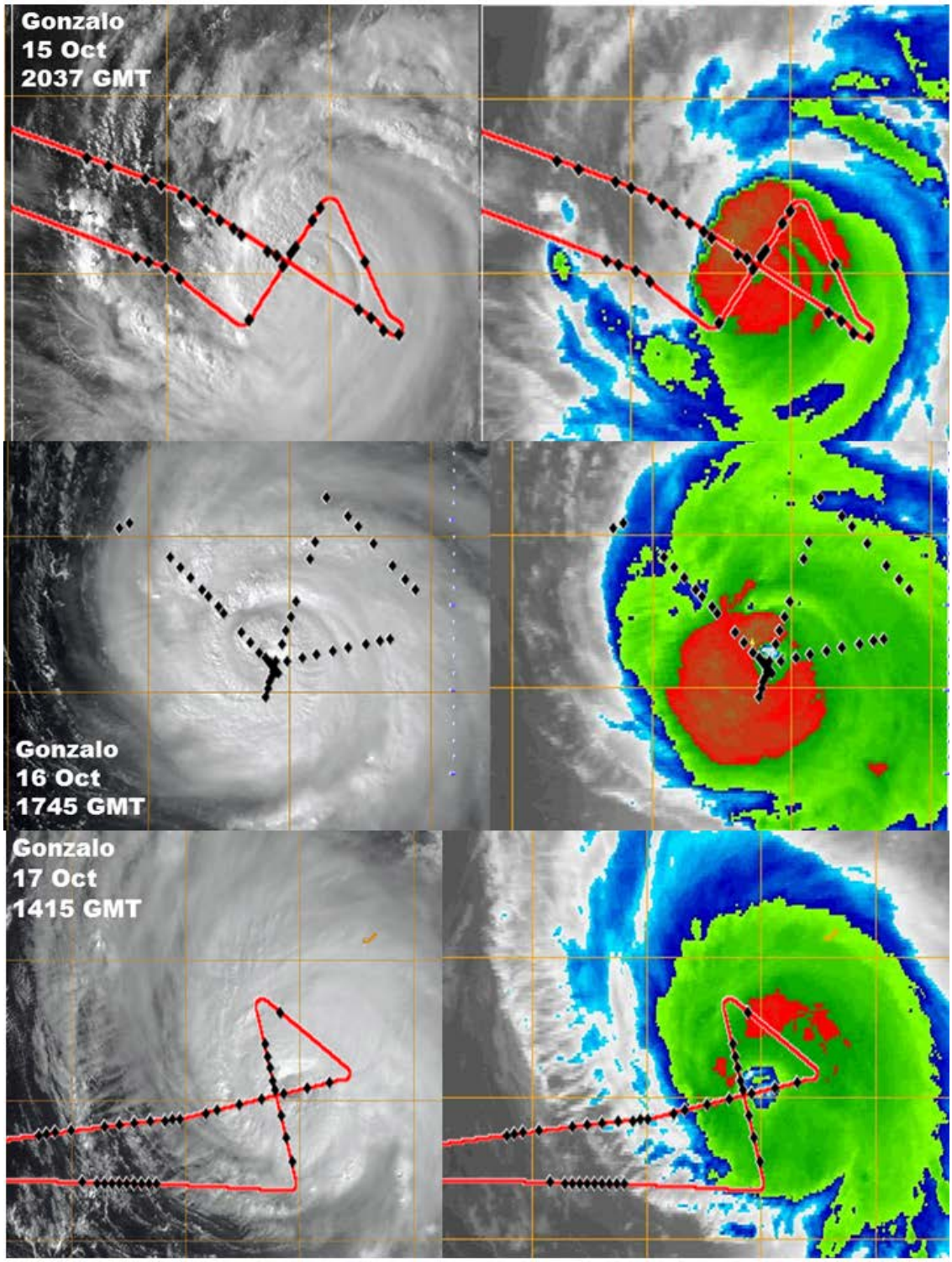

Figure 16. XDD sonde locations and aircraft track relative to eyewall and rainband features of Gonzalo on 15, 16 and 17 Oct, as represented by visible (left column) and infrared (right column) imagery from GOES satellite operating in rapid scan mode, i.e. images every 15 minutes.

