NOAA Technical Memorandum OAR UAS-001

Sensing Hazards with Operational Unmanned Technology: 2015–2016 Campaign Summary, Final Report

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UNITED STATES DEPARTMENT OF COMMERCE

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Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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NOTICE

EXECUTIVE SUMMARY

The primary scientific goal of the Sensing Hazards with Operational Unmanned Technology (SHOUT) Project is to determine the potential utility of observations from high-altitude, long-endurance unmanned aircraft systems (UAS) such as the Global Hawk aircraft to improve forecasts of high-impact weather events and mitigate potential degradation of forecasts in the event of a future gap in satellite coverage. Tropical cyclones (TCs), especially hurricanes, are among the most potentially destructive high-impact weather events and pose a major forecasting challenge to NOAA. Major winter storms over the Pacific Ocean, including atmospheric river events, which make landfall and bring strong winds and extreme precipitation to the U.S. West Coast and Alaska are also important to forecast accurately because of their societal impact in those parts of the country. In response, the SHOUT project has supported field campaigns with the Global Hawk aircraft and dedicated data impact studies (NOAA 2017b) exploring the potential to improve the forecasting of both TCs and landfalling Pacific storms.

As the final SHOUT Campaign Summary report, this document provides an overview of the Global Hawk aircraft and its deployed sensors. It also summarizes the three major field campaigns that included 15 Global Hawk missions led by SHOUT from 2015-2016: 2015 Hurricanes, 2016 El Niño Rapid Response (ENRR), and 2016 Hurricane Rapid Response (HRR). The Global Hawk and instruments deployed on the aircraft during SHOUT collected a unique set of observations that can be used to assess the utility of a UAS platform like the Global Hawk, to evaluate the potential forecast impact of Global Hawk observations, and improve model forecasts of high impact weather events. Details of data impact assessments that were made using these observations (NOAA 2017b) and analyses of the cost and operational effectiveness of using the Global Hawk aircraft, including cost reductions achieved by operating in the Rapid Response (RR) mode in 2016 (Kenul et al. 2018), are presented in companion documents produced by the NOAA UAS Program Office. The success of the SHOUT project has demonstrated the utility of a UAS platform like the Global Hawk to observe TCs in a cost-effective manner and to provide data that can improve forecasts of high impact weather. Additionally, this program affords a foundation of UAS field operations that could be applied to future NOAA field campaigns and collaborative efforts that have a research or operational focus.

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LIST OF ACRONYMS

Abbreviation	Description
AFB	Air Force Base
AFRC	Armstrong Flight Research Center
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Meteorological Laboratory
AVAPS	Airborne Vertical Atmospheric Profiling System
COAMPS-TC	Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones
Co-I	Co-Investigator
CrIS	Cross-track Infrared Sounder
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ECMWF	European Center for Medium Range Weather Forecasting

EMC	Environmental Modeling Center
ENRR	El Niño Rapid Response
EOL	Earth Observing Laboratory
ESRL	Earth System Research Laboratory
ETS	Ensemble Transform Sensitivity
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GH	Global Hawk
GHOC	Global Hawk Operations Center
GPS	Global Positioning System
GRIP	Genesis and Rapid Intensification Processes
GSD	Global Systems Division
GTS	Global Telecommunication System
HALO	High Altitude and Long Range
HAMSR	High-Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer
HDSS	High Definition Sounding System
HIRAD	Hurricane Imaging Radiometer
HIWRAP	High-Altitude Imaging Wind and Rain Airborne Profiler
HRD	Hurricane Research Division
HRR	Hurricane Rapid Response
HS3	Hurricanes and Severe Storm Sentinel
HWRF	Hurricane Weather Research and Forecasting
IFEX	Intensity Forecasting Experiment
IWRAP	Imaging Wind and Rain Profiler
LIP	Lightning Instrument Package
MMIC	Monolithic Microwave Integrated Circuit
NARVAL	Next Generation Aircraft Remote-Sensing for Validation Studies
NAWDEX	North Atlantic Waveguide and Downstream Impact Experiment
NCAR	National Center for Atmospheric Research
NCEI	NOAA Center for Environmental Intelligence
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite Data and Information Service
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
ONR	Office of Naval Research
PSD	Physical Sciences Division
S-HIS	Scanning High-resolution Interferometer Sounder
SHOUT	Sensing Hazards with Operational Unmanned Technology
TC	Tropical Cyclones

TCI	Tropical Cyclone Intensity
TWiLiTE	Tropospheric Wind Lidar Technology Experiment
UAS	Unmanned Aircraft Systems
UTC	Coordinated Universal Time
WFF	Wallops Flight Facility
WRF	Weather Research and Forecast
WSR	Winter Storms Reconnaissance

ABSTRACT

NOAA's Sensing Hazards with Operational Unmanned Technology (SHOUT) Project supported three major field campaigns from 2015 to 2016: 2015 Hurricanes, 2016 El Niño Rapid Response, and 2016 Hurricane Rapid Response. These campaigns used NASA's Global Hawk, along with a suite of sensors, to assess the use of high altitude, long endurance unmanned aircraft systems (UAS) for collecting atmospheric data to diminished the risk of polar-orbiting satellite observing gaps on high impact weather forecasts and warnings. An overview of the Global Hawk aircraft and its sensor payloads is provided, as well as detailed discussions about operations for each of the 15 Global Hawk missions flown during these campaigns. Details include the various targeting strategies, sensor performance, data use, and collaborative efforts, which provide context and perspective applicable to the follow-on impact assessment (Wick et al. 2018) and cost analyses (Kenul et al. 2018). Furthermore, this material provides a foundation of UAS field operations for potential application to future NOAA field campaigns and collaborative efforts with a research or operational focus.

1 INTRODUCTION

The NOAA Unmanned Aircraft Systems (UAS) Program designed the NOAA Sensing Hazards with Operational Unmanned Technology (SHOUT) project to address an overarching goal of demonstrating and testing a prototype UAS concept of operations that could be used to mitigate the risk of diminished high impact weather forecasts and warnings in the case of polar-orbiting satellite observing gaps. Guided by this goal, the NOAA UAS Program focused on two objectives for the SHOUT program:

1. **Assess the impact of UAS data** by performing Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs), as well as utilizing adaptive aircraft sampling strategies for improving real-time tropical cyclone (TC) track and intensity forecasts.
2. **Perform a cost-operational benefit analysis** that quantifies the cost and operational benefit of UAS observing technology for high impact weather prediction.

To address these objectives, NOAA UAS partnered with NASA to conduct the following three SHOUT field campaigns from 2015 to 2016: 2015 Hurricanes, 2016 El Niño Rapid Response, and 2016 Hurricane Rapid Response. These field campaigns were designed to assess the operational effectiveness of UAS platforms for mitigating possible satellite data gaps and quantifying the influence of UAS environmental data on high impact weather prediction. The NASA Global Hawk unmanned high altitude aircraft used in these campaigns was equipped with an array of in-situ and remote sensing payloads, to measure pressure, temperature, moisture, precipitation, winds, and electric fields both within storms and in their surrounding ambient environments. The data collected from all SHOUT field campaigns were routinely sent to the Global Telecommunication System (GTS) in real-time for potential assimilation into operational numerical weather prediction (NWP) models.

The subsequent sections provide a high level overview of the Global Hawk aircraft and the instrument payload used for SHOUT, in addition to details about each field campaign that includes a discussion of campaign objectives, mission designs and targeting, mission summaries, instrument performance, and data delivery and use. This campaign overview provides important background information, perspectives, and context for the data impact results presented by Wick et al. (2018).

2 GLOBAL HAWK AIRCRAFT

The NASA Global Hawk aircraft (AV-6) is a developmental-model Northrop Grumman Global Hawk designed for high-altitude, long endurance science missions. The aircraft has a wingspan of more than 35 m (116 feet), a gross take-off weight of 12,135 kg (26,750 pounds), including a 680kg (1,500 pound) payload capacity, and is powered by a single Rolls-Royce AE3007H turbofan engine that provides a cruising speed of approximately 620 km h^{-1} (335 kt). Additionally, the Global Hawk operates at a flight level of 16,765-19,810 m (55,000-65,000 ft), has a flight duration of roughly 24 h, and a range of 14,815-18,520 km (8,000-10,000 nm). During the 2015-2016 SHOUT field campaigns, the Global Hawk flight crew could support one mission per 48 h (e.g., a take-off at 1100 UTC on day-1, landing at 1100 UTC on day-2, follow-on mission with a take-off of 1100 UTC on day-3) and could support seven days of continuous operations before a “hard down” (i.e., no-fly) day for crew rest was required. This provided the capability to conduct three consecutive missions over a seven-day period. All Global Hawk missions were flown from either NASA Armstrong Flight Research Center (AFRC) in California or from a forward deployed base at NASA Wallops Flight Facility (WFF) in Virginia. Each base had an on-site Global Hawk Operations Center (GHOC), where pilots, support personnel, mission scientists, and instrument teams monitored active missions.

3 GLOBAL HAWK PAYLOAD

The selection of instruments for the Global Hawk payload was based both on their potential to support improvements in TC forecasts and the requirement that they had successfully been flown on the aircraft before. The SHOUT advisory group, comprised of representation from all relevant NOAA line offices, discussed and agreed upon the primary instruments selected, which included the Airborne Vertical Atmospheric Profiling System (AVAPS), High-Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR), and High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP). A secondary instrument, the Lightning Instrument Package (LIP), was also part of the payload exclusively during the missions for the 2015 SHOUT Hurricanes campaign. This same four primary instrument configuration was used in the NASA Genesis and Rapid Intensification Processes (GRIP) experiment in 2010.

Terry Hock of the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) developed the AVAPS, or Global Hawk GPS dropwindsonde system, with support from the NOAA UAS program. The GPS dropwindsondes (or GPS dropsondes, Hock and Franklin 1999) provide very high vertical resolution measurements of pressure, temperature, and humidity (2 Hz sampling rate), as well as wind speed and direction (4 Hz sampling rate). The Global Hawk GPS dropsonde system carries up to 90 dropsondes per flight and supports up to eight simultaneous soundings. The sampling rate coupled with typical fall speed corresponds to a vertical resolution of about 3 m for winds near the ocean surface and 6 m for temperature and humidity. While the Global Hawk GPS dropsondes are smaller in size than those deployed from traditional manned aircraft (e.g., Vaisala RD94 GPS dropsondes), the sensor packages are nearly identical. GPS dropsondes were included on the Global Hawk payload because of their well-established potential for positive impact on TC forecasts and their immediate readiness for operational model assimilation.

HAMSR is a cross-track scanning passive microwave radiometer (Lambrigtsen et al. 2009) with 25 spectral channels located near the 50-60 and 118 GHz oxygen lines and the 183 GHz water vapor lines. These channels are very similar to those on the Advanced Microwave Sounding Unit (AMSU) aboard NOAA polar orbiting satellites used to retrieve vertical profiles of atmospheric temperature and humidity. Development of the instrument has been led by Dr. Bjorn Lambrigtsen of the NASA Jet Propulsion Laboratory. The approximate vertical resolution of HAMSR measurements is 2 km for water vapor and 4 km for temperature, while the approximate horizontal resolution is 2 km at nadir with a surface swath width of roughly 40 km from typical Global Hawk cruising altitudes.

HAMSR was selected for inclusion on the Global Hawk payload because of its strong similarity to AMSU, which has had a positive effect on NWP forecasts of all standard assimilated observations. This capability is highly desirable, given the satellite data gap mitigation focus of the SHOUT campaign. However, despite HAMSR's similarity to AMSU, further work is required before brightness temperature observations from HAMSR can be directly assimilated into models. This has been identified as a priority within SHOUT and work has been initiated.

