Hurricane and severe storm Sentinel (HS3)
Summary of the 2013 campaign

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1.0 Introduction

Nearly 100 million Americans live within 50 miles of a coastline—exposing them to the potential destruction caused by landfalling hurricanes, as was so amply demonstrated in the fall of 2012, when Hurricane Sandy struck the U.S. East Coast. While hurricane track prediction has greatly improved in the last 30 years, improvements in hurricane intensity forecasts have lagged, primarily because of our poor understanding of the processes involved in intensity change. The Hurricane and Severe Storm Sentinel (HS3) Mission is designed to investigate some basic questions to further address this issue:

- What impact does the large-scale environment, particularly the Saharan Air Layer (SAL), have on hurricane intensity change?
- What is the role of storm internal processes, such as deep convective towers?
- To what extent are these intensification processes predictable?

HS3 involves three deployments of NASA's Global Hawk (GH) Unmanned Airborne System (UAS) to NASA's Wallops Flight Facility (WFF) on the coastline of Virginia during the 2012, 2013, and 2014 hurricane seasons, with distinct payloads onboard to address these science questions. WFF provides easy access to storms over the Atlantic Ocean, Gulf of Mexico, and Caribbean. NASA's Air Vehicle-1 (AV-1) Global Hawk carries an *over-storm* payload; AV-6 carries an *environmental* payload.

The environmental GH AV-6 carried three instruments to examine the environment and outflow layer of storms. The scanning High-resolution Interferometer Sounder (S-HIS), Advanced Vertical Atmospheric Profiling System [(AVAPS) also known as a *dropsonde*], and the Cloud Physics Lidar (CPL) collectively provide measurements of the vertical structure of temperature, relative humidity, winds, Saharan dust, and clouds.

Onboard AV-1, the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) conically-scanning Doppler radar provides three-dimensional wind and precipitation fields, the Hurricane Imaging Radiometer (HIRAD) measures surface wind speeds and rainfall, and the High-Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (HAMSR) microwave sounder provides measurements of temperature, water vapor, and liquid water profiles; total precipitable water; sea-surface temperature; rain rates; and vertical precipitation profiles.

Details on the mission, aircraft, and instruments can be found on the HS3 web page at https://espo.nasa.gov/missions/hs3. Links to data from the 2012 campaign can be found at the web page, while links to 2013 campaign data will be posted as soon as available (expected around February or March 2014). All data is freely available.

2.0 Atlantic Tropical Cyclone Activity in 2013

The 2013 HS3 campaign took place between August 20-September 23, 2013. Although the 2013 Atlantic hurricane season produced 13 tropical cyclones, it only produced two hurricanes of category-1 intensity, the lowest number in three decades. The accumulated cyclone energy for the season was only 30% of normal. Of the 13 tropical cyclones, only four occurred during the HS3 campaign (Fernand, Gabrielle, Humberto, and Ingrid). Fernand was very short-lived and occurred in the extreme southwestern Bay of Campeche. Humberto formed just off the coast of Africa, moved westward very slowly, then before reaching 30°W turned due north over cooler waters and dissipated. It later reformed into a weak tropical storm before undergoing extratropical transition. Hurricane Ingrid formed in the southwestern Gulf of Mexico and moved northward before turning westward into Mexico. The only other tropical disturbance of interest was Invest 95L in the southwestern Gulf of Mexico that, on the day of flight, had a 70% chance of becoming a tropical cyclone but failed to develop.

Figure 2-1. Atlantic storm tracks for 2013. In some cases, in which storms dissipated before reforming (Dorian, Gabrielle, Humberto), the active stages of the storms are connected by a straight-line segment giving, the appearance of a long, straight track.

3.0 Flight Summaries

3.1 Overview

During the 2013 deployment, HS3 conducted seven flights of the environmental GH and two of the over-storm GH. The first flight (August 20-21, AV-6) was over the remnants of Tropical Storm (TS) Erin, which had dissipated two days prior to flight. The dropsonde system lost power shortly after getting on-station, but S-HIS and CPL obtained information on the movement of a major Saharan Air Layer (SAL) outbreak over the low-level remnants of Erin. On August 24-25, AV-6 obtained detailed measurements of another intense SAL outbreak. The next four flights (3 with AV-6, 1 with AV-1) over the period of August 29-September 8 examined the pre-Gabrielle disturbance, its formation into a TS, and its later potential for redevelopment. An AV-1 flight on September 15-16 obtained two overpasses of Hurricane Ingrid in the Gulf of Mexico before low fuel temperatures required a return to base. A September 16-17 AV-6 flight examined the reformation of TS Humberto, revealing a hybrid tropical/extratropical storm structure. The final science flight, on September 19-20, used AV-6 to examine the potential genesis of a disturbance (Invest 95L) in the Gulf of Mexico. Ultimately this storm failed to develop and the HS3 data should provide valuable information on the factors that prevented genesis.

Table 3-1. Summary of the 2013 HS3 science flights. Color shading indicates groupings of flights with blue indicating Saharan air layer flights; light green Gabrielle-related flight; and light purple, blue, and orange indicating individual flights associated with Ingrid, Humberto, and Invest 95L.

Date	Aircraft	Storm	Description
August 20-21	AV-6	Ex-Erin/SAL	Environmental sampling of shallow former TS Erin and SAL air mass
August 24-25	AV-6	SAL	SAL flight in weak African wave disturbance
August 29-30	AV-6	Pre-Gabrielle/SAL	Pre-Gabrielle African wave with SAL air
Sept. 3-4	AV-1	Pre-Gabrielle	Measurement of convective structure of Pre-Gabrielle and adjacent convective disturbance
Sept. 4-5	AV-6	TS Gabrielle	Environmental sampling of TS Gabrielle and adjacent convective disturbance
Sept. 7-8	AV-6	Ex-Gabrielle	Potential redevelopment of former TS Gabrielle
Sept. 10	AV-1	TS Gabrielle	Convective structure of Gabrielle. Flight was aborted after navigation unit failure.
Sept. 15-16	AV-1	Hurricane Ingrid	Precipitation and wind structure measurements in H. Ingrid. Flight cut short due to fuel temperature problems.
Sept. 16-17	AV-6	TS Humberto	Redevelopment of TS Humberto. Hybrid low-level warm/upper-level cold structure observed.
Sept. 17	AV-1	TS Humerto	Convective structure of Humberto. Flight was aborted after navigation unit failure.
Sept. 19-20	AV-6	Invest 95L	Environmental measurements of Invest 95L that, despite a good low-level circulation and moisture, failed to develop into a tropical depression.

3.2 Saharan Air Layer Flights

Tropical Storm Erin dissipated just days before the first science fight opportunity in August. With a very low probability of tropical activity during the first week of operations, the HS3 science team decided to pursue secondary science objectives related to the SAL. Figure 3-1 shows flight tracks for the SAL flights. The first flight on August 20-21 examined a surge of Saharan air overrunning the remnants of TS Erin. The second flight on August 24-25 investigated a significant dust outbreak associated with a weak tropical wave. The following subsections summarize these fights.

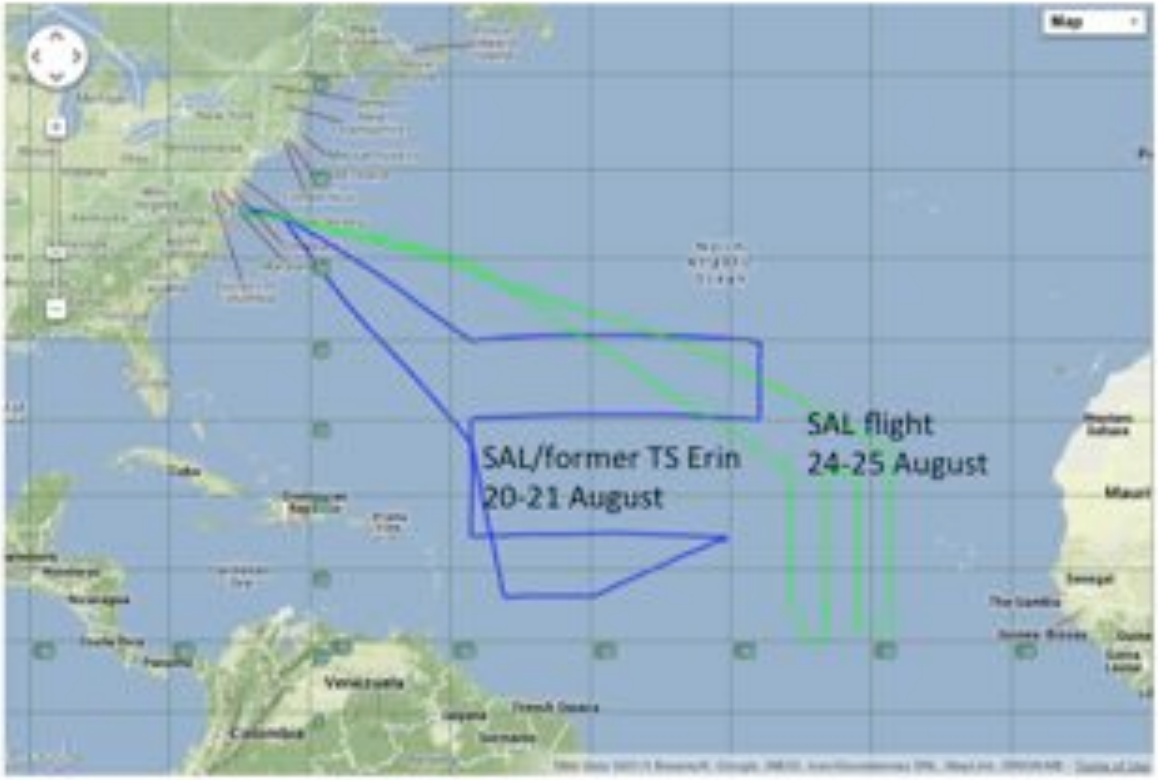
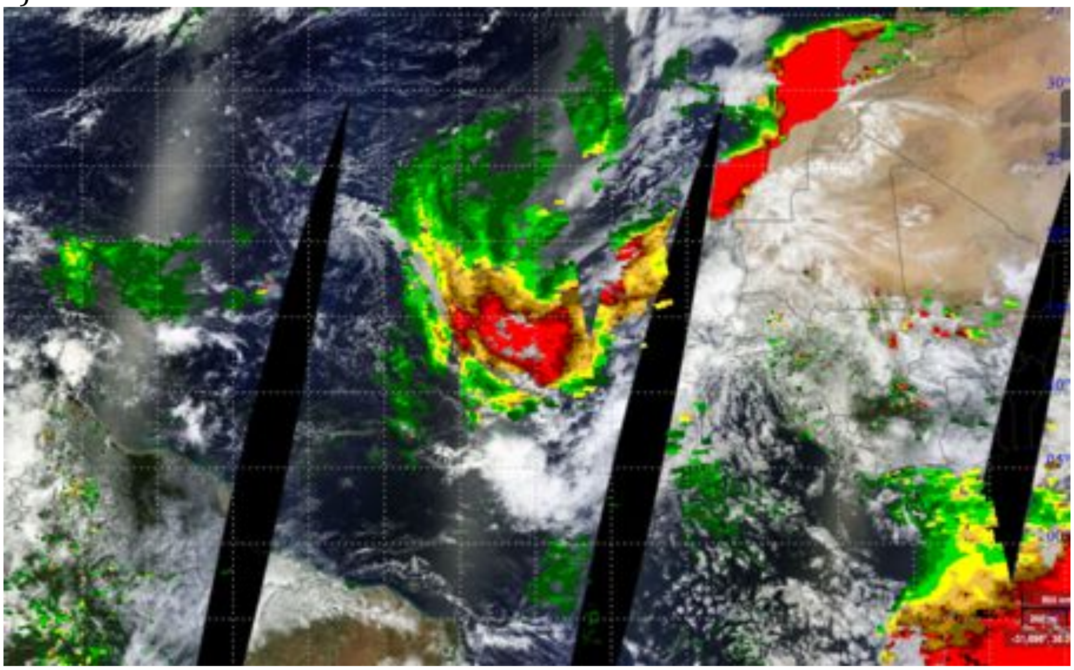


Figure 3-1. Environmental Global Hawk (AV-6) flights for August 20-21 and 24-25 to investigate SAL outbreaks.