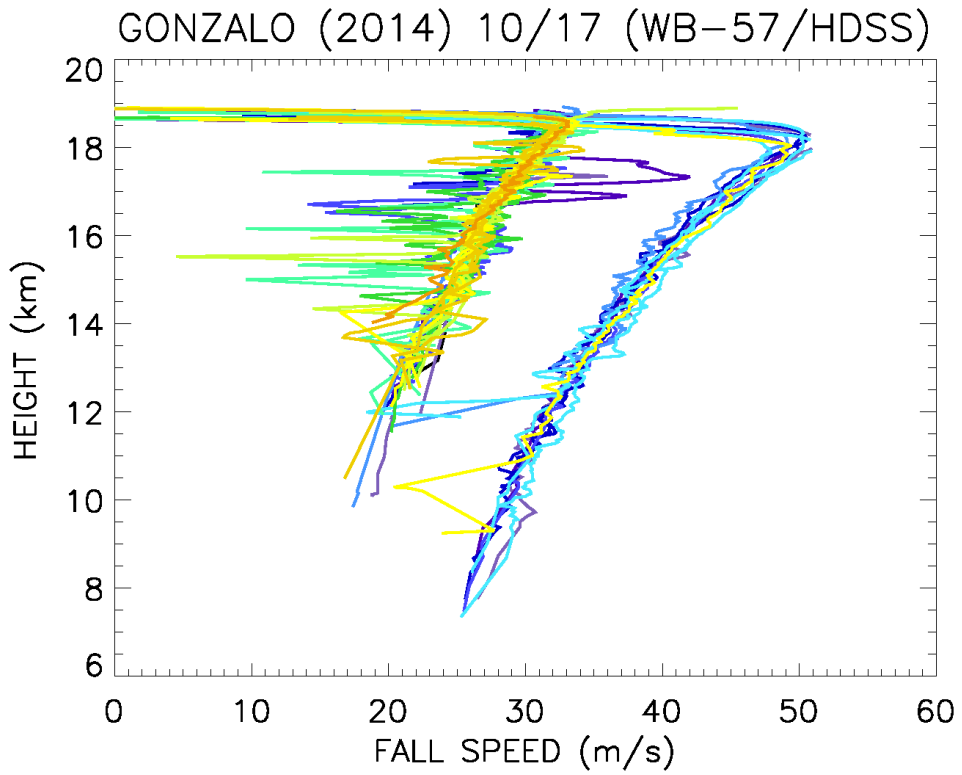

Figure 17. Raw sonde fall speed data reveal dual fall speed characteristic of XDDs with slow-fall, spiral-dive mode upper level fall speeds on order of 20-30 m/s and fast-fall, ballistic mode on order of 30-50 m/s. Sondes terminated prematurely at a range of 60 km from the aircraft due to system noise issues.

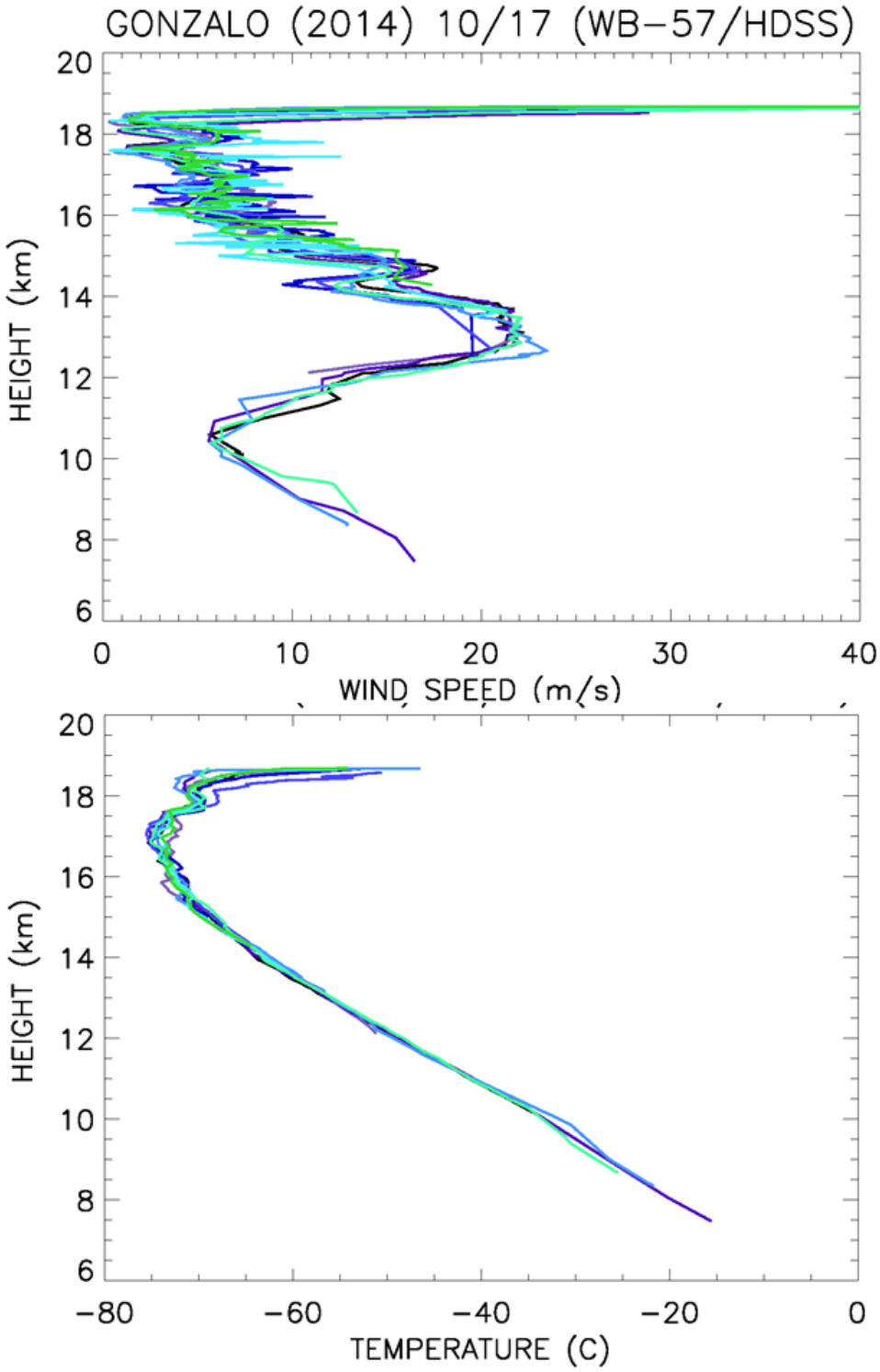

Figure 18. Sample of raw wind (upper) and temperature (lower) profiles from fast-fall XDD's on the 17th deployed across the outflow boundary. Fast fall sondes remained within useable range of the aircraft long enough to return repeatable observations of fine scale detail within the outflow layer. Note outflow layer jet maximum at 13 km level and the tropopause at 16 km level.