HIWRAP is a dual-frequency, conically scanning Doppler radar developed by Dr. James Carswell of Remote Sensing Solutions, Inc. and operated and supported by Dr. Gerald Heymsfield of the NASA Goddard Space Flight Center (Li et al. 2011). The instrument operates at both Ka band (i.e., 35 GHz) and Ku band (i.e., 14 GHz) and scans at 30- and 40-degree incidence angles, respectively. It provides reflectivity measurements yielding information on precipitation, three-dimensional winds within precipitating areas, and ocean vector winds. The vertical resolution is approximately 60 m and the horizontal resolution is about 1 km. HIWRAP was included on the Global Hawk payload because of the demonstrated utility of the tail Doppler radar (TDR) on the NOAA WP-3Ds and the previous positive HIWRAP research results provided by Dr. Jason Sippel of NOAA, as documented in Wick et al. (2018). Real time data delivery capabilities from HIWRAP are advancing, but data assimilation into numerical models continues to be a post mission research effort.

LIP, developed by Dr. Richard Blakeslee of the NASA Marshall Space Flight Center, provides electric field measurements in the vicinity of the Global Hawk aircraft derived from six field mills installed around the aircraft fuselage (Hood et al. 2006). LIP was included on the Global Hawk payload during the 2015 SHOUT Hurricanes campaign primarily for extra situational awareness and hazard avoidance (e.g., aircraft proximity to active areas of lightning); however, information about a storm's electrical environment may also be useful to operational forecasters.

After careful consideration, AVAPS, HAMSR, and HIWRAP, were selected as the final primary payload for the SHOUT field campaigns. Other instruments that were considered for inclusion on the Global Hawk payload, but not selected, included the Scanning High-resolution Interferometer Sounder (S-HIS) and the Tropospheric Wind Lidar Technology Experiment

(TWiLiTE). S-HIS provides infrared-derived vertical profiles of temperature and humidity closely resembling the capabilities of the Cross-track Infrared Sounder (CrIS) satellite sensor. While S-HIS was successfully flown on the Global Hawk during HS3, it was not included in the SHOUT payload because the best quality retrievals are limited to regions with limited cloud cover and the instrument competes with HIWRAP for integration location on the Global Hawk aircraft.

Deployment cost was also a factor. S-HIS remains a primary sensor of interest to SHOUT and was considered in the SHOUT data assessment studies. The TWiLiTE instrument, while providing the potential for highly valuable atmospheric wind profiles, was not included because its operation has not been successfully demonstrated on the Global Hawk.

4 2015 SHOUT HURRICANES

Prior to the start of the 2015 SHOUT Hurricane missions, the project collaborated with the NASA- led Hurricanes and Severe Storm Sentinel (HS3) experiment in 2014 supporting a one week extension of the field project and gaining access to all data collected throughout the five-week deployment. The first field deployment of the Global Hawk aircraft supported solely by the SHOUT project took place during August – September 2015 with the primary goal of collecting observations to support assessing the impact of UAS-based data on forecasts of TCs. Such observations are critical to the successful completion of SHOUT's data impact studies. The missions were to focus on high-value TC forecasts, prioritizing storms where significant forecast uncertainty existed or where there was a high potential for human impact, and sampling strategies were designed to optimize the impact of the data on the forecasts. The 2015 SHOUT Hurricanes campaign marked a move to an operationally motivated experiment from previous research oriented missions.

Based on climatological studies of peak hurricane activity in the Atlantic basin, the 2015 SHOUT Hurricanes deployment had a planned five-week science flight period extending from 25 August to 27 September. However, funding was available for up to ten 24 h duration flights. The Global Hawk initially deployed to NASA WFF in Virginia to target Atlantic TCs with an option to reposition the aircraft back at NASA AFRC in California to target eastern North Pacific TCs if TC activity in the Atlantic waned. This optional repositioning strategy was made in light of NOAA forecasts for a developing El Niño, which often equates to limited TC activity in the tropical Atlantic. Ultimately, three Global Hawk flights were conducted in the Atlantic between 26 August and 5 September, including two missions in Tropical Storm Erika (26-27 August and 29-30 August) and one mission in Tropical Storm Fred (5 September). The total number of flights was less than planned due to a limited number of suitable targets and an early end to the campaign that was necessitated by damage sustained by the Global Hawk during ground handling after the aircraft was repositioned back at NASA AFRC in early September.

Operations Overview

Significant consideration went into the base deployment location for the 2015 SHOUT Hurricanes campaign to maximize data value. Both the NASA WFF on the eastern shore of Virginia and the NASA AFRC at Edwards Air Force Base (AFB) in California support Global Hawk operations. Operations from WFF enables sampling of TCs most anywhere in the North Atlantic, the Caribbean, and the Gulf of Mexico, while maximizing time-on-station over Atlantic basin storms. Restrictions on allowable Global Hawk flights over land; however, preclude sampling of eastern North Pacific cyclones from WFF. From AFRC, the Global Hawk can still target storms over the Gulf of Mexico, the Caribbean, and the western Atlantic closer to the U.S. coast, albeit with less sampling time, while enabling the study of eastern North Pacific storms as well. Yet, operations from AFRC are subject to additional limitations associated with Edwards AFB. For example, the assurance for seven-day-a- week operations could not be obtained during mission planning. Moreover, this capability was not confirmed until just prior to the start of the campaign.

Several factors motivated prioritization of Atlantic storms as mission targets. Guidance from the SHOUT advisory group and mission scientists suggested that the forecast uncertainty is generally greater for storms in the Atlantic basin. Potential impacts on U.S. coastal populations are also greater for Atlantic storms. With the known state of the developing El Niño event in 2015, seasonal forecasts called for a below-average hurricane season in the Atlantic basin. This implied a greater risk for not having sufficient valid flight targets in that basin. Given all the factors, the decision was made to deploy initially to WFF with an option to shift operations to AFRC after two weeks if it appeared there would not be a sufficient number of Atlantic targets during the final portion of the campaign. The relocation decision point was based on a detailed schedule allocating one week for the transition while leaving two final weeks for AFRC operations.

The 2015 SHOUT Hurricane campaign operated from WFF from 24 August to 6 September. Tropical storms Erika and Fred provided flight targets during this time for three missions, described in detail in Section 4.3. The media prominently covered the early forecasts of Tropical Storm Erika that predicted a significant threat to Florida. Tropical Storm Fred was a fairly weak system as it traversed the Atlantic and its intensity was not well forecasted. However, the storm unexpectedly intensified from a tropical depression to Tropical Storm Fred the day of the Global Hawk mission. This unanticipated intensification provided a useful case study for assessing SHOUT data impact on numerical model forecasts.

On 4 September, after two weeks of operations at WFF, SHOUT exercised the option to move field operations to AFRC for the final portion of the campaign following completion of the third flight on 6 September. Extended forecasts at that time indicated little potential for Atlantic storms to threaten the U.S. while continued eastern North Pacific storm activity was probable. With no potential targets in the intervening days, it was an optimal time to schedule the move. The relocation of aircraft and personnel took less time than was originally allocated; therefore, the Global Hawk was ready for flight operations from AFRC on 11 September. The ability to successfully shift the location of flight operations quickly was a highly significant demonstration of flexibility potentially applicable to future NOAA operations. AFRC based operations enabled access to study eastern North Pacific cyclones and TCs in the western Atlantic, as well as sampling high- impact weather events that threaten Alaska. Ultimately, no SHOUT flights were conducted from AFRC. Following the relocation, the eastern North Pacific became inactive with respect to TC activity despite the continued potential in extended forecasts. Opportunities for flights supporting improved forecasting of Alaska weather events were also explored. Forecast sensitivity targeting for the northern Pacific (see Section 4.2) was enabled and forecast discussions with the National Weather Service (NWS) Alaska and Western Regions were initiated. No suitable flight targets were identified prior to 16 September. Even though no Alaska related flights were conducted, the preparations were highly valuable. The targeting calculations and forecast discussions provided an important dry run for planned activities in the coming year.

An early termination of SHOUT Global Hawk operations occurred on 17 September because of damages sustained to the Global Hawk's wing tip and nose landing gear, while being towed outside for satellite communication testing the previous day. The estimated time required for completing the repairs exceeded the time remaining in the scheduled campaign, which necessitated the conclusion of the deployment.

Mission Design and Targeting

The 2015 SHOUT Hurricanes missions were designed with the goal of collecting data that could be used to improve forecasts and reduce forecast uncertainty. To achieve this goal, targeting strategies were developed for individual TCs and Alaska storms and were focused on identifying regions of greatest forecast sensitivity. The results highlighted regions where the forecasts are most sensitive to environmental conditions, which are desirable for additional sampling.

For the TC objective, a team led by Dr. Ryan Torn at the University at Albany-SUNY developed a real-time technique for targeting Global Hawk GPS dropsonde observations in the TC environment. This TC targeting algorithm identifies regions where high model forecast uncertainty (e.g., track or intensity) and a high sensitivity to data assimilation (e.g., GPS dropsonde data) exist. Model input includes 80-member Hurricane Weather Research and Forecast (HWRF) ensemble forecasts made available through a collaboration with Dr. Zhan Zhang from the National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC). However, due to computational constraints, these forecasts were generated as four sets of 20-member forecasts initialized every six hours. Once the forecasts were completed, Co-Investigator (Co-I) Torn carried out the sensitivity and target location calculations to identify where assimilating GPS dropsonde data at a specific time, typically when the Global Hawk would be flying, might decrease the ensemble variance in forecasted TC track and/or intensity at some lead time in the future. This approach helped SHOUT mission scientists to identify where to deploy GPS dropsondes and to assess whether forecast models would be sensitive to added GPS dropsonde data in those regions. Examples of the output used in planning a flight into Tropical Storm Erika are shown in Figure 4.1 (all generated results are available at: http://www.atmos.albany.edu/facstaff/torn/SHOUT/SHOUT_target.php). To support aircraft operations, Co-I Torn composed daily reports tailored toward the storm of interest (see http://catalog.eol.ucar.edu/tci/150363/files for archived reports). During Tropical Storm Erika, the targeting guidance highlighted the importance of having an accurate estimate of a subtropical ridge to the north of the storm early in its lifecycle and a trough over the Gulf of Mexico during its dissipation stage (Figure 4.1).

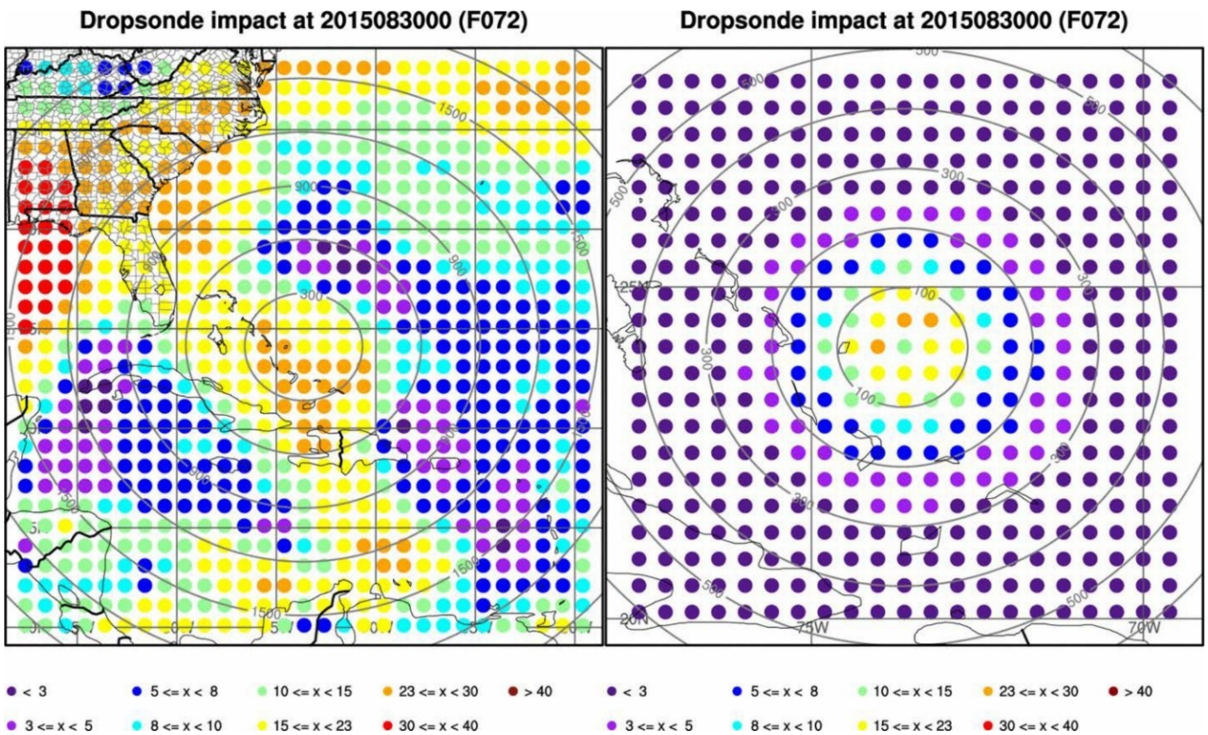

Figure 4.1. Example results of the HWRF targeting showing computed sensitivity for track (left) and intensity (right) forecasts of Tropical Storm Erika. The results consider the potential impact of all GPS dropsonde variables on a 72-hour forecast valid on 30 August 30 at 0000 UTC. Numerical values represent the percent reduction in forecast variance resulting from assimilation of a GPS dropsonde observation at that location. Warm colors indicate the greatest impact. Graphics provided courtesy of Dr. Ryan Torn.