3.2.1 August 20-21

The goal of this flight was to examine the remnants of TS Erin and the leading edge of a significant dust outbreak (Fig. 3-2a). The originally planned flight pattern (modified during flight) is overlaid on the GEOS-5 dust forecast (00Z 20 AUG run, 10-hr forecast, valid at 10Z 20 Aug) in Fig. 3-2b. The objective of the flight was to sample the vertical structure of the environment of Erin's remnants as well as the leading edge of the SAL surge by having flight legs that were roughly normal to the SAL "front". The remnants of Erin can be seen just ahead and toward the northern end of the dust plume (Fig. 3-2a), and was composed of mostly low-level clouds. During flight, power to the AVAPS dropsonde system was lost due to a failure of a relay in the Experimenter Interface Panel after dropsonde number 15. As a result, no drops were obtained after the north-to-south flight segment following the first west-to-east flight leg, including during the key crossing of the remnants of Erin.

a)



b)

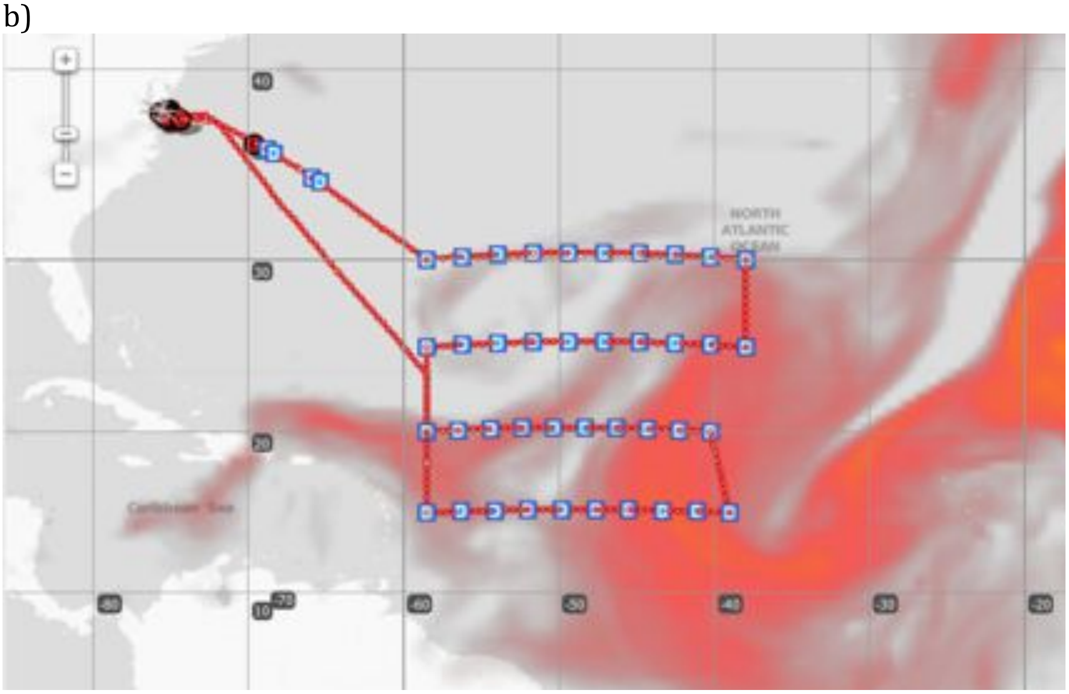


Figure 3-2. (a) MODIS clouds and aerosol optical depth for August 20. Low-level clouds associated with the remnants of TS Erin are seen at the northwestern edge of the dust (color shading). (b) GEOS-5 forecast of aerosol optical depth (red shading) and the initial (pre-takeoff) AV-6 flight track.

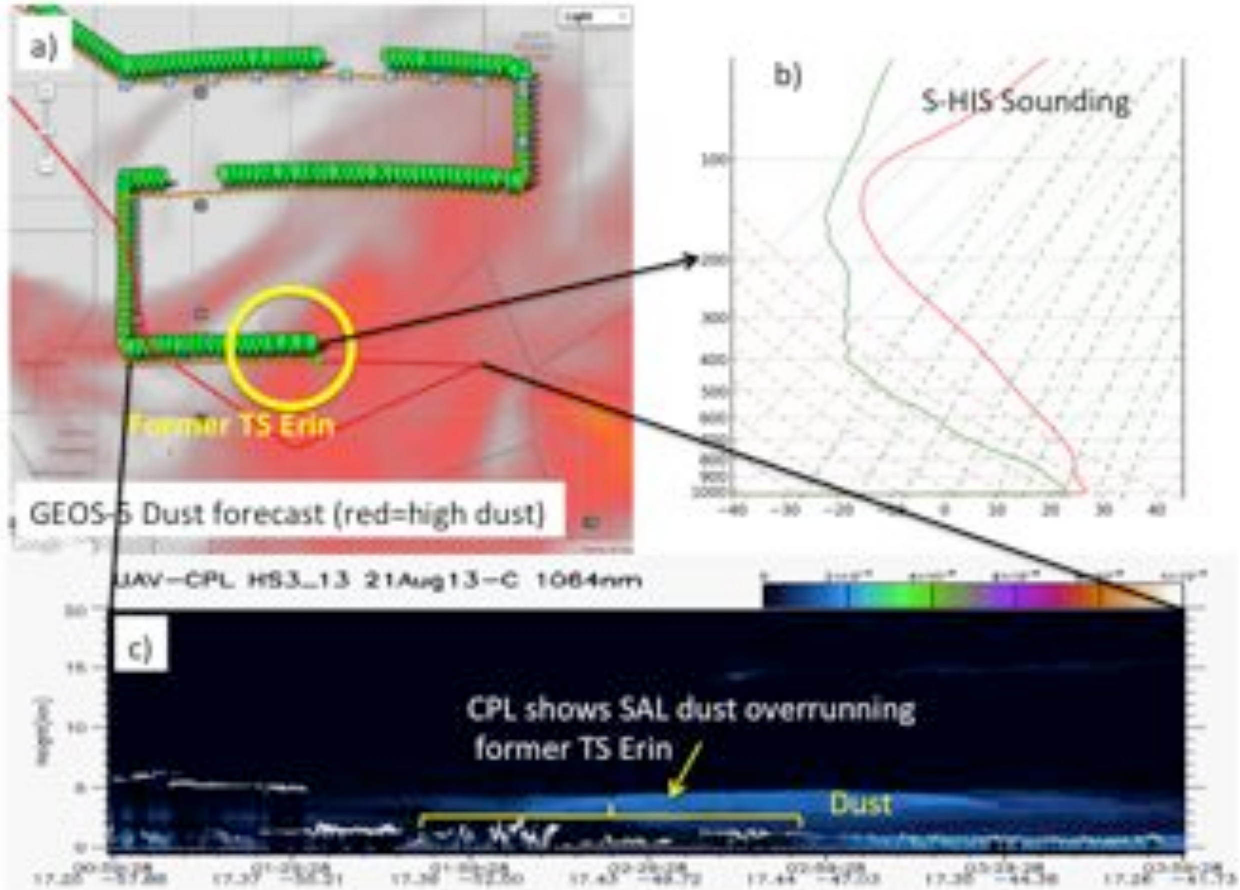


Figure 3-3. (a) GEOS-5 dust forecast and AV-6 flight track during midflight. Green symbols represent S-HIS real-time temperature and humidity retrieval locations. The yellow circle indicates the approximate position of the remnants of TS Erin. (b) Real-time Skew-T, log-p sounding plot from the S-HIS instrument. (c) CPL backscatter showing Saharan dust overrunning the remnants of Erin.

Examples of data from the flight leg crossing over the remnants of Erin are shown in Figure 3-3. During flight, the flight path was adjusted on the third east-west leg in order to cross over the approximate center of Erin (Figure 3-3a). A real-time sounding from the S-HIS instrument is shown in Figure 3-3b for a location near Erin's center. It shows very dry air from 800 to 200 hPa associated with the low-level Saharan air mass and dry subsiding air aloft, and a strong inversion near the bottom of this layer. Data from the CPL lidar in Figure 3-3c shows low-level clouds (white shading) associated with the remnants of Erin being overrun by Saharan dust (blue shading). This dust layer was thickest to the east and over the eastern portion of Erin and became thinner out to the west. While the dry stable air associated with the SAL was limiting the vertical extent of the clouds associated with Erin, the fact that the Saharan air moved so readily over Erin likely attests to the weak and shallow nature of Erin prior to this time.

3.2.2 August 24-25

The goal of this flight was to study a major SAL outbreak and an associated tropical wave moving westward from Africa. Convection in the wave died off shortly after it moved offshore, so no development was expected in this case. However, it was seen as an excellent opportunity to get detailed measurements of SAL structure. The flight consisted of a lawnmower pattern with four north-south oriented legs. Samples of data at 800 hPa for this flight are overlaid over the GOES SAL product in Figure 3-5. Dropsonde winds show strong easterlies on the southern boundary of the SAL and weaker easterlies or southerlies farther to the south, suggesting a weak cyclonic circulation. Temperature and humidity data show very hot and dry air wrapping around the northern and western sides of the wave and cooler, more moist air wrapping around the southern and eastern sides. CPL data from the first three flight legs is shown in Figure 3-5c along with temperature anomalies. The transition from dusty to non-dusty air from north to south is readily apparent in all three legs. However, there is significant variability in dust layer structure between the three legs. For example, in leg two, there is a suggestion of two distinct dust layers, one during the middle of the leg in which the top of the dust layer descended fairly sharply to the north and a second, more diffuse layer farther to the north. Temperature anomalies, taken as the departure from the average over the three legs, show very hot air typically in the dust layers, but with cool air near the top of the dust layer and extending well above. The temperature data suggest that a cold-core low lay above the dust layer.

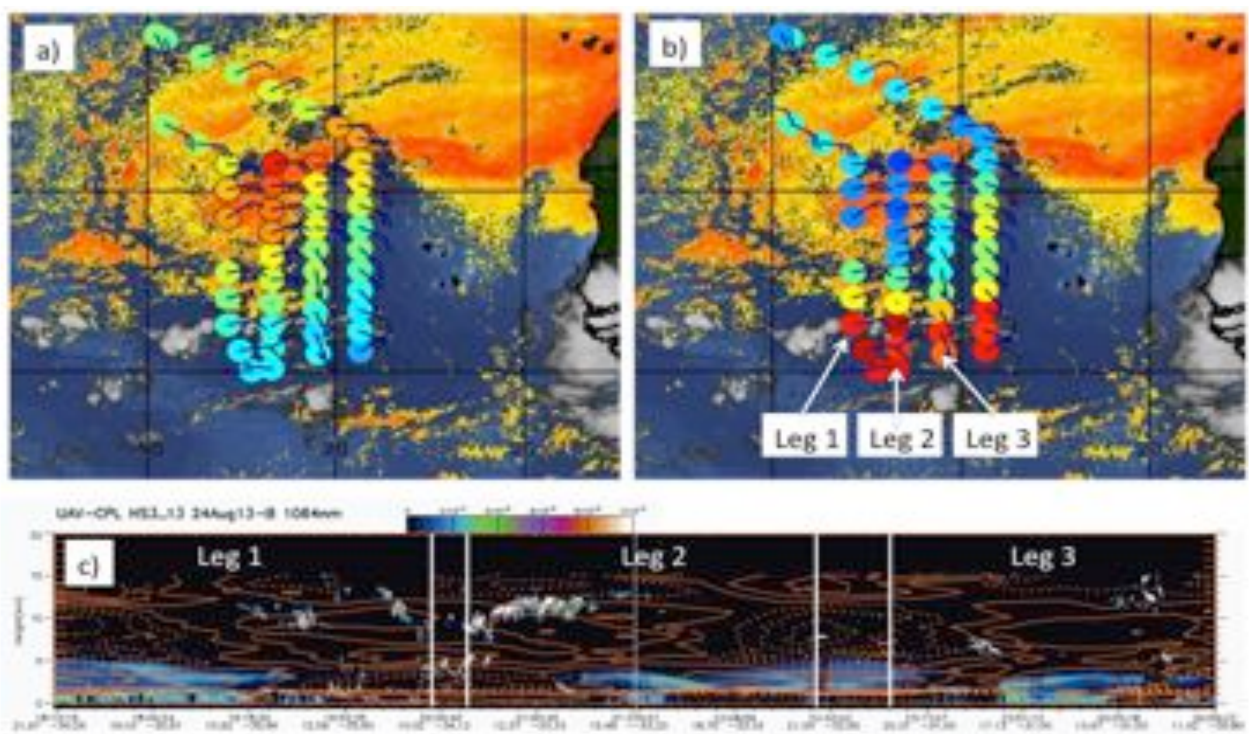


Figure 3-5. Dropsonde (a) temperature and (b) relative humidity and wind barbs at 800 hPa superimposed on GOES SAL product. (c) CPL backscatter indicating clouds and aerosols on the first three legs of the fight track. Orange contours show temperature anomaly, with solid lines indicating positive and dashed lines negative values. Temperature anomalies are defined with respect to the average over the three legs.

3.3 Tropical Storm Gabrielle

Between August 29 and September 8, four flights were conducted into the disturbance that became TS Gabrielle, including three environmental flights and one over-storm flight (Figure 3-6). The first environmental flight (August 29-30) focused on the weak initial disturbance and its interaction with the SAL. The second flight, on September 3-4, was HS3's first over-storm flight of the investigation and focused on the structure and organization of convection as the storm neared genesis. The September 4-5 environmental flight sampled the storm and environment during the time shortly after formation of Gabrielle. However, due to strong vertical wind shear, Gabrielle was short-lived and dissipated shortly after the flight. In the days that followed, there was high likelihood for redevelopment of Gabrielle back into a tropical storm. Another environmental flight was conducted on September 7-8. A second over-storm flight was attempted on September 10, but had to be aborted shortly after takeoff due to a failure of one of the navigation systems. The following subsections provide brief overviews of each of the flights.

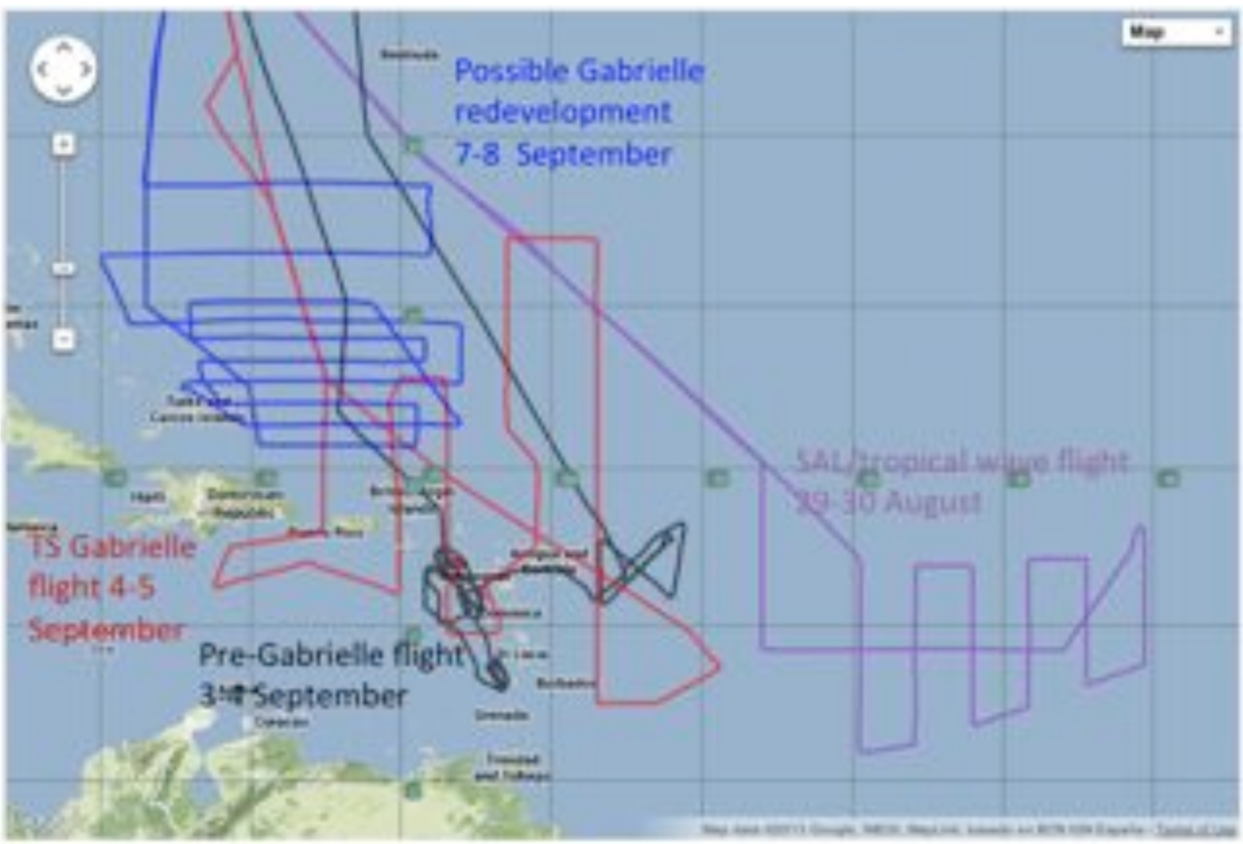


Figure 3-6. Global Hawk flights related to the life cycle of TS Gabrielle, including three flights of AV-6 and one of AV-1.

3.3.1 August 29-30

The goal of this flight was to investigate the role of the SAL in suppressing deep convection and development of a tropical wave disturbance. Early on, the numerical models suggested a potential for development (as was typical of the season as a whole), but over time gradually backed off on this development. The overall circulation was large, with a low-level circulation on the southern side of the African easterly jet and a mid-level cyclonic circulation likely on the northern side. Convection was somewhat active in the northern region, but the circulation had been entraining dry air into itself. Closer to the southern vortex, there was substantial moisture, but the convection was weak at best.

GOES infrared imagery and the GEOS-5 dust forecast indicate the large nature of the cyclonic circulation and the scattered distribution of convection primarily in the eastern portion of the circulation. The driest air mid-levels was found on the westernmost north-south leg of the flight pattern whereas closer to the center of circulation, relative humidities were closer to 60% or greater. The vorticity along both wave axes was relatively weak, but was somewhat stronger in the western wave.

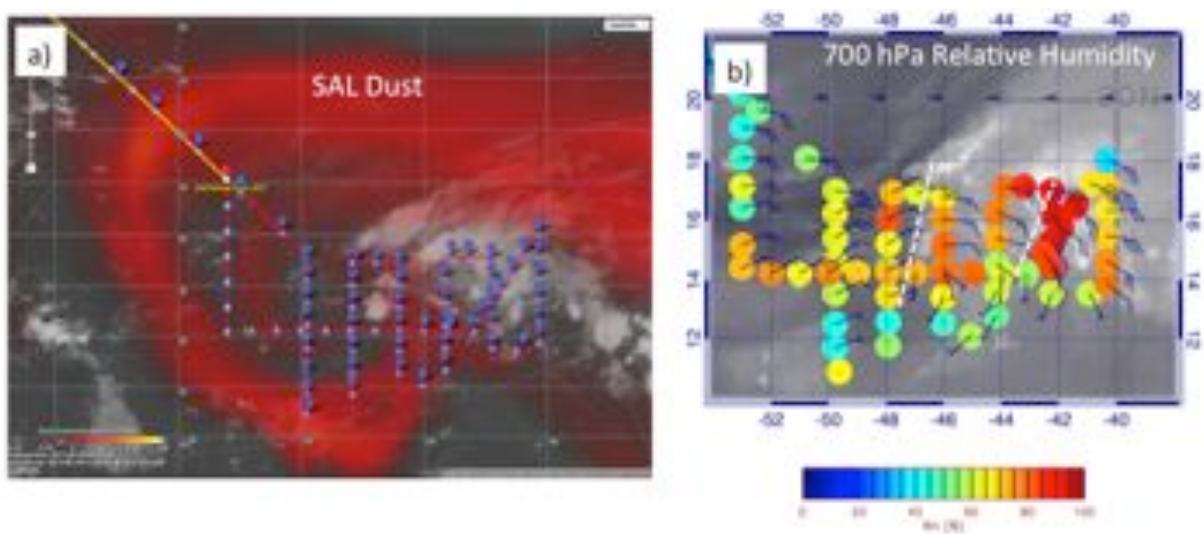


Figure 3-7. (a) GOES infrared imagery depicting convective organization. Red shading indicates the distribution of Saharan dust as forecasted by the GEOS-5 global model. The Global Hawk flight track is superimposed. (b) Dropsonde-derived 700 hPa relative humidity and wind barbs. A full wind barb indicates 5 m s^{-1}, a half barb 2.5 m s^{-1}. Dashed white lines indicate the axes of tropical waves.

3.3.2 September 3-4

The goal of this flight was to study convective organization and its contribution to the potential genesis of the disturbance. It was the first flight of the over-storm Global Hawk as part of the HS3 field campaign. It was a follow-on to the earlier environmental flight, but had been delayed due to aircraft issues. The two wave disturbances that were apparent during the August 29 flight continued to move westward and possessed better organization than that seen in previous days (Figure 3-8a). However, it was unclear which of the two waves was more likely to develop. Satellite imagery suggested that both disturbances were in areas of high low-level moisture and both appeared to have sufficient protection from dry air. Sea surface temperatures were near 29-30°C.