Once operations shifted from WFF to AFRC and high-impact Alaska weather events became potential targets, a team at NOAA's Earth Systems Research Laboratory (ESRL)/Global Systems Division (GSD) led by Dr. Lidia Cucurull provided forecast sensitivity targeting over the eastern North Pacific based on global models. Her methodology employed two different approaches and models. In both approaches, the first step was to identify the high-impact weather threat region of interest and lead-time to improve the forecast. Next, relative to the identified threat region, both approaches then computed a measure of forecast variance based on a total energy norm derived from the temperature and wind forecast fields. The first approach used an Ensemble Transform Sensitivity (ETS) methodology (e.g., Bishop and Toth 1996) applied to the operational ensemble forecasts from NCEP using the Global Ensemble Forecast System (GEFS). The second approach employed an adjoint-based sensitivity analysis (e.g., Langland et al. 1995) to the Weather Research and Forecast (WRF) model. By sampling the regions with highest forecast variance, the goal was to reduce the ultimate forecast uncertainty for the target region. Use of multiple approaches provided greater confidence in the identified target regions where the results coincided. The ETS methodology was similar in approach to that employed in the former operational Winter Storm Reconnaissance (WSR) program, but used the current operational forecast system.

During the AFRC portion of the flight campaign, sensitivity results were generated daily for potential high-impact weather targets identified by Alaska and Western region offices of the NWS. Sample output generated for a large precipitation event predicted to affect the Juneau, Alaska region (on 20 September 1200 UTC) is shown in Figure 4.2. The colored areas in this figure indicate the regions of greatest forecast sensitivity at a one-and-a-half-day lead-time. A preliminary flight box and flight plan was drafted based on these products; however, the flight was cancelled when the aircraft was damaged (see Section 4.1). The original objective was to improve forecasts at a three-day lead time, but the identified sensitive regions for the potential events affecting Alaska at this time fell primarily in the Bering Sea which was outside the permitted flight domain of the Global Hawk.

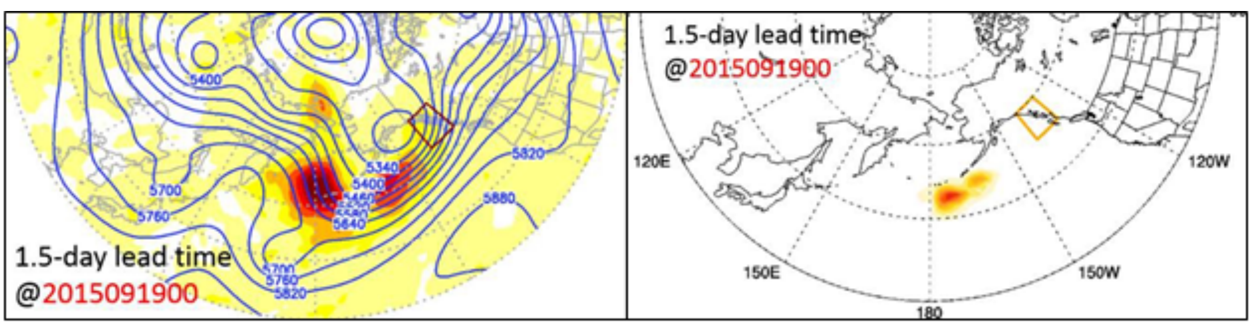

Figure 4.2. Example of targeting results using an ETS method (left) and an adjoint-based sensitivity analysis (right) for a storm predicted to affect the Juneau, Alaska area. Warm colored areas denote regions where dropsonde observations at a one-and-a-half-day lead time have the greatest potential to improve forecasts for the boxed region along the Alaska coast. Graphics courtesy Dr. Lidia Cucurull and Dr. Hongli Wang.

Implementation of the automated ETS-based system for targeting and flight track design was an important contribution from the group at ESRL/GSD. The method was tested first on historical events to demonstrate its function and highlight potentially desired flight regions in advance of the actual operations. The work was deemed highly beneficial as it enabled consideration of additional flight targets in a year with limited TC targets and it paved the way for the full set of potential SHOUT mission objectives that were under consideration for flights in 2016.

Flight Summary and Instrument Performance

Tracks of the three flights conducted during 2015 SHOUT Hurricanes are shown in Figure 4.3 and key details are summarized in Table 4.1. The first two flights were directed toward studying Tropical Storm Erika while the third flight targeted Tropical Storm Fred.

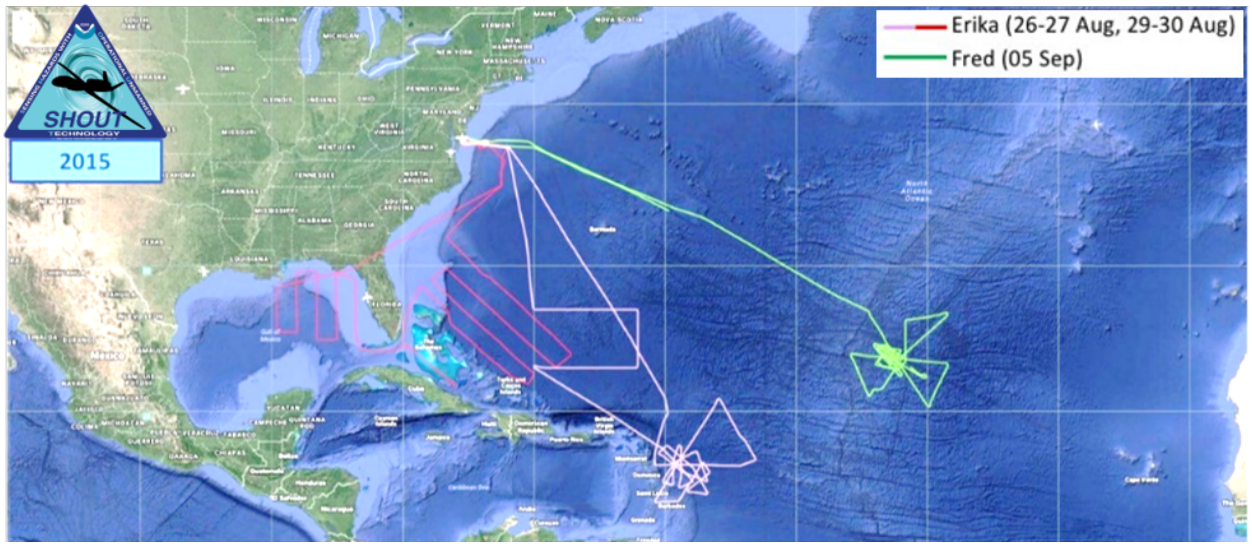

Figure 4.3. Map of the flight tracks for the three Global Hawk missions conducted during the 2015 SHOUT Hurricanes campaign. Graphic generated using NASA's Mission Tools Suite (MTS).

Table 4.1. Summary of Global Hawk flights conducted during the 2015 SHOUT Hurricanes campaign.

Dates (2015)	Target	Duration (hours)	No. Sondes Deployed
August 26-27	Erika	23.7	14
August 29-30	Erika	23.7	58
September 5-6	Fred	24.0	16

4.1.1 2015 SHOUT Hurricanes – Mission 1

The first flight into Tropical Storm Erika was conducted on 26-27 August. Tropical Storm Erika was forecast to pose a potential threat for landfall in Florida; therefore, it was a valuable candidate for analysis of data impact. The flight plan included large and small butterfly patterns centered over the storm to sample the immediate storm environment. Further to the northwest, a lawnmower pattern was used to sample the upstream environment where the HWRF sensitivity calculations indicated an impact on the storm track forecasts. The butterfly segments were flown first in an effort to overfly the system before it approached the islands in the Lesser Antilles. After the first three successful sonde drops, the AVAPS GPS dropsonde system encountered a problem attempting to load a dropsonde for deployment. An early return to WFF to address the problem and preserve the option for an additional flight on 28

August was explored but was not possible due to required landing protocols at WFF. Meanwhile, the HIWRAP and HAMSR instruments provided good observations over and around the storm. Also, the AVAPS team was eventually able to temporarily mitigate the instrument anomaly and deploy additional GPS dropsondes over the storm; however, during an attempt to complete an abbreviated lawnmower pattern in a data sensitive region, the GPS dropsonde system failed again. Despite the limited GPS dropsonde data obtained, this was the first time that Global Hawk GPS dropsonde data that was being transmitted to the GTS in real-time was also being operationally assimilated into the HWRF model (see Section 4.4).

4.1.2 2015 SHOUT Hurricanes – Mission 2

A second flight into Tropical Storm Erika was originally planned for takeoff on 28 August, one day after completion of the first flight. This flight would have provided good data continuity and addressed the significant uncertainty regarding the future track of the system over the Greater Antilles. However, flight operations would have been challenging given the proximity of the system to the Lesser Antilles at that time and the limited amount of space where the Global Hawk was permitted to pass between islands during transit between the Atlantic and Caribbean. Therefore, the flight was delayed a day, which allowed time for repairs to the AVAPS instrument. The next flight was conducted on 29-30 August, although the storm system had started to weaken from interactions with land in the Greater Antilles and was less of a threat for direct landfall in Florida. Yet, the track forecasts remained uncertain and Erika was predicted to produce significant rainfall in Florida. The planned mission included elements to sample a potentially sensitive region north of the Bahamas, a segment passing over the forecast system track between the Bahamas and Cuba, and a broad region of identified sensitivity associated with an upper level shortwave trough in the eastern Gulf of Mexico (see Figure 4.1 sensitivity maps). Approximately three hours into the flight the National Hurricane Center declared that Tropical Depression Erika had dissipated and was considered a remnant low pressure area. This meant that operational runs of the HWRF model would end and there would be no opportunity for operational assimilation of any GPS dropsonde data. Still, the flight continued because of the sensitive region in the Gulf of Mexico and the potential data impact on precipitation forecasts in Florida. All planned elements of the flight were conducted, and all instruments performed well throughout. The Gulf of Mexico sampling, in particular, appeared to be successful, and a GPS dropsonde deployed at 0251 UTC on 30 August was closely collocated with the center of an upper level low pressure system over the northern Gulf of Mexico.