Data collection began in the westernmost area of convection to the west of the islands. There were numerous challenges during flight including the fact that cloud-top heights were near 50,000 feet and did not allow for the required 5000 foot clearance. In addition, the aircraft needed to maintain about 15 nautical mile distance from the islands, making maneuvering around the convection quite difficult. As shown in Figure 3-8b, the overall area of deep convection was relatively small. The aircraft sampled the eastern tropical wave during the latter part of the flight. Because of the higher altitude of the aircraft, it was better able to get over regions a deep convection, allowing a more organized flight pattern over the disturbance. This eastern disturbance appeared to be larger and more organized than that to the west, although some of the differences could be related to diurnal variations in convection.

During flight, it was determined that the aircraft was burning fuel at a higher rate than anticipated. The crew deliberated on whether to bring the aircraft back to Wallops early, but since chase aircraft would be unavailable at night, the decision was made to continue flight until the latest possible time early the next morning. The Global Hawk landed at Wallops at dawn without the assistance of the chase aircraft.

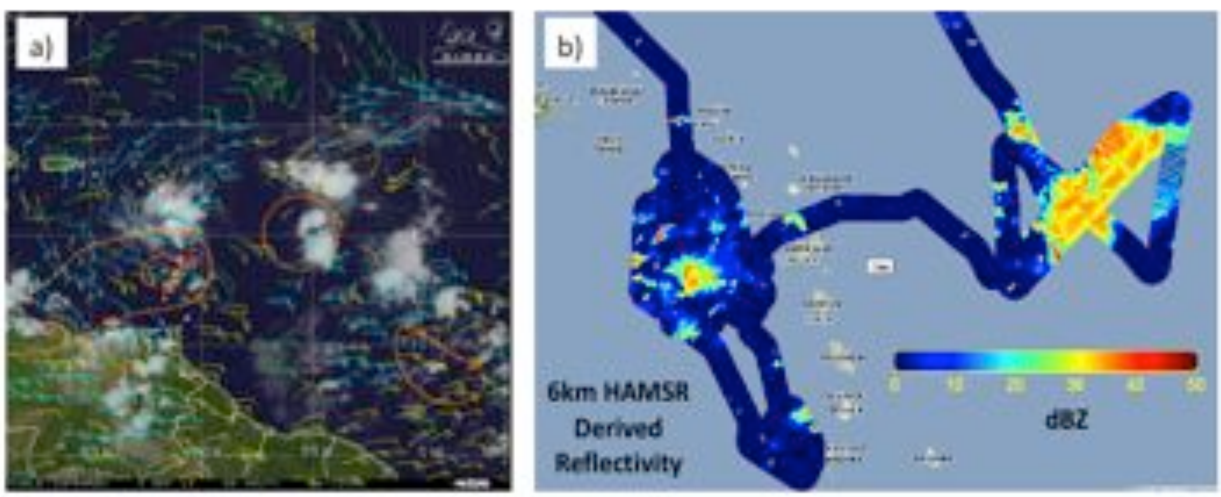


Figure 3-8. (a) GOES infrared imagery and feature-tracked winds for 0845 UTC September 3. Orange contours are 850 hPa vorticity. (b) HAMSR derived proxy "radar reflectivity" at 6 km altitude for the September 3-4 flight.

3.3.3 September 4-5

This environmental flight accomplished the first back-to-back series of Global Hawk flights, following up on the over-storm flight of the previous day. As with the previous day, satellite imagery suggested that both disturbances were in a region of high low-level moisture with sufficient protection from dry mid-level air. The morning of flight, new convection erupted in the western disturbance with multiple cells extending west to east between 17-18°N

(Figure 3-9) in the region south of Puerto Rico. Southerly shear associated with an upper anticyclone was evident with the cells. New convection was also occurring near 65°W and was the dominant feature in the western disturbance at takeoff.

Prior to getting on station, the western disturbance developed into TS Gabrielle just south of Puerto Rico. Because of the islands and restrictions with Venezuelan airspace, there was little room to operate around Gabrielle and, as a result, the observations were limited to the region north of Puerto Rico and just east and west of Gabrielle to the south. The latter portion of the flight focused on the eastern disturbance that had more prominent convection and was associated with significant upper-level outflow.

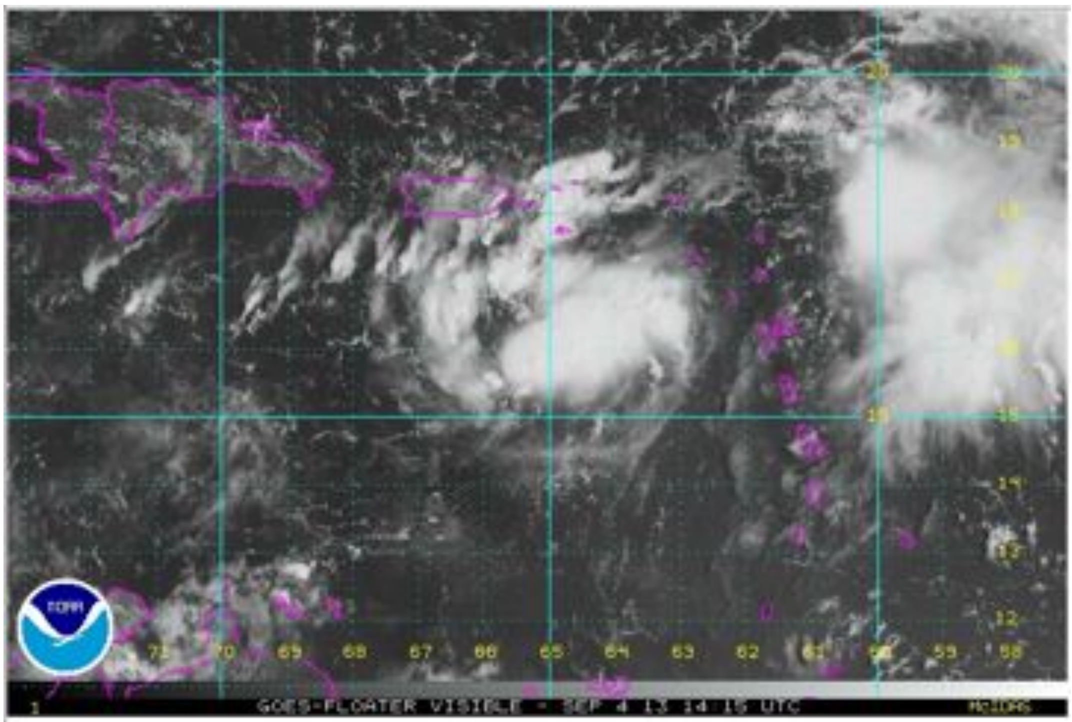


Figure 3-9. GOES visible image for 1415 UTC September 4.

As with all environmental flights, dropsonde data were processed in real time and made available to operational agencies via the Global Telecommunication System. The data were regularly used by the National Hurricane Center (NHC). An example of their usage in their weather discussions is shown below.

The NHC discussion at 11 pm demonstrates the use of the dropsonde data by operational centers:

TROPICAL STORM GABRIELLE DISCUSSION NUMBER 2
NWS NATIONAL HURRICANE CENTER MIAMI FL AL072013
1100 PM AST WED SEP 04 2013

DROPSONDE DATA FROM THE NASA GLOBAL HAWK AIRCRAFT SUGGEST THAT THE CIRCULATION OF GABRIELLE IS TILTED TO THE NORTHEAST WITH HEIGHT...

WITH A MID-LEVEL CIRCULATION SEEN IN DATA FROM THE SAN JUAN WSR-88D RADAR. THIS TILTED STRUCTURE IS CONSISTENT WITH SOUTHERLY TO SOUTHWESTERLY VERTICAL SHEAR OF 5 TO 10 KT SHOWN OVER THE CYCLONE BY THE UW-CIMSS AND SHIPS MODEL ANALYSES. **IN ADDITION...THE DROPSONDE DATA SHOWED DRY AIR IN THE MID LEVELS OF THE ATMOSPHERE AROUND GABRIELLE.** GIVEN THE ENVIRONMENT...THE SOMEWHAT DISORGANIZED STATE OF THE CIRCULATION...POSSIBLE LAND INTERACTION...AND THE PRESENCE OF THE LARGE AREA OF DISTURBED WEATHER NORTHEAST OF GABRIELLE...NOT MUCH STRENGTHENING IS EXPECTED IN THE SHORT TERM.

THE LOW-LEVEL CENTER HAS BEEN DIFFICULT TO LOCATE...BUT THE GLOBAL HAWK DROPSONDE DATA SUGGEST IT REMAINS SOUTHWEST OF THE MID-LEVEL CENTER SEEN IN RADAR IMAGERY…

Dropsonde data from the flight is overlaid on GOES infrared imagery in Figure 3-10. At 850 hPa, the low-level circulation associated with Gabrielle can be seen just south of Puerto Rico with nearly calm winds just south of the storm center. North of 17°N, winds were primarily out of the east. Relative humidities generally exceeded 70% at most locations. At 600 hPa, winds were much weaker from the east, resulting in fairly strong low-level westerly wind shear. Dry air was seen well to the north and wrapping around to the western side of the storm center. Dry air was also found well to the east-southeast in association with an approaching Saharan air layer.

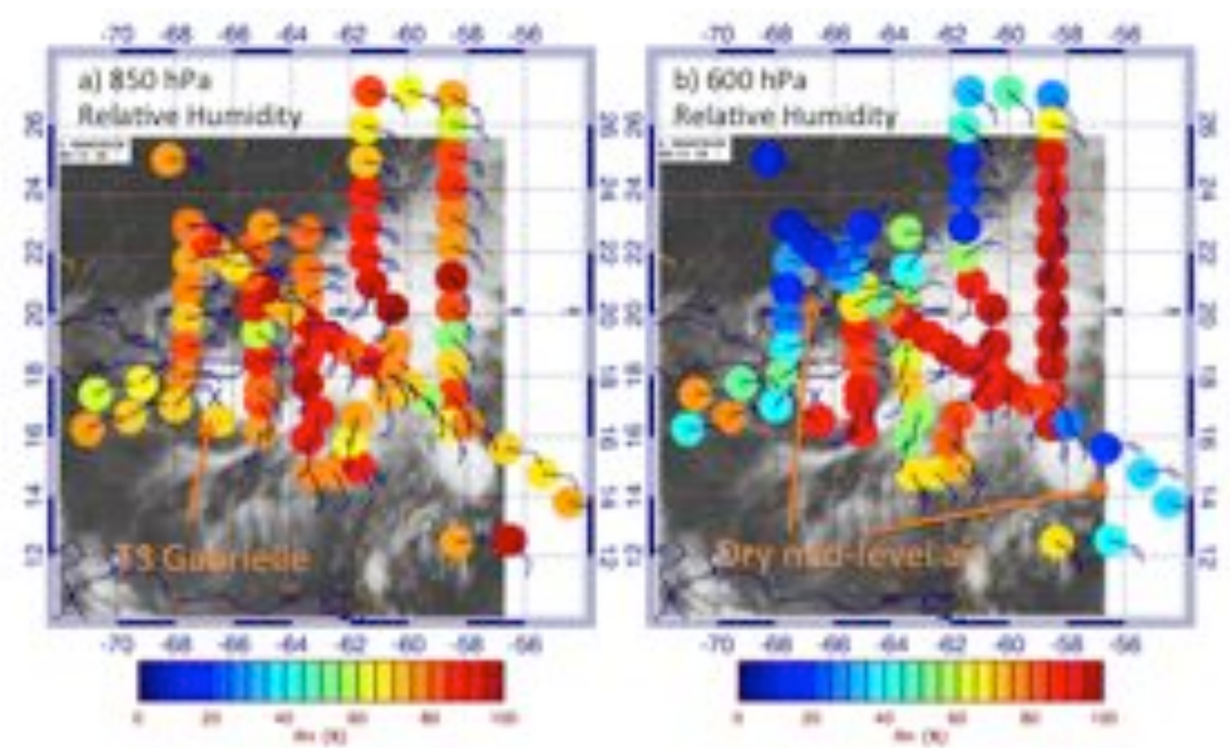


Figure 3-10. Dropsonde-derived (a) 850 hPa and (b) 600 hPa relative humidity and wind barbs. The "X" just south of Puerto Rico marks the approximate center location.

The strong low-level westerly shear led to a fairly quick demise to Gabrielle as the near-surface center moved to the west of Puerto Rico while the mid-level center moved to the east of the island. The storm was quickly downgraded to post tropical. However, conditions were expected to be favorable for potential redevelopment in the following days.

3.3.4 September 7-8

This environmental mission was focused on assessing the favorability of the environment for redevelopment of TS Gabrielle and was a follow-on to the earlier back-to-back set of flights into TS Gabrielle, which formed and dissipated during the Sept 4-5 AV-6 flight. The NHC was giving the disturbance northeast of the Dominican Republic a 10% chance of formation in 48 hours and a 40% chance in 5 days.

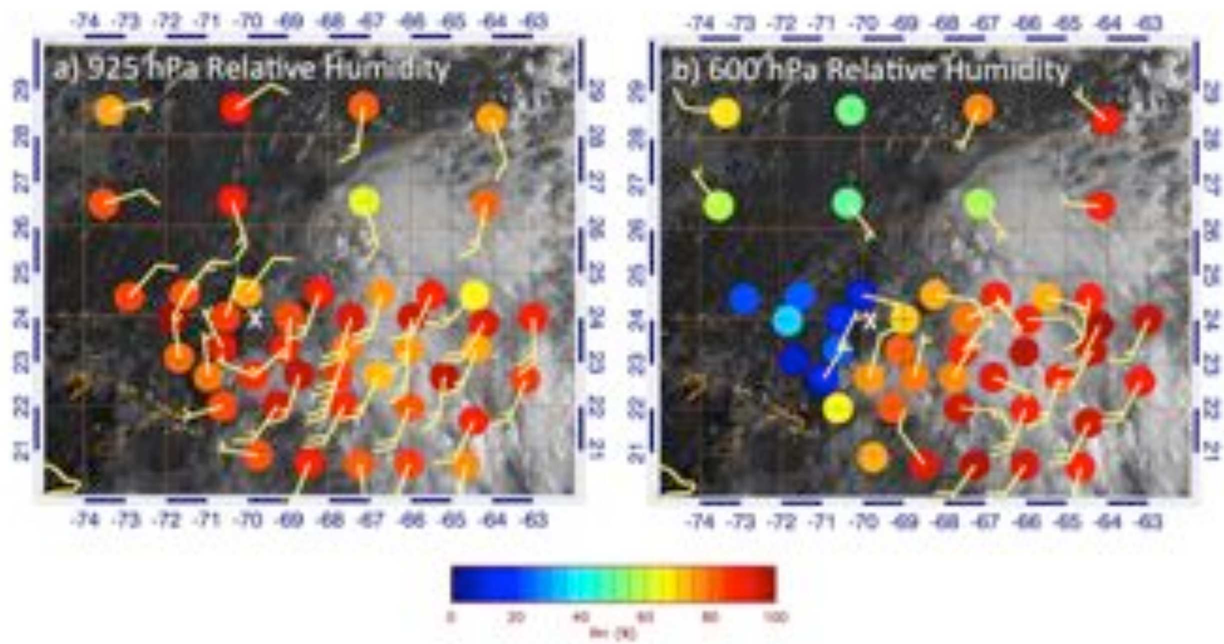


Figure 3-11. Dropsonde-derived (a) 925 hPa and (b) 600 hPa relative humidity and wind barbs from the September 7-8 flight. The "X" marks the approximate surface center location.

Figure 3-11 shows dropsonde data for this flight overlaid on GOES visible imagery. At 925 hPa, high relative humidities were present in a well-defined circulation (Figure 3-11a). Convection was displaced well to the east of the center, suggesting the continued presence of strong westerly wind shear. At 600 hPa, the center was displaced nearly 300 km to the southeast, with a prominent region of very dry air above and just to the west of the low-level storm center. Thus, conditions remained unfavorable for redevelopment.

3.3.5 September 10

September 10 was media day and started off with the takeoff of the over-storm Global Hawk, with the goal to look at the precipitation and wind structure in the newly redeveloped TS Gabrielle. However, one of the four navigation units failed and, following mission operations procedures, the Global Hawk returned to Wallops. The aircraft remained unavailable for the next four days as it was being serviced.

3.4 Hurricane Ingrid (September 15-16)

Starting around September 11, HS3 shifted focus to the potential development of a tropical storm in the Gulf of Mexico. As the potential for genesis increased, the HS3 team planned for an environmental flight into the disturbance that would become TS Ingrid on September 13. However, as the aircraft waited on the runway, a direct-current generator failure was detected and the flight was scrubbed. The over-storm Global Hawk became available again for flight on September 15, so a mission was flown to then Hurricane Ingrid to examine the precipitation and wind structure of the storm. At the time, Ingrid was a category-one hurricane with an intensity of 37 m s^{-1} (75 kts) and central pressure of 986 hPa, moving in a northwest direction at 3 m s^{-1} (6 kts). The forecasted storm track (Figure 3-12) shows that the storm was expected to turn westward and make landfall in Mexico.

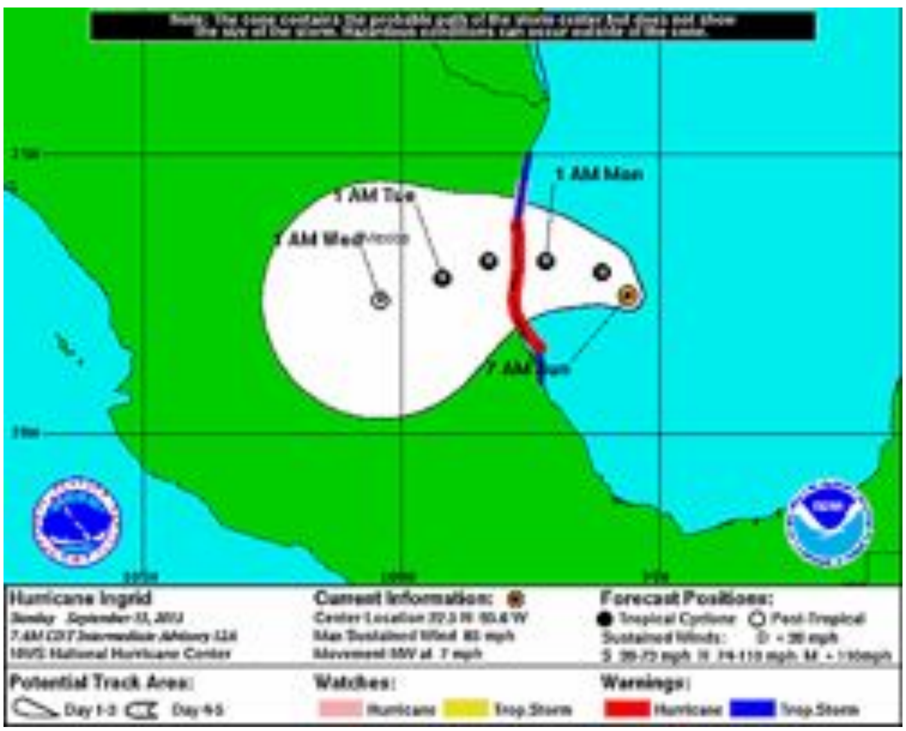


Figure 3-12. National Hurricane Center track forecast for Hurricane Ingrid at 12 UTC September 15.

Flight rules required at least 5000 feet clearance above cloud tops. When the over-storm Global Hawk reached Ingrid, there was a widespread region of cloud tops greater than 50,000 feet and at times extending up to 56,000 feet. It was discovered during the course of the 2013 campaign that the over-storm Global Hawk was not climbing as fast as the environmental aircraft, but was typically 1500 to 2000 feet lower. As a result of the slower climb, such deep cloud tops could not be overflown until much later into the mission. Upon reaching Ingrid, cloud tops reached or exceeded flight altitude (Figure 3-13), so the aircraft was initially required to circumnavigate the storm system, moving counterclockwise around the storm starting on the northern side. Upon coming back around to the northern side again, the upper cloud tops split into two regions of high cloud tops, so the aircraft was turned southward in order to split the two cloud systems and obtain some measurements over the core the storm (Figure 3-14). As the aircraft proceeded to the south, it passed over the eastern eye wall of Ingrid. Pilots reported that fuel temperatures were getting very low, approaching the freezing point of the fuel, so the aircraft was redirected northward to try to move toward warmer atmospheric temperatures. Upon reaching the northern side of the storm again, fuel temperatures remained low, so the aircraft continued northward and then eastward to try to find warmer temperatures. However, fuel temperatures remained stubbornly low, so the science mission was aborted and the aircraft directed to return to base.