4.1.3 2015 SHOUT Hurricanes – Mission 3

The final system sampled during the 2015 SHOUT Hurricanes field campaign was Tropical Storm Fred. Flights earlier in the life cycle of Fred were considered but not conducted because forecasts generally agreed that the system would rapidly dissipate. There appeared to be little forecast uncertainty to address, and the system did not pose any significant threat to life or property at the time. However, the forecasts proved to be premature in the predicted weakening of the storm, and the system continued to persist for several additional days. The SHOUT team's decision to fly the storm was made on 5-6 September because the system was beginning to undergo some strengthening, and there was notable uncertainty in the intensity forecast and the potential for re- intensification at a later time. Also, the flight represented another opportunity for operational assimilation of GPS dropsonde data in the HWRF model. The flight plan contained multiple butterfly patterns over the storm with additional GPS dropsonde deployments on the inbound and outbound transit to sample identified upstream sensitivity. Sixteen dropsondes were successfully deployed during the inbound transit and first pass over the storm before AVAPS again experienced a malfunction with the loading of dropsondes. Following completion of the first large butterfly pattern, the flight plans were reworked to maximize sampling over convective regions and, despite a delay in delivering real-time data, the HIWRAP system was able to retrieve good data. During the last planned convective over-flight of the storm, the Global Hawk lost communications with the Global Hawk Operations Center due to a disruption in phone line service to WFF, which initiated an automatic return-to-base. This is the standard, pre-programmed response to a loss of communications and all backup systems functioned properly. Communication was restored during the return flight and the UAS landed without issue.

Overall, the HAMSR, HIWRAP, and LIP instruments performed extremely well throughout the 2015 SHOUT Hurricanes campaign. HAMSR encountered no major issues during any of the flights. HIWRAP experienced several minor issues in receiving its navigation data, which affected its real- time data delivery but did not affect the final data products. HIWRAP also had occasional outages of its Ku band data, but this did not affect a significant portion of the flights. The LIP instrument had some issues with one field mill and the associated electronics, but the problems did not greatly affect the end products. The most significant payload issues involved AVAPS. Problems with loading dropsondes from the dispenser assembly persisted, and the system became inoperative during large portions of two-out-of-the-three flights. Therefore, very few dropsondes were deployed, which will have a negative effect on impact studies that are based on the 2015 SHOUT Hurricanes flights. Prior to the conclusion of the 2015 SHOUT Hurricanes deployment, system testing at AFRC revealed a potential issue was found with the latches and associated solenoids that release dropsondes from the columns in the dispenser assembly when fully loaded. The temporary solution that was implemented reduced the maximum system capacity from 88 dropsondes to approximately 70 dropsondes for flights during the 2016 El Niño Rapid Response campaign in February 2016. Furthermore, the AVAPS team at NCAR completed a major redesign effort prior to the start the 2016 SHOUT Hurricane Rapid Response field campaign.

Data Delivery and Utilization

Significant strides were made in the real-time delivery of data from the Global Hawk aircraft during 2015 SHOUT Hurricanes. The provision of data products for real-time use by forecasters at the NOAA National Hurricane Center (NHC) were prioritized for the campaign based on discussions with NOAA NHC representatives prior to deploying the UAS and an external web page that was designed and implemented under the leadership of Jebb Stewart at ESRL/GSD hosts all of the data products in one location for ease of forecaster access (Figure 4.4). Many of the products are also available within the NASA Mission Tools Suite (MTS) package used to monitor and manage the flights, but MTS access is password controlled and its use requires training.

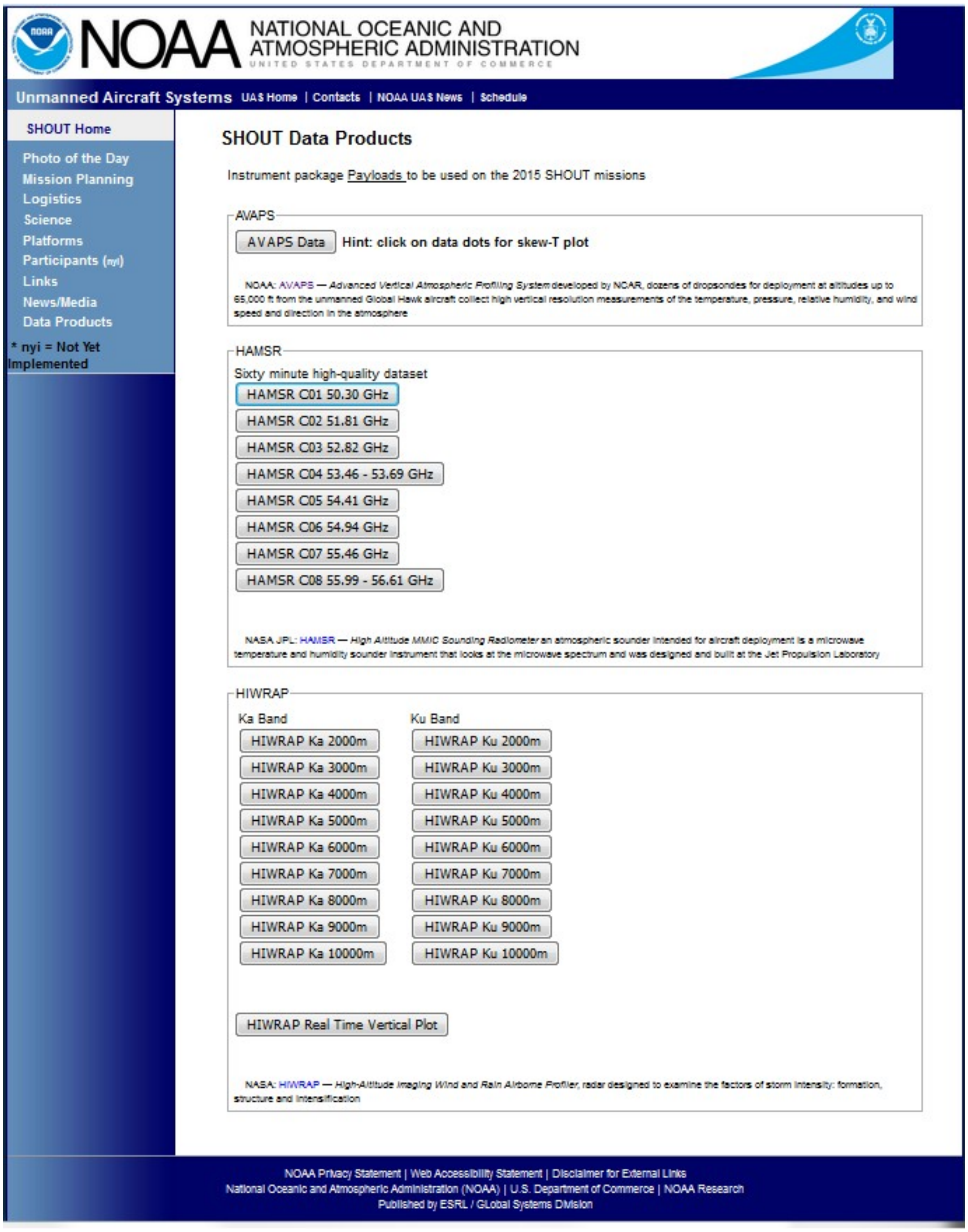

Figure 4.4. Screen capture of the real-time data access page implemented for 2015 SHOUT Hurricanes (http://uas.noaa.gov/shout/dataProducts.html).

Vertical reflectivity profiles along the aircraft track, as well as two-dimensional maps of reflectivity at specified atmospheric levels from HIWRAP, were produced and displayed in real-time for the first time during 2015 SHOUT Hurricanes. Examples of these products are shown in Figure 4.5. The detailed storm structure revealed by these data provides important new information to forecasters for expanding upon currently available tail Doppler radar (TDR) data from the operational manned NOAA aircraft. Derivation of wind speeds for model assimilation applications are still being pursued in a post-mission mode.

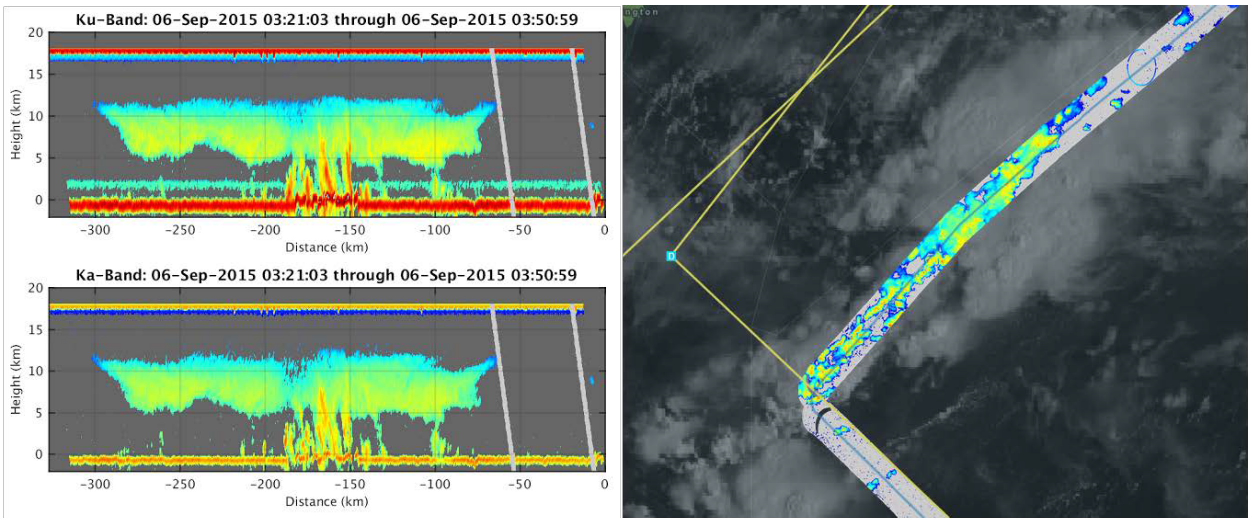

Figure 4.5. Example of HIWRAP real-time imagery available during 2015 SHOUT Hurricanes. Left: Vertical slices of stratiform precipitation with embedded convection observed over Tropical Storm Fred at Ku- (top) and Ka-band (bottom); Right: Spatial map of Ku-band reflectivity at ~2000 m altitude observed off the US East coast after departure from WFF en route to Tropical Storm Erika.

Real time data delivery from AVAPS and HAMSR was mature prior to the start of the campaign; although, data access and use of the data have been enhanced. HAMSR provides two-dimensional maps of the instrument brightness temperatures over the complete instrument swath as well as real-time retrievals of quantities including total precipitable water and cloud liquid water. The real-time retrievals employ a simplified neural network technique while a more sophisticated approach is employed in the generation of the final data products. An example of HAMSR data available to interested users during the flights is shown in Figure 4.6 for the flight over Tropical Storm Fred. The HAMSR products were available through the SHOUT data portal, NASA MTS, and a web page hosted by

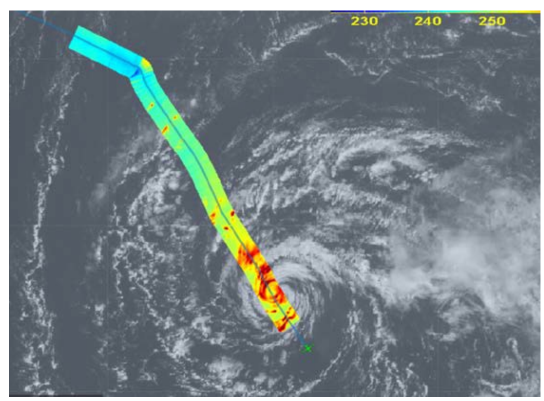

Figure 4.6. Example of real-time brightness temperature imagery provided by HAMSR during the first pass over Tropical Storm Fred on 5 September. Graphic generated using NASA's Mission Tools Suite (MTS).

NASA JPL and the HAMSR team.

A highly significant accomplishment of 2015 SHOUT Hurricanes was that Global Hawk GPS dropsonde data were operationally assimilated in NOAA's HWRF model for the first time. Previous to the 2015 SHOUT Hurricanes campaign, the only operational use of real-time dropsonde data distributed through the GTS was by the European Center for Medium Range Weather Forecasting (ECMWF). The GPS dropsonde observations from the first Erika flight (see Section 4.3.1) and the Fred flight (see Section 4.3.3) were assimilated operationally in HWRF at NCEP/EMC. A detailed analysis of the impact of these observations on Tropical Storms Erika and Fred were not available at the time of writing, but the number of observations was relatively small due to the problems with AVAPS on those flights, which limited the potential impact of the data. The Global Hawk GPS dropsonde data are still not assimilated operationally in the Global Forecast System (GFS) model, but recent studies by NCEP/EMC indicate that this data has a positive impact on GFS TC forecasts. Highlights of these positive impacts are discussed in Wick et al. (2018). Forecasters at NOAA NHC also continued to use real-time AVAPS data and incorporated the information into their forecast discussions.

Direct discussions have been initiated between the SHOUT-funded data impact assessment teams and the instrument teams to facilitate provision and usage of final data products. The ESRL/GSD team is obtaining the final calibrated HAMSR brightness temperature products to initiate assimilation studies with HAMSR, and a meeting between the HIWRAP and data teams is forthcoming. All data currently available from the SHOUT missions can be obtained from the interim website at: https://www.esrl.noaa.gov/psd/psd2/coastal/satres/shout_prelim_data_archive.html. The data management team at ESRL/GSD is working to complete a final data archive that will be available through the NOAA Center for Environmental Intelligence (NCEI). New SHOUT data products will continue to be added to the archives as they become available.

U.S. Collaborations

During the 2015 hurricane season, SHOUT collaborated with the Office of Naval Research (ONR) Tropical Cyclone Intensity (TCI) Experiment (Doyle et al. 2017). The goal of TCI is to improve the prediction of TC intensity and structure change particularly through an improved understanding of TC upper-level outflow layer processes and dynamics. TCI successfully collected observations using the high-altitude WB-57 NASA manned aircraft, instrumented with the Hurricane Imaging Radiometer (HIRAD) and the High Definition Sounding System (HDSS). During the SHOUT deployment at WFF, the TCI operations center was collocated with SHOUT, enabling close coordination and shared staffing among the mission scientists. While the two experiments did not fly coordinated missions into a common storm, the collaboration has made the data collected in TCI available for use in the SHOUT data impact analyses as well. This increased the amount and type of data available to help achieve the SHOUT objectives.

The HIRAD instrument is an airborne passive microwave radiometer, initially developed by

Robbie Hood while at NASA Marshall Spaceflight Center (MSFC), Calvin Swift at the University of Massachusetts-Amherst, and Linwood Jones from University of Central Florida (UCF). The instrument is managed at NASA MSFC and the University of Alabama in Huntsville under the leadership of principal investigators Dr. Daniel Cecil (MSFC) and Dr. Linwood Jones (UCF). HIRAD is primarily used to retrieve TC wind speeds at the ocean surface, along with rain rate intensities and has the capability of mapping these parameters over the entire hurricane eyewall during a single aircraft pass over the storm. Using four unique C-band frequencies (4.0, 5.0, 6.0, and 6.6 GHz) to obtain measurements, HIRAD takes advantage of the same observational concept as the operational Stepped Frequency Microwave Radiometer (SFMR). However, this new instrument provides added value with a much wider swath of data at the surface, approximately +/-60 degrees across track field of view for HIRAD, versus +/-10 to 12 degree field of view for the nadir-looking SFMR. This wider swath of data allows for the inner cores of many TCs to be mostly sampled in a single "figure- 4" pass (i.e., two perpendicular storm-center crossings) of the airborne platform, which provides a more accurate snapshot of a storm's two-dimensional surface wind speed distribution at any given time. HIRAD obtains data by using its antenna to make measurements of microwave radiation that is emitted by the ocean surface (i.e., surface emissivity). As increasingly stronger winds move across the surface, they generate increasing amounts of white, frothy sea foam. The more sea foam (i.e., air bubbles in the water) that is produced, the more microwave radiation is emitted. HIRAD is able to measure these variations in surface emissivity to deduce the magnitude of the wind speed at the ocean's surface. However, raindrops also emit microwave radiation proportional to the rain intensity which can also be deduced using HIRAD. The wind and rain emissions can be separated due to a basic law of physics that causes rain emissions to vary at different C-band frequencies while wind speed induced emissions remain invariant. Thus, multiple C-band frequencies from HIRAD can be used to segregate the contributions from each source and determine both the surface wind speed and the rain rate.

Despite the absence of HIRAD from the payload sensor suite onboard the Global Hawk during the SHOUT field campaigns, the instrument was successfully integrated onto this platform during NASA HS3, and there remains a distinct possibility that it may be integrated again in the future. The instrument is a candidate, should NOAA eventually pursue operational Global Hawk flights, and is a priority for evaluation within SHOUT. However, the similarity of the Global Hawk’s operating altitude with the WB-57 allows the WB-57-based observations to be evaluated as an extension by proxy of the Global Hawk's existing sensor payload.

There were many important TCI deployments of note for the NASA WB-57 that included HIRAD data sets, which will be made available from the 2015 hurricane season. These include, but may not be limited to, Hurricane Joaquin in the Atlantic, and Hurricanes Marty and Patricia (see Figure 4.7) in the eastern North Pacific. Combined, these deployments comprised a total of nine independent flights, all of which provided good collections of HIRAD data in tandem with HDSS dropsonde data and, in some cases, coincident SFMR data. An example of HIRAD data collected over Hurricane Patricia is shown in Figure 4.7. The HDSS provides nearly identical in-situ dropsonde data (e.g., pressure, temperature, humidity, and wind vector information) to that from the Global Hawk's AVAPS GPS dropsondes. The information provided by these dropsonde sensors was critical for validating much of the information retrieved by HIRAD during this period of advanced development and demonstration (Cecil and Biswas 2017).

HIRAD data collected during the 2015 ONR TCI Experiment, along with previously obtained HIRAD retrievals from NASA HS3, is being evaluated by the NOAA/ Atlantic Oceanographic and Meteorological Laboratory (AOML)/Hurricane Research Division (HRD) data impact team under the leadership of Dr. Altug Aksoy. It is hypothesized that the data provided by the HIRAD instrument has the potential to greatly assist in accurately characterizing the surface wind field in the initialization of NWP forecast models for TCs. This, in turn, could lead to significantly increased accuracy in model forecasts of TC track and intensity. Similar wind speed retrievals from HIRAD collected during ONR TCI missions into 2015 Hurricane Joaquin were provided to the impact assessment team at NOAA/AOML/HRD and were included in their experiments as documented in Wick et al. (2018).

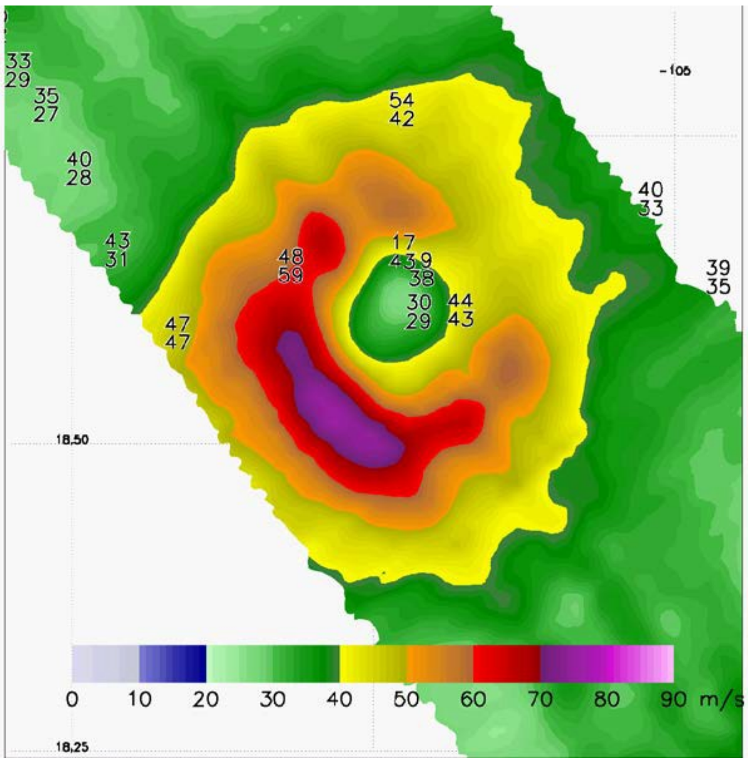

Figure 4.7. HIRAD surface wind speed retrieval (colored shading) from Hurricane Patricia on 23 October 2015. The thirteen number pairs indicate collocated surface wind speed measurements (m s^{-1}) from (top value) HDSS dropsondes and (bottom value) HIRAD. Graphic provided by Dr. Daniel Cecil from NASA MSFC.

5 2016 SHOUT EL NIÑO RAPID RESPONSE

The 2016 SHOUT El Niño Rapid Response (ENRR) deployment was conducted between 2-23 February from NASA AFRC located at Edwards AFB in California with the original goal of exploring the ability of observations from the Global Hawk aircraft to improve forecasts of major precipitation events anticipated to impact California during the strong 2016 El Niño event. Support was available for up to four 24 h duration flights during the deployment window and, ultimately, three flights were performed. Since the storms that occurred during the experimental period had less impact on California than was climatologically expected, the target objectives were expanded to include significant precipitation and wind events affecting coastal regions of the Pacific Northwest and Alaska.

Operations Overview

The 2016 SHOUT ENRR mission was planned and conducted in coordination with the broader NOAA ENRR project led by the NOAA/ESRL/Physical Sciences Division (PSD). The broader project was proposed in response to the unique opportunity presented by the occurrence of an ongoing major El Niño event. The overarching science goal of the experiment was to determine the tropical convective response to a major El Niño and its implications for predicting midlatitude storm activity, including impacts on U.S. West Coast rainfall. Other elements of the experiment design included flights of the NOAA G-IV aircraft, equipped with GPS dropsondes and its tail Doppler radar (TDR), from a location in Honolulu, Hawaii. Rawinsonde launches occurred from a temporary site established on the island of Kritimati, Kiribati, and additional rawinsonde launches were made from the NOAA Research Vessel Ronald H. Brown during a Tropical Atmosphere Ocean survey cruise.

Based on the opportunity for highly complementary observations from the Global Hawk, the ENRR management team approached the NOAA UAS Program and SHOUT leads to request collaboration on the project. The overall plan was presented to and approved by NOAA management. SHOUT participation in the project was conducted entirely with funds remaining from the shortened 2015 SHOUT Hurricanes deployment, so no new funding was required to support Global Hawk operations. In the end, two Air Force WC-130J aircraft also participated in the NOAA ENRR mission with flights deploying GPS dropsondes being staged from the West Coast and Hawaii.

Collaboration with the NOAA ENRR experiment provided SHOUT with an opportunity and extra justification to add the investigation of potential forecast improvement of major Pacific winter storms to its impact study topics. The assessment of forecasts of winter storms and atmospheric river events had been identified as a possible element of SHOUT at its inception, but concerns surrounding the effectiveness of the former operational WSR project had reduced its priority among other high impact weather events. Use of the Global Hawk aircraft with its long range and endurance coupled with the collection of continuous measurements from its remote sensors and larger numbers of GPS dropsondes, however, offered the potential for greater forecast impact than possible from the G-IV mission profiles previously employed during the WSR program.

Improvements in target sensitivity calculations also made the 2016 SHOUT ENRR campaign distinct from the WSR missions that had been conducted in the past. As a result, the campaign supplied the added benefit of revisiting the potential merit of a refined WSR-type program with significantly improved observational capabilities.