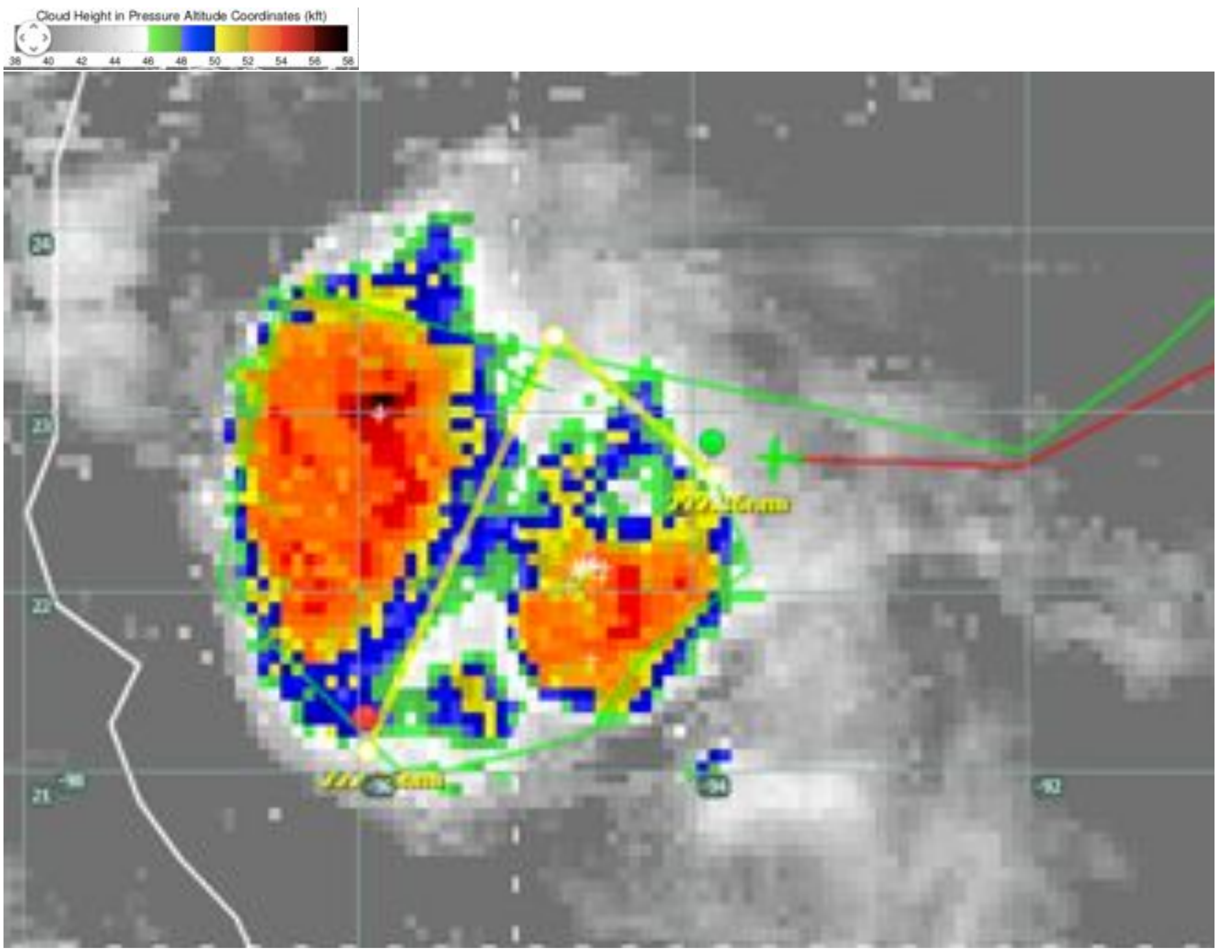


Figure 3-13. GOES cloud-top height estimates from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) for Hurricane Ingrid. Lightning locations from ground networks are indicated by white "+" signs.

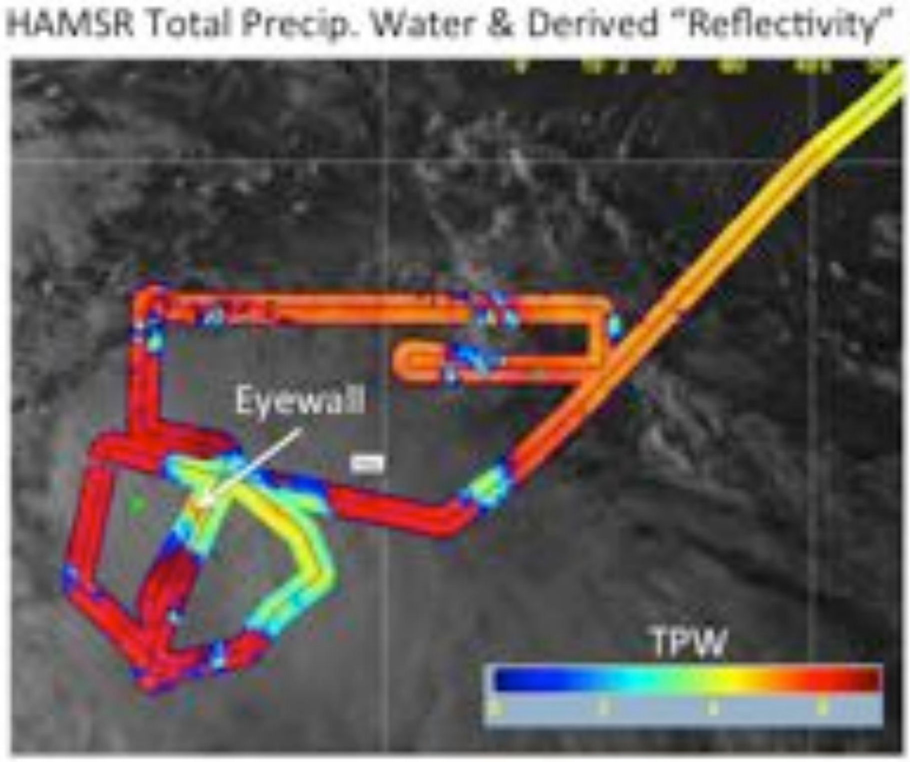


Figure 3-14. HAMSR derived proxy radar reflectivity for the September 15 AV-1 flight. The location of the eastern eyewall of Ingrid is indicated.

During the return-to-base transit, the aircraft loitered in two regions in order to sample some convection. The first area was just south of the Florida Panhandle (Figure 3-15a) while the second region was just southeast of North Carolina (Figure 3-15b).

a) b)

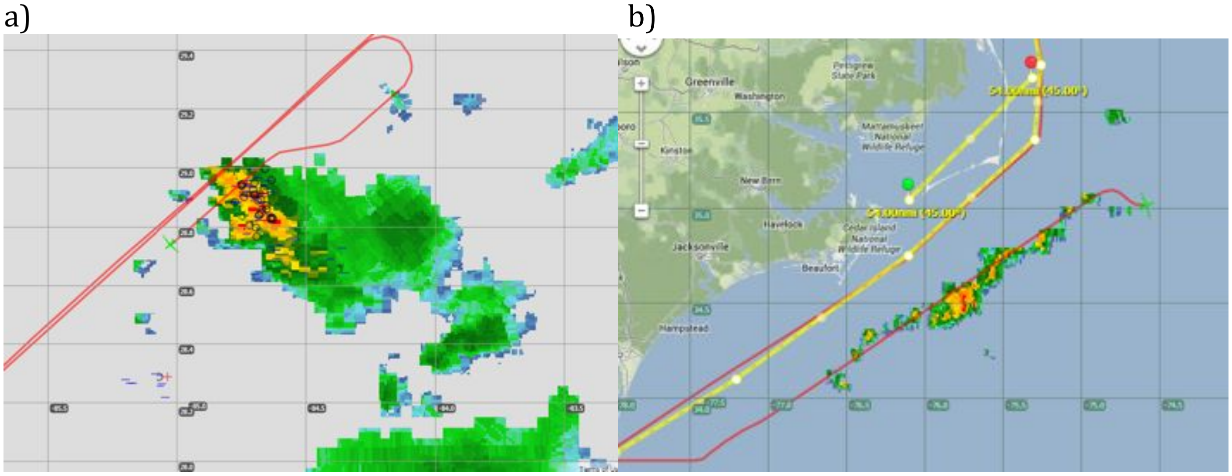


Figure 3-15. Radar reflectivity from the coastal radar network for (a) a convective system south of the Florida Panhandle and (b) a frontal rainband south of Cape Hatteras, North Carolina.

3.5 Tropical Storm Humberto

3.5.1 September 16-17

Hurricane Humberto formed off the coast of Africa on September 8 and tracked very slowly westward. Its position east of 30°W placed it just outside the practical range of the Global Hawks. The storm turned due northward on September 11 moving over much colder sea surface temperatures and eventually dissipating before coming within range of the aircraft. Forecast model guidance suggested that the storm had potential to redevelop after it turned westward, so the storm was monitored continuously to determine the best opportunity for flight. After the September 15-16 over-storm flight to Hurricane Ingrid, an environmental mission was planned for the redevelopment of TS Humberto in the central Atlantic. The second HS3 back-to-back flight series was carried out as the environmental aircraft was sent out to Humberto on September 16-17 (unlike the first back-to-back flight series, the second one split the aircraft between two targets).

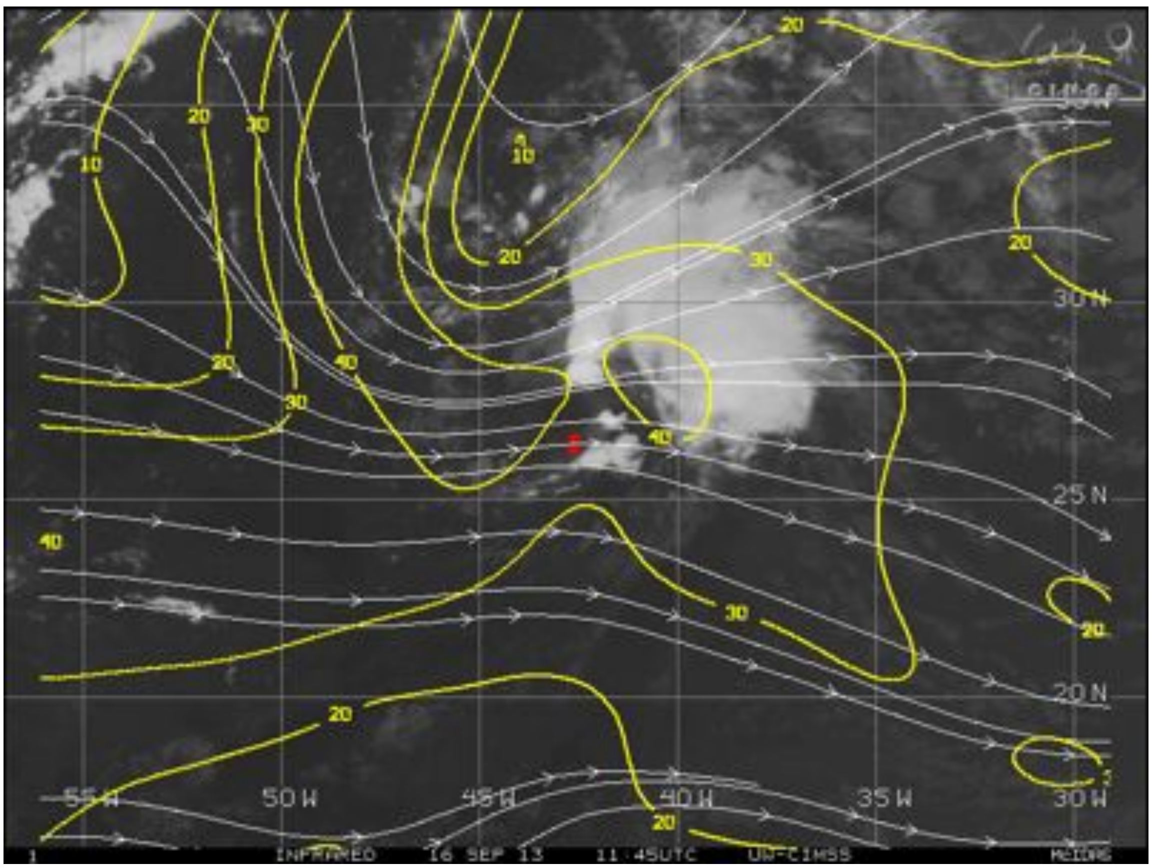


Figure 3-16. GOES infrared image and deep-layer vertical wind shear at 1145 UTC September 16 during the redevelopment of TS Humberto.