Mission Design and Targeting

The specific goal of the 2016 SHOUT ENRR campaign was to improve forecasts at a two to three-day lead time for high impact weather events that bring extreme precipitation and/or high winds to the West Coast of the continental U.S. or the coast of Alaska. Flight tracks for high impact storm targets were developed with the assistance of models that targeted regions most sensitive to the environmental conditions. Model forecast sensitivity calculations were performed multiple times per day by the team at GSD led by Lidia Cucurull using the methodologies described in Section 4.2, and sensitivity maps were automatically uploaded to a web page where they were accessible by SHOUT mission scientists. Figure 5.1 shows a sample sensitivity map that originally focused on a pre-defined target region centered on California, but was then expanded to include specific regions based on individual storm systems of interest.

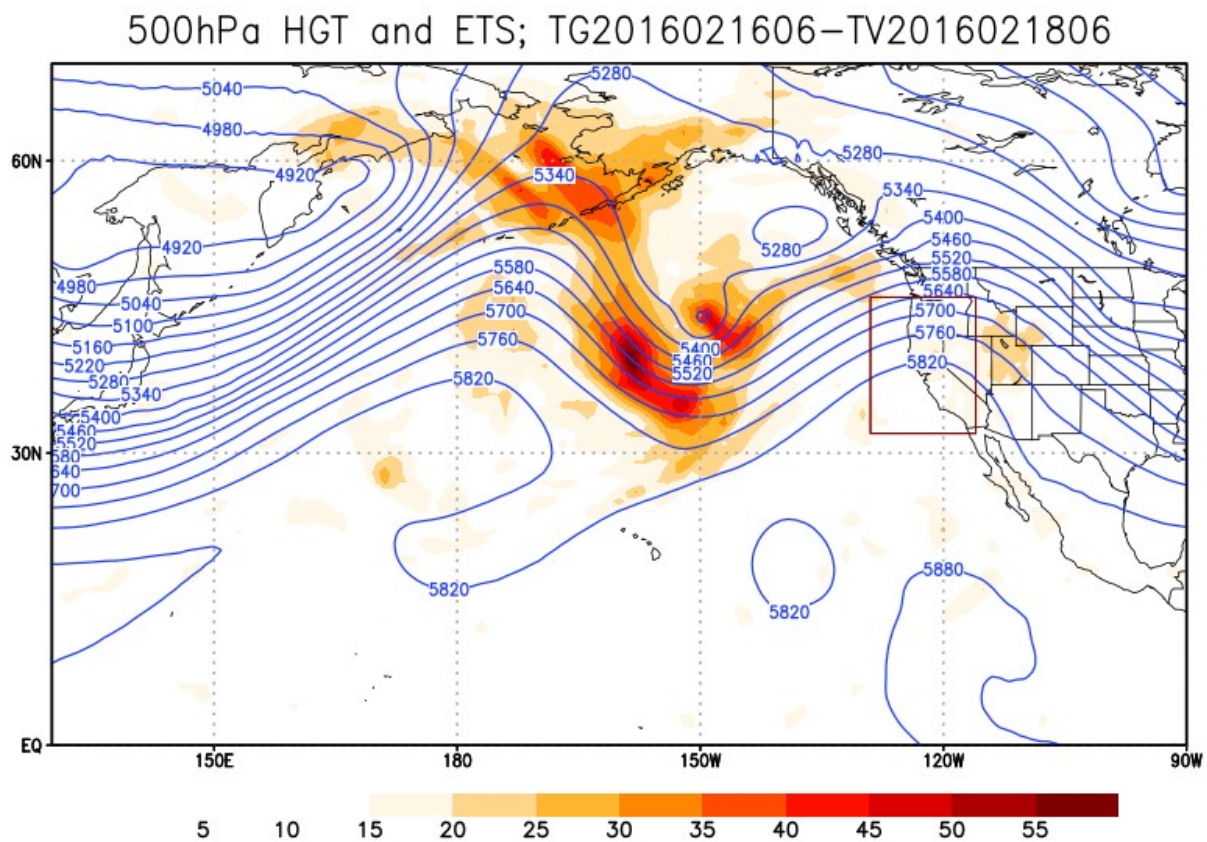

Figure 5.1. Example of the forecast sensitivity calculations employed for Global Hawk mission targeting during the 2016 SHOUT ENRR campaign. This graphic was generated from the 1800 UTC forecast run on 14 February and highlights potential sampling on 16 February 0600 UTC to improve a forecast valid on 18 February 0600 UTC. Warm colored contours indicate regions of greatest sensitivity to GPS dropsonde observations. The red box illustrates the target region for which the improved forecast is desired. This output was used in the planning of the 15 February SHOUT ENRR mission as described in Section 5.3. Graphic generated by ESRL/GSD and provided by Hongli Wang and Andrew Kren.

The design of Global Hawk flight plans was made using the sensitivity calculations to identify key meteorological features to sample. This approach differs from simply trying to maximize the sampling of the regions with greatest forecast sensitivity because it also incorporates targeting of actual atmospheric features. The approach was adopted to facilitate modification of the flight plan in real time while conditions evolved. Comparison of the sensitivity graphics between successive model runs demonstrated that the spatial extent and patterns of the sensitive regions would evolve as features in the forecast fields changed. Additionally, updated targeting information was not available in real time during the flight, and it was more efficient to modify the flight track to follow features identifiable from available satellite and model fields. Targeting meteorological features also provided an effective way of combining the input from the different approaches which would often highlight similar features but with different spatial extents.

Flight Summary and Instrument Performance

Flight tracks of the three missions conducted during the 2016 SHOUT ENRR field campaign are shown in Figure 5.2 and key details are summarized in Table 5.1. The three Global Hawk missions included a total of 90 GPS dropsondes deployed and transmitted to the GTS and over 71 hours of flight.

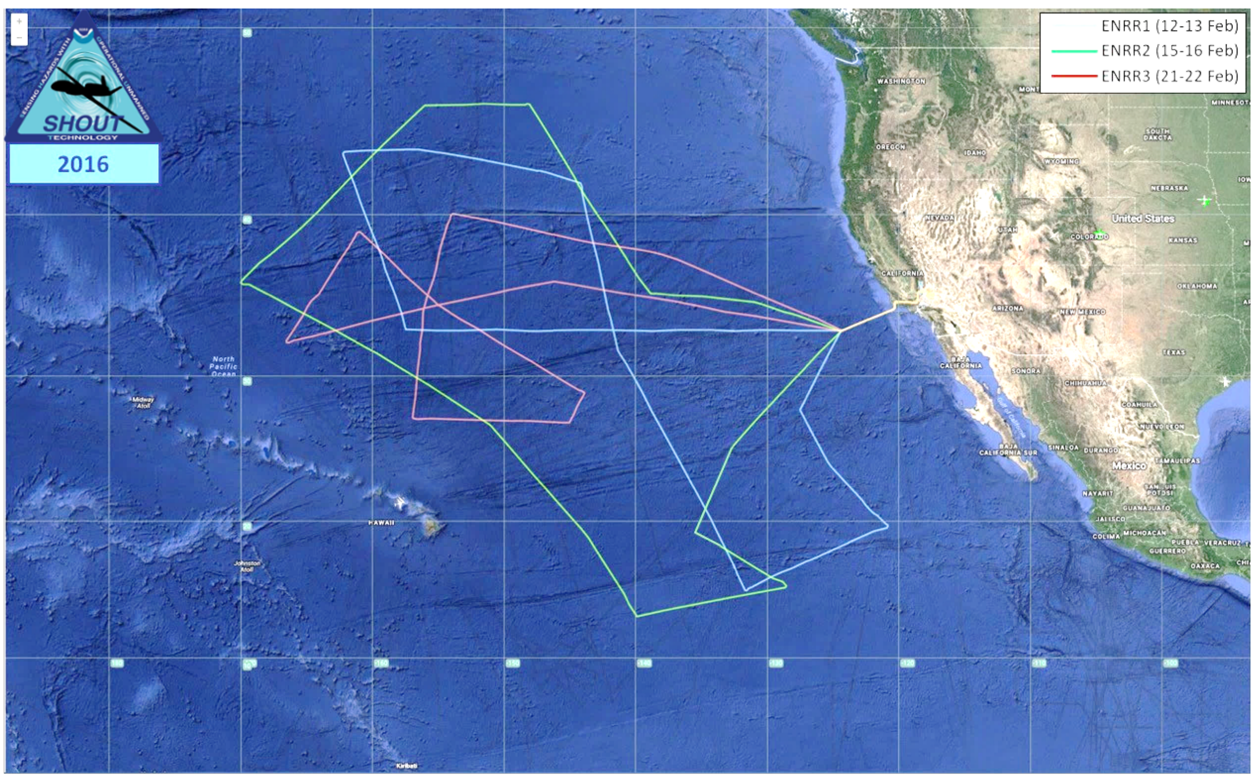

Figure 5.2. Map of Global Hawk flight tracks for the three missions conducted during the 2016 SHOUT ENRR field campaign. Global Hawk track targets included atmospheric river impacts in the Pacific northwest and British Columbia (12-13 February, blue track), trough interactions and a cutoff low pressure system in advance of a southern California precipitation event (15-16 February, green track), and dual precipitation and high wind event impacts in Alaska and the SE U.S. (21-22 February, red track).

Table 5.1. Summary of Global Hawk flights conducted during the 2016 SHOUT ENRR campaign.

Dates (2016)	Target	Duration (hours)	No. Sondes Deployed
12-13 February	Atmospheric River impacts in the Pacific northwest and British Columbia	22.9	2
15-16 February	Trough interactions and a cutoff low-pressure system in advance of a southern California precipitation event	24.5	22
21-22 February	Dual precipitation and high wind event impacts in Alaska and the southeastern United States	23.6	66

5.1.1 2016 SHOUT ENRR Campaign – Mission 1

On 12-13 February, the first flight of the 2016 SHOUT ENRR campaign collected observations to support the evaluation of the impact of UAS data on forecasts of precipitation in the Pacific Northwest and British Columbia associated with a moderate atmospheric river event. Forecasts predicted between 5-10 cm (2-4 in) of rain with mountain snow. Also, uncertainty was present in the models with regard to timing of the system and the position of heaviest precipitation. The planned mission duration was less than the normal 22 h due to limited pilot availability as a result of illness. The key feature expected to bring precipitation to the Pacific Northwest two days later was an atmospheric river located north-northwest of Hawaii. Evolution of the atmospheric river was forecast to be influenced by the evolution of a trough positioned between Hawaii and the mainland. Elements of the original flight plan included sampling an identified region of sensitivity associated with the trough, transects of the atmospheric river and associated jet structure, and a region at the base of the trough where a cutoff low pressure system was forecast to form.

AVAPS failed when attempting to load the third GPS dropsonde, so only two dropsondes were successfully deployed during the mission. Since the failure occurred so early in the flight, there was concern about whether to continue with the mission or cancel the remainder of the flight. The SHOUT team's decision to continue the mission was based on the targeted weather event having a potentially high impact, continued good performance of the HAMSR and HIWRAP instruments, and that a specific SHOUT priority was to evaluate the impact of the remote sensing instruments on model analyses forecasts. Additionally, there would be adequate time to investigate and potentially fix the AVAPS failure prior to the next expected flight of interest. Remaining elements of the flight plan were revised to optimize sampling with the remote sensors and included capturing an area of significant convection that developed near the cutoff low at the southern end of the flight track (Figure 5.2). The HAMSR and HIWRAP instruments continued to function well throughout the remainder of the flight, providing useful data for the planned impact assessments.

5.1.2 2016 SHOUT ENRR Campaign – Mission 2

On 15-16 February, the second 2016 SHOUT ENRR mission was conducted in coordination with the NOAA ENRR's two Air Force Reserve Command WC-130J aircraft, which flew missions from

Hickam AFB near Honolulu, Hawaii and McCord AFB near Seattle, Washington, to collect data for a precipitation event extending from northern California down to the southern portion of the state. The primary effect was expected to occur in northern California with 2.5-7.6 cm (1-3 in) of precipitation forecast for the Sierra Nevada mountains resulting from an atmospheric river. However, there was notable uncertainty about the possibility of precipitation in southern California associated with the position and evolution of the cutoff low east of Hawaii as it interacted with a Pacific trough. The flight plans of the Global Hawk and WC-130Js were coordinated to distribute transects of the atmospheric river along its extent and improve its sampling. The NOAA G-IV aircraft also flew during this period, sampling the outflow that was originating from convection in the tropical region south of Hawaii (Figures 5.2 and 5.3). Elements of the planned Global Hawk flight track included sampling of the atmospheric river and entrance region to the jet as well as the region of the extratropical cutoff low (Figure 5.3). By takeoff time, the forecast sensitivity calculations indicated reduced sensitivity to the cutoff low, but sampling of the region was retained because of its potential to serve as a source of moisture for precipitation in southern California. Sampling by the WC-130Js was focused on multiple transects of the atmospheric river with the goal of improving forecasts of its impact in the Pacific Northwest at a shorter, one-day lead time. The resulting precipitation in southern California was more than anticipated, making the event interesting for analysis of forecast impact. Coordination between the Global Hawk, two Air Force WC-130J aircraft and the NOAA G-IV aircraft allowed for all features of interest to be sampled within several hours of each other with the longer Global Hawk flight anchoring the other shorter complimentary flights (i.e., Air Force C-130Js and NOAA G-IV). This multi-aircraft configuration exemplifies an operational demonstration where sampling of key atmospheric features and data assimilation into regional and global models can be optimized.

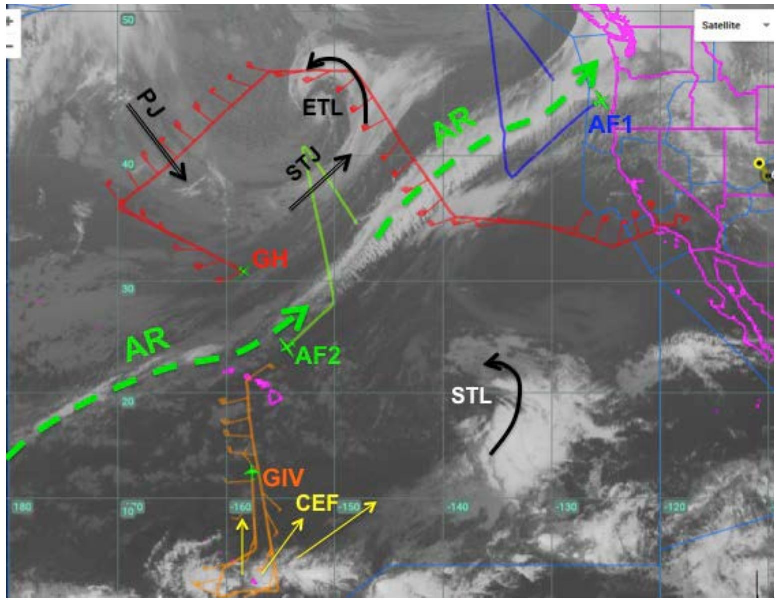

Figure 5.3. Schematic of cloud features during a 2016 SHOUT ENRR Global Hawk Mission 2 on 15-16 February (red curve). Coordinated missions with two Air Force WC-130J aircraft (blue and green curves) and the NOAA G-IV jet (orange curve) are also shown. An atmospheric river (AR; thick green curve), atmospheric jet features (black arrows) associated with a polar jet (PJ), subtropical jet (SJ), extratropical low (ETL), and subtropical low (STL), and an area of upper-level cross equatorial flow (CEF; yellow arrows) are indicated.

The AVAPS instrument also failed during this second mission. After a first transect of the atmospheric river and associated jet, 22 GPS dropsondes were successfully deployed and wind speeds in excess of 61.5 m s^{-1} (120 kt) were observed before the AVAPS dispenser became jammed and no further dropsondes could be launched. The remainder of the mission was again completed with minor modifications to the planned track to benefit the Global Hawk's remote sensors. Of note, the sampling near the cutoff low was modified to increase sampling of precipitation that developed on its eastern side. The track approaching the region of precipitation also had to be shifted slightly to the east to avoid a region of very cold temperatures aloft that approached the structural limit of the aircraft. HAMSR functioned well throughout the flight aside from some dropouts in the real-time data return and HIWRAP returned excellent data until the final portion of the flight returning to base when the instrument experienced a transmitter failure in its Ku band.

5.1.3 2016 SHOUT ENRR Campaign – Mission 3

The third and final 2016 SHOUT ENRR mission was conducted on 21-22 February with sampling centered on a rapidly intensifying extratropical low pressure system in the Pacific and an adjacent atmospheric river (Figures 5.2 and 5.4). The primary objective of the flight was the collection of observations in support of forecasts of high winds and precipitation in southern Alaska, including Anchorage, for 24 February. Precipitation amounts of 2.5-10 cm (1-4 in) were anticipated, corresponding to over 61 cm (2 ft.) of snow in mountainous regions. Initial forecasts during early mission planning had suggested possible impacts for the California coast but development of a high pressure ridge over California focused the primary projected impacts on the Alaska region by the time of the flight. A major secondary downstream impact of the sampled storm system was its subsequent influence on a severe weather outbreak in the southeastern U.S. from 23-24 February. Forecasts for the region from the Gulf coast states through the Atlantic seaboard had been wavering between a possible ice storm and severe weather outbreak until the primary upper level trough made

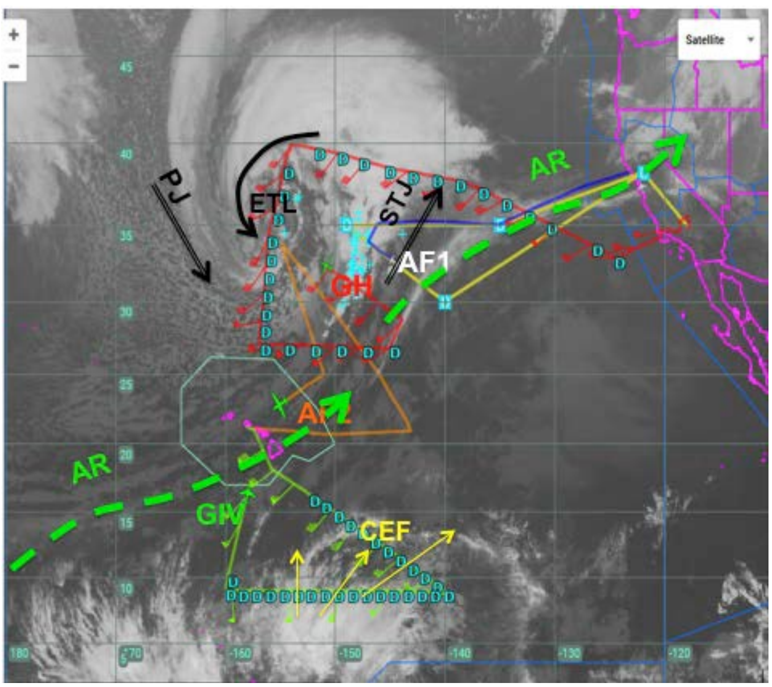

Figure 5.4. Same as Fig 5.3 except for a 2016 SHOUT ENRR Global Hawk Mission 3 on 21-22 February. 'D' indicates a Global Hawk GPS dropsonde location. Coordinated missions with two Air Force WC-130J aircraft (blue and orange curves) and the NOAA G-IV jet (orange curve) are also shown.

it inland and was sampled by the operational upper air network. Sampling of the storm offshore provided the unique opportunity to evaluate the effect of the Global Hawk observations on two distinct high-impact weather events affecting the U.S.

This mission also incorporated significant coordination with both the Air Force C-130J aircraft and the NOAA G-IV flying as part of the NOAA ENRR experiment. The WC-130J aircraft flew from both Hickam AFB, Hawaii and Travis AFB near Sacramento, California, providing additional sampling of the atmospheric river and extratropical low. Evolution of the weather system was also forecasted to be affected by cross-equatorial flow advecting mid- and high-level moisture northward in the region southeast of Hawaii. The NOAA G-IV flying south from Honolulu, Hawaii deployed GPS dropsondes farther north and east than it had typically been operating during the NOAA ENRR mission, providing valuable observations of this cross-equatorial flow. This joint mission represented the greatest degree of coordination achieved during the NOAA ENRR experiment and was a major project success. The suite of observations collected over the Pacific is perhaps the most extensive of its kind to date.

The performance of all the Global Hawk instruments was good throughout the flight. The AVAPS anomaly that occurred during the previous flights was identified and successfully mitigated prior to the mission. The issue was traced to out-of-specification spacing between a couple of the bin separators in the AVAPS dispenser and GPS dropsondes whose shape had become slightly distorted during storage between campaigns. The problem was addressed by carefully testing the shape of all GPS dropsondes loaded and reducing the maximum GPS dropsonde capacity, which meant not using two bins identified as being too narrow. A 100 percent success rate was achieved in deploying the 66 GPS dropsondes requested during the flight. Warmer-than-normal atmospheric temperatures, resulting from the extratropical low and associated meteorological features, made it difficult to keep the HIWRAP instrument cool. Consequently, the instrument had to be turned off for short periods of time during the early portion of the flight to avoid overheating, but the outages were performed during periods when there were no significant radar targets so no critical data were lost. Also, there were again outages in the real-time data return from HAMSR, but all data were successfully stored on the aircraft.

After completing the 2016 SHOUT-ENRR campaign, scientists from the AVAPS team discovered that the humidity observations from all GPS dropsondes deployed since the introduction of the current sensor version in 2010 were biased dry at high altitudes where temperatures are colder than approximately -10°C. This affected the observations from all Global Hawk GPS dropsondes that had been deployed in SHOUT studies prior to the ENRR campaign, as well as all GPS dropsondes deployed from various manned aircraft since 2010; however, a team led by Holger Vömel from NOAA/NCAR/EOL implemented a corrective algorithm and revised data were supplied for all previous Global Hawk GPS dropsonde observations. Unless otherwise stated, all of the analyses reported in this document and by Wick et al. (2018), use the corrected data.

During the intervening period between the 2016 SHOUT-ENRR campaign and 2016 SHOUT Hurricane Rapid Response field campaign (Section 6), significant modifications were made to the AVAPS dispenser assembly that corrected the anomaly encountered with loading GPS dropsondes. The structure separating the individual bins in the dispenser was made more rigid so that the required dimensional tolerances could be maintained after installation in the aircraft. The original design had been made as light as possible to address uncertainties in the allowable payload weight in the rear of the Global Hawk aircraft. The structural modifications to resolve the dropsonde loading issues made this more rigid, which resulted in a weight increase to the dispenser, but the experience gained by NASA since the start of the Global Hawk science flights established that greater weights could be safely accommodated in that zone of the aircraft.

U.S. Collaborations

During the 2016 SHOUT ENRR campaign, the NOAA UAS Program collaborated with several government and university groups that were participating in the larger NOAA El Niño Rapid Response Campaign. These partners included NOAA ESRL/PSD, NOAA/NCEP, the NOAA National Weather Service, Observing Services Division, the NOAA Office of Marine and Aviation Operations, the Air Force Reserve Command 53rd Weather Reconnaissance Squadron, and the Cooperative Institute for Research in the Atmosphere (CIRA), and the Colorado State University Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado. Several airborne and ground-based assets were incorporated into this joint three-month campaign, including the Global Hawk, NOAA G-IV jet, two Air Force WC-130Js, twice daily rawinsonde launches from Kiritimati (Christmas) Island, Kiribati, and a scanning X-band radar positioned in San Francisco, California. Coordination between the NOAA UAS Program and its partners during the NOAA El Niño Rapid Response Campaign resulted in the collection of an unprecedented dataset during one of the top three strongest El Niño events on record.