The morning of flight, the NHC gave Humberto an 80% likelihood of redeveloping over the next two days and 90% over five days. However, shortly thereafter, the disturbance was upgraded back to a tropical storm. Vertical wind shear was strong and convective development was highly asymmetric with convection primarily on the eastern side of the storm (Figure 3-16). Dropsonde data from this flight (Figure 3-17) indicated a hybrid nature of the tropical storm, with low levels resembling a tropical warm-core disturbance while upper levels was characterize by a cold-core low. Temperatures at 800 hPa (Figure 3-17a), showed a warm core collocated with the storm center, with the strongest winds on the eastern side of the storm. At 400 hPa (Figure 3-17b), cold air was found within and more toward the western side of the upper-level cyclone. The upper cold core was associated with a dip in the tropopause, with the tropopause height near 300 hPa close to the center (Figure 3-17c) and near 200 hPa just to the east (Figure 3-17d). During the flight, convection was primarily found on the eastern and northern sides.

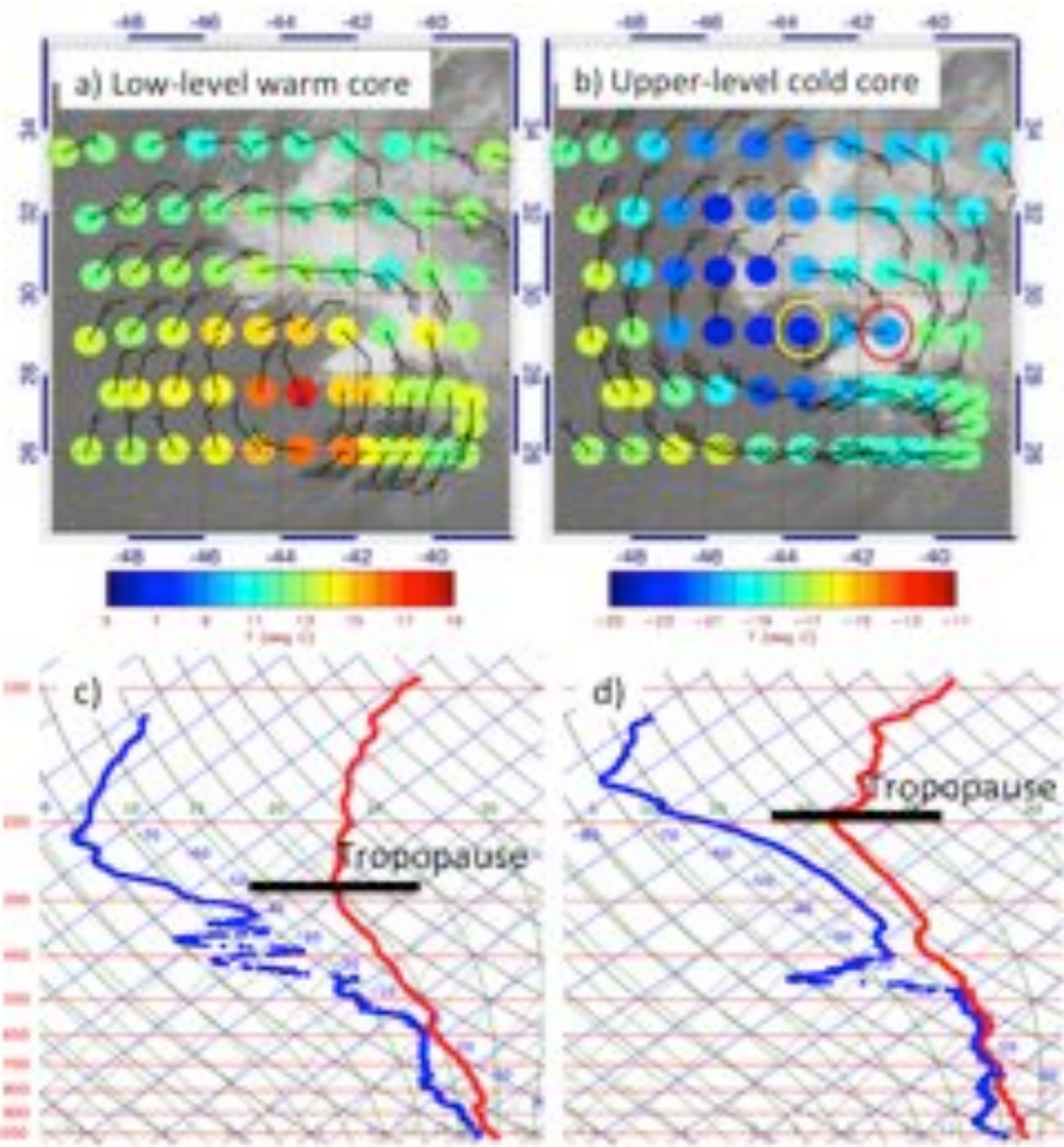


Figure 3-17. Dropsonde-derived (a) 800 hPa and (b) 600 hPa temperature and wind barbs. The "X" marks the approximate surface center location. (c, d) Skew-T, log-p soundings at the locations indicated in (b), with (c) corresponding to the yellow circle, (d) the red circle.

3.5.2 September 17

On September 17, Humberto remained a weak tropical storm under high vertical wind shear (Figure 3-18), with the strongest convection on the eastern side, but wrapping around to the western side. The over-storm Global Hawk took off with the goal to sample the convective structure, thus initiating the first back-to-back-to-back fights series for the Global Hawks. However, 105 minutes into flight, one of the four navigation units again failed, necessitating a return to base before getting any data in Humberto.

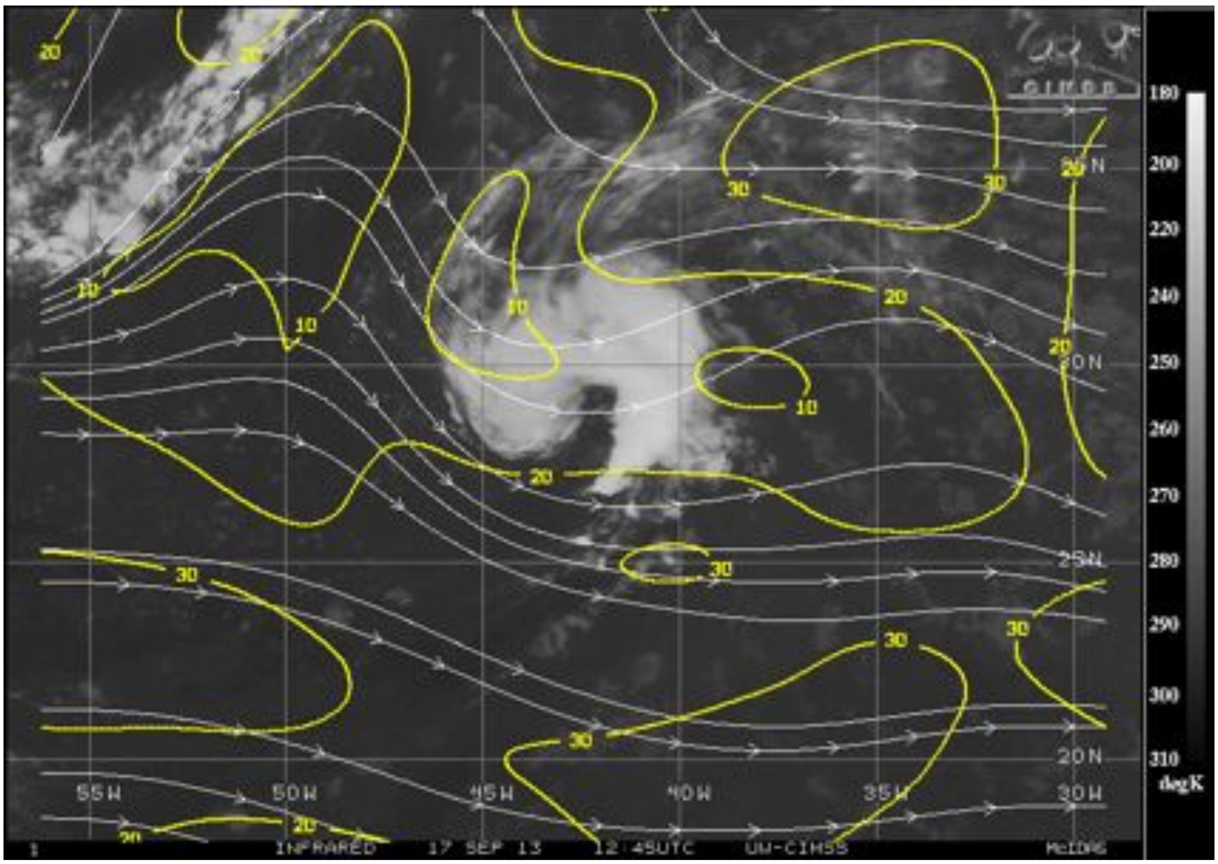


Figure 3-18. GOES infrared image and deep-layer vertical wind shear at 1245 UTC September 17 showing Tropical Storm Humberto.

3.6 Invest 95L (September 19-20)

With Humberto expected to undergo extratropical transition and quickly dissipate, HS3 again turned its eyes toward the Gulf of Mexico and a new disturbance with a high probability for genesis. On the morning of flight, the NHC gave Invest 95L a 70% chance of forming within 48 hours and 80% over the next five days (Figure 3-19). Air Force and NOAA reconnaissance decided to forgo flights into the storm, so the environmental Global Hawk was the only mission into the disturbance.

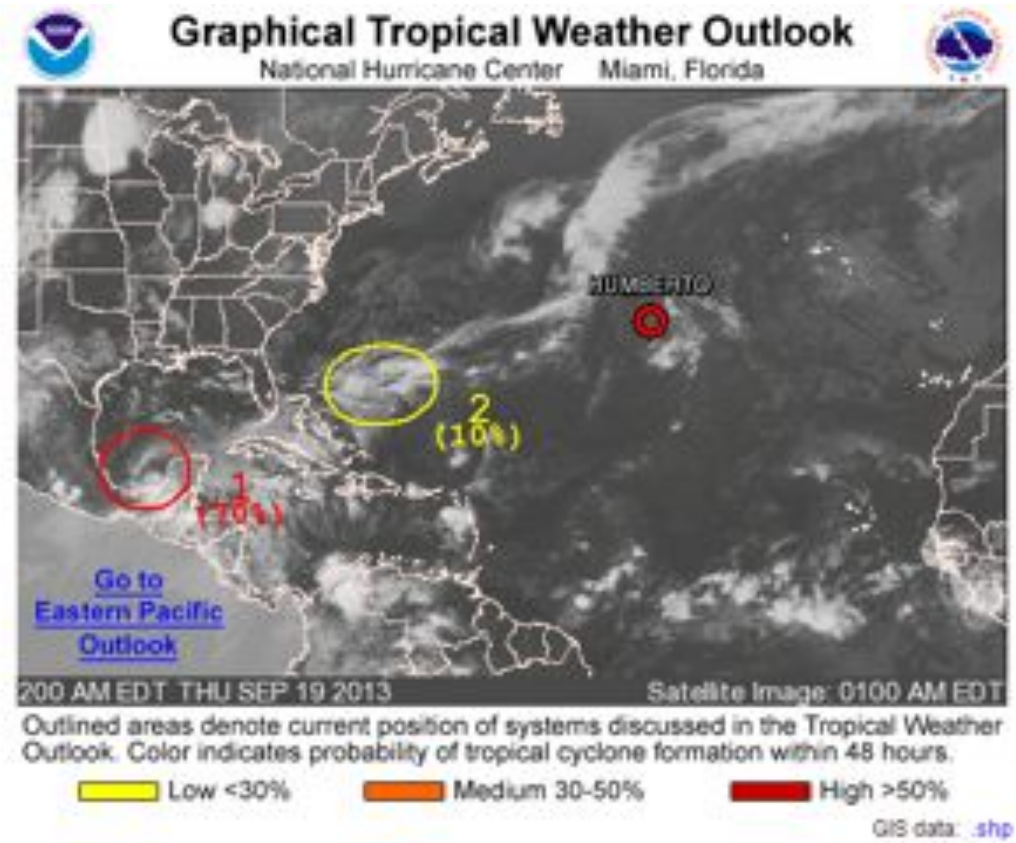


Figure 3-19. NHC tropical forecast for genesis on September 19.

The NHC discussion for the Gulf of Mexico stated the following:

1. A LOW PRESSURE SYSTEM LOCATED OVER THE SOUTHWESTERN GULF OF MEXICO IS PRODUCING DISORGANIZED SHOWER AND THUNDERSTORM ACTIVITY. CONDITIONS STILL APPEAR CONDUCIVE FOR THE FORMATION OF A TROPICAL DEPRESSION DURING THE NEXT DAY OR TWO...AND AN AIR FORCE RESERVE HURRICANE HUNTER PLANE IS SCHEDULED TO INVESTIGATE THE LOW THIS AFTERNOON...IF NECESSARY. THIS SYSTEM HAS A HIGH CHANCE...70 PERCENT...OF BECOMING A TROPICAL CYCLONE DURING THE NEXT 48 HOURS WHILE IT MOVES WEST-NORTHWESTWARD AT ABOUT 5 MPH...AND A HIGH CHANCE...80 PERCENT...OF BECOMING A TROPICAL CYCLONE DURING THE NEXT 5 DAYS. THIS DISTURBANCE WILL LIKELY SPREAD HEAVY RAIN OVER PORTIONS OF EASTERN AND SOUTHERN MEXICO AND COULD CAUSE LIFE-THREATENING FLOODS AND MUDSLIDES OVER AREAS ALREADY IMPACTED BY TORRENTIAL RAIN DURING THE PAST SEVERAL DAYS.

The environmental mission laid down a dense network of dropsondes to thoroughly map the storm and its environment. A record 88 dropsondes were released during the flight, the maximum possible. Once on station, it was clear that convection was being suppressed and that development was unlikely. The surface wind field (Figure 3-20) from the dropsondes showed a closed circulation with 12-15 m s^{-1} (25-30 knot) winds on the northern side of the storm. Given the westerly winds to the south of the storm center, it was somewhat surprising that the storm was not at least declared to be a tropical depression by the hurricane center.

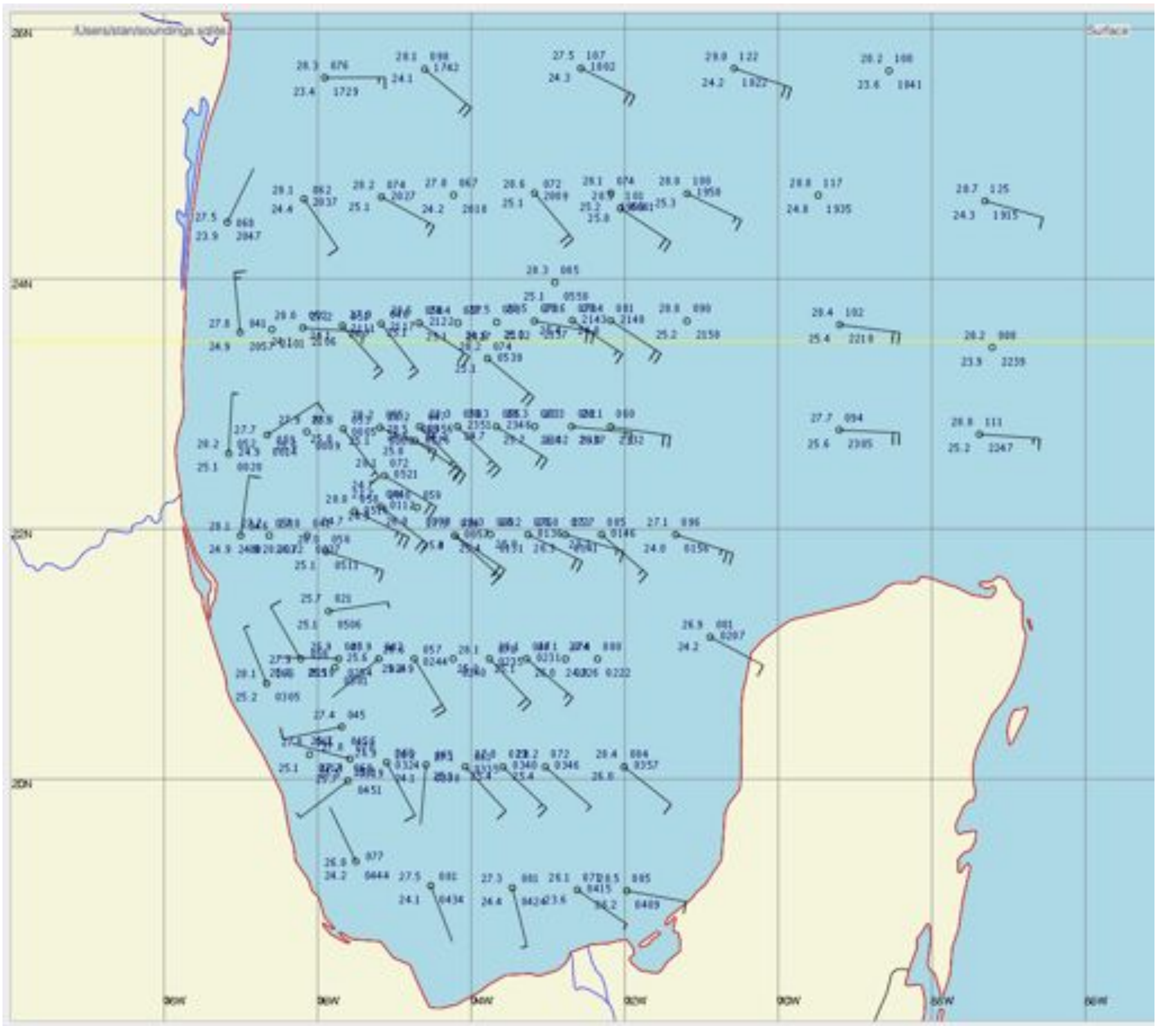


Figure 3-20. Dropsonde surface winds analysis. A full wind barb indicates 5 m s-1, a half barb 2.5 m s-1. The data suggests a closed surface circulation with a center near 21.0°N, 95.8°W.

Data for this flight show very moist conditions near the surface (Figure 3-21b) and a well-defined low-level cyclonic circulation. At 400 hPa (Figure 3-21a), easterly winds resided above the storm and conditions were very dry. A sounding near the storm center (Figure 3-21c) shows moist conditions up to 450 hPa, topped by very dry conditions aloft. The temperature profiles in the drier air suggest three layers of distinct subsidence with slight inversions near the base of each layer. The results suggest significant large-scale subsidence at mid-to-upper levels that may been suppressing deep convective development and therefore the development of the storm.

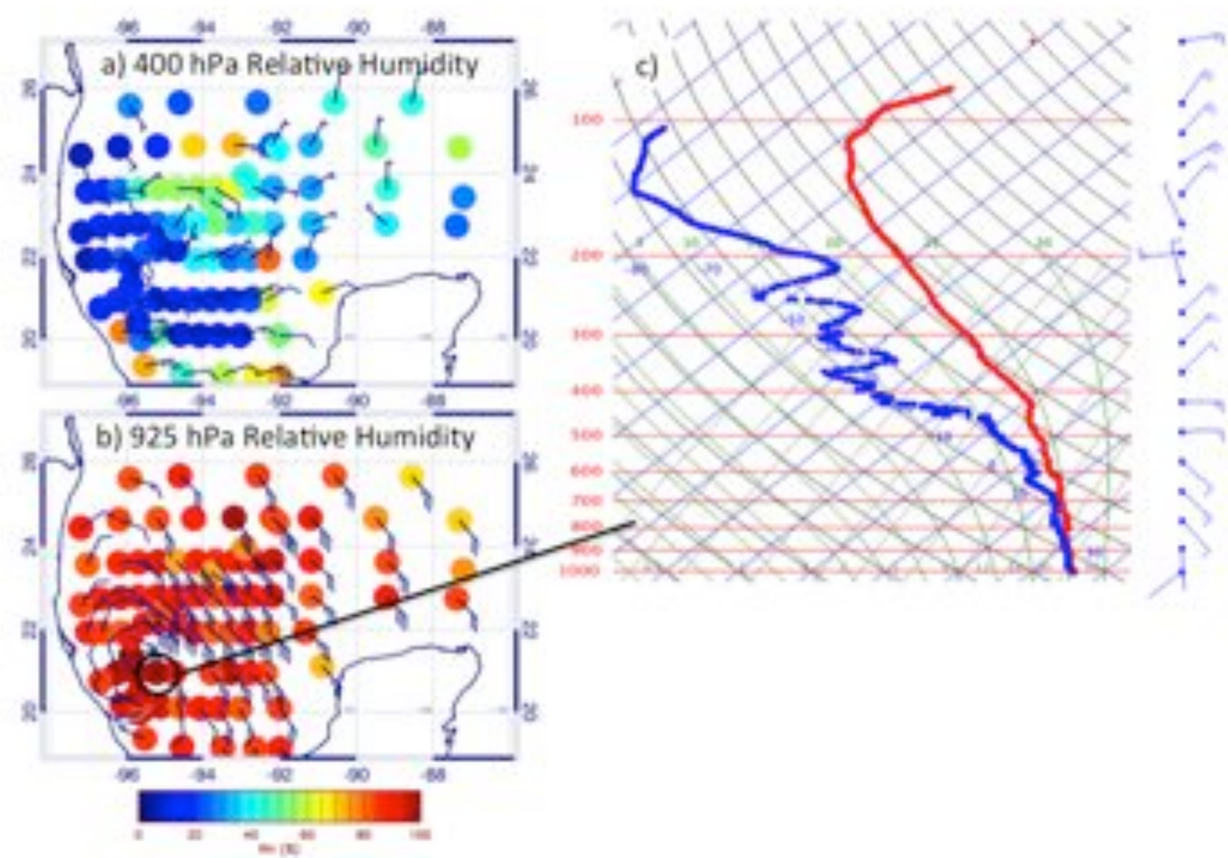


Figure 3-21. Dropsonde-derived (a) 400 hPa and (b) 925 hPa relative humidity and wind barbs. The "X" marks the approximate surface center location. (c) Skew-T, log-p sounding near the storm center.

4.0 Mission Accomplishments in 2013

The Global Hawk operations included the first deployment of both Global Hawks, the first use of the Wallops Global Hawk Operations Center (known as GHOC-East), and the first back-to-back flights. HS3 even proved that back-to-back-to-back flights are possible. All of the instruments performed extremely well and HS3 set a record for sondes dropped in one flight (88) and dropped a total of 439 sondes. HS3 flew approximately 273 flight hours.