6 2016 SHOUT HURRICANE RAPID RESPONSE

The final Global Hawk observational campaign supported through the SHOUT project was conducted between August-October 2016 to address potential improvements in forecasts of TCs. The 2016 Hurricane Rapid Response (HRR) campaign focused on maximizing the opportunity for capturing suitable scientific targets, reducing costs, and demonstrating a mission concept for future potential operational surveillance and reconnaissance flights of the Global Hawk. The aircraft and experimental teams were scheduled for an extended two-month period from August-September with the goal of conducting up to eight 24 h flights studying high-impact targets. To avoid the high costs associated with deploying personnel for the full two-month period the campaign planned for staff to travel once a target was identified and would remain deployed only during the period of the missions. The goal of this rapid response model was to identify flight opportunities and deploy personnel 72 h in advance of a potential mission. The 2016 SHOUT HRR campaign was highly successful in this regard with a total of nine Global Hawk flights conducted that observed four different named storms, including two landfalls, between 24 August and 10 October. A notable highlight was the ability to conduct three back-to-back (i.e., three flights flown every other day for seven days) high-profile missions studying Hurricane Matthew in early October after the originally scheduled campaign completion date at the end of September. This supplementary series of Matthew missions also included a change in staging bases from east (WFF) to west coasts (AFRC) and again demonstrated program flexibility that was first executed during the 2015 SHOUT Hurricanes campaign. With the exception of aircraft personnel and one member of the AVAPS team, staff were able to deploy and support the missions with as little as 48 h notice. Improvements in operational efficiency were also achieved through reduced staffing and increased remote participation. Further discussion of the benefits and success of the rapid response deployment model is included in the SHOUT cost study analysis document (Kenul et al. 2018).

Operations Overview

The 2016 SHOUT HRR operations were conducted from both NASA AFRC and WFF. The study of Atlantic storms was prioritized due to their generally greater forecast uncertainty and potential impact on the U.S. coastal population, but the option was preserved to also observe eastern North Pacific storm targets early in the campaign. Space and operational constraints at NASA WFF prevented deployment of the Global Hawk to the U.S. East Coast any earlier than 11 August. During the period from 1-15 August, potential eastern North Pacific and Atlantic basin storms reachable from AFRC were monitored, but no suitably high-impact targets were identified. Therefore, the Global Hawk was transited to WFF on 18 August. Six missions over three named storms were conducted from WFF between 24 August and 25 September. Additional specific details on these flights are included in Section 6.3. While Hurricane Matthew had been identified as a potential target-of-interest prior to the end of September, staffing plans developed for the originally-defined experiment period and additional travel constraints associated with the end of the fiscal year necessitated transit of the Global Hawk back to its home base at AFRC before the start of the Matthew flights. Three Hurricane Matthew flights were then conducted between 5-10 October from AFRC with staffing using facilities at both AFRC and WFF.

Mission Design and Targeting

As for all previous SHOUT flights, the designs for 2016 SHOUT HRR Global Hawk missions had the goal of collecting data that would optimize potential forecast impact and reduce forecast uncertainty. For hurricane and tropical storm targets, the objective specifically focused on the potential to improve forecasts of storm track and intensity. To help accomplish this, targeting strategies based on identification of regions of greatest forecast sensitivity were again employed.

The primary hurricane and tropical storm adaptive sampling computations were performed by a team led by Ryan Torn at the University at Albany-SUNY using the techniques described in Section 4.2. Similar to the 2015 SHOUT Hurricanes campaign, adaptive sampling targets during the 2016 SHOUT HRR campaign were based on ensembles of forecasts from the Hurricane Weather Research and Forecast (HWRF) model. However, this campaign expanded the computations to include the global European Centre for Medium-Range Weather Forecasts (ECMWF) model. An example of the track forecast sensitivity output is shown in Figure 6.1 for the first of the Hurricane Matthew flights (see Section 6.3.7). Results from the computations were placed on a web page and e-mailed to mission scientists along with a discussion providing guidance on interpreting the results. The targeted lead time for achieving forecast improvements was in the two- to three-day range depending on specifics of the storm such as potential landfall.

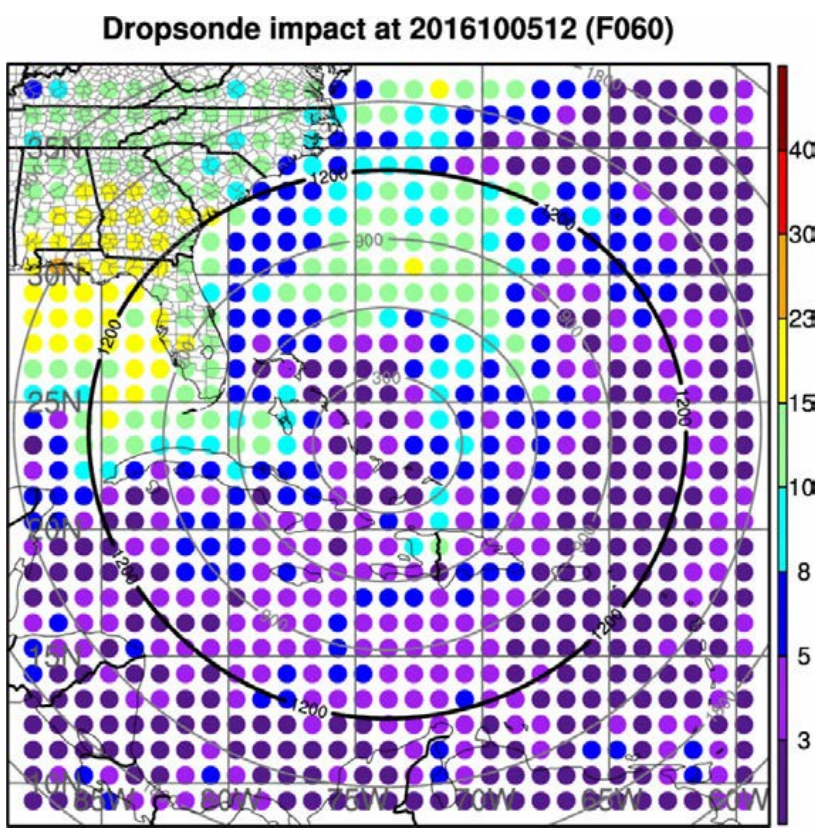

Figure 6.1. Example of the TC targeting outputs used in Global Hawk mission design showing track sensitivity computed from the HWRF model for a 60-h forecast of Hurricane Matthew valid for 5 October 1200 UTC. Numerical values represent the percent reduction in forecast variance resulting from assimilation of a GPS dropsonde observation at that location. Warm colors indicate the greatest impact. Graphic provided by Dr. Ryan Torn.

Additional targeting guidance was provided by James Doyle from the Naval Research Laboratory, Monterey - at no cost to the 2016 SHOUT HRR project. The technique he employed was based on an adjoint methodology applied to forecasts from the Coupled

Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) modeling system (Doyle et al. 2012; Doyle et al. 2014). The guidance, while distinct and different in some details, generally highlighted similar regions and meteorological features as priorities for sampling that were indicated in the previously discussed adaptive sampling analyses (Section 4.2).

Global Hawk flight plans were constructed by SHOUT mission scientists based on guidance from the targeting computations, storm characteristics, and other inputs from the operational community (e.g., NOAA EMC and NHC). The primary flight plan element employed for the TC flights were variably sized rotated butterfly patterns centered on the expected storm position. The sensitivity to evolution of storm intensity was usually greatest for observations closely centered on the inner core of the system. Over-storm sampling was also emphasized to take advantage of the unique observations provided by the remote sensing payloads. The butterfly patterns emphasize this sampling of the center of the system while providing good azimuthal and radial distributions of observations surrounding the storm. The orientation and extent of the legs of the butterfly pattern were designed to capture the additional guidance provided by the forecast sensitivity calculations. The route of transit to the storm and additional sampling displaced from the storm center were based heavily on the forecast track sensitivity results. The simultaneous presence of multiple storm systems on a couple of occasions also provided the opportunity to collect observations in support of forecasts of more than one storm. A final objective considered in flight plan design was sampling of TC outflow in support of complementary TCI project goals.

Key guidance on additional regions for dedicated sampling was provided by NOAA NHC for some flights. This input was based primarily on the scheme used operationally at NHC for designing environmental targeted GPS dropsonde sampling with the G-IV aircraft (Aberson and Franklin 1999; Aberson 2002). The incorporation of this guidance is evidence of the close coordination between SHOUT and other operational NOAA activities and provides a model of how the Global Hawk could potentially be used as an operational platform in the future.

Flight Summary and Instrument Performance

An overview of the flight tracks of the nine missions conducted during the 2016 SHOUT HRR campaign is shown in Figure 6.2 and key statistics are summarized in Table 6.1. The four named storms included Hurricanes Gaston and Hermine, Tropical Storm Karl, and Hurricane Matthew. Overall, 648 GPS dropsondes were deployed over 214 h of Global Hawk science flights.

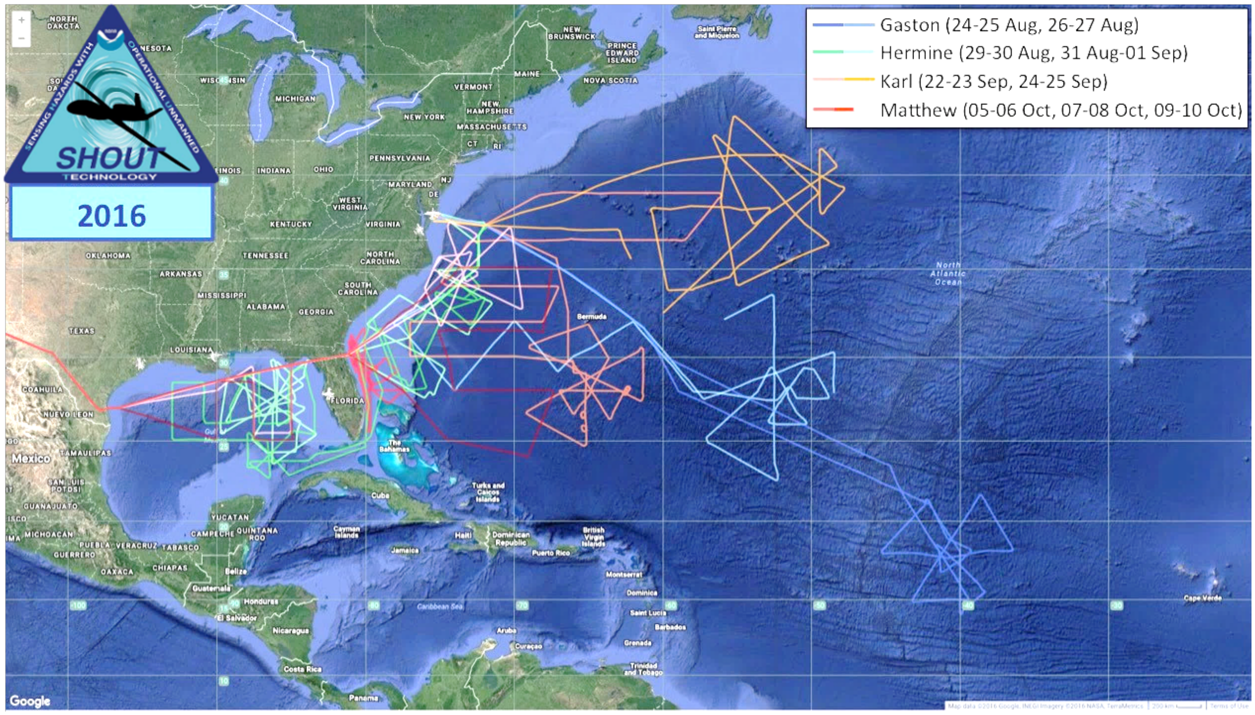

Figure 6.2. Map of the Global Hawk flight tracks conducted during 2016 SHOUT HRR. Graphic generated using NASA's Mission Tools Suite (MTS).

Table 6.1. Summary of Global Hawk flights conducted during the 2016 SHOUT HRR campaign.

Dates (2016)	Target	Duration (hours)	No. Dropsondes Deployed
24-25 August	Gaston	23.9	85
26-27August	Gaston	23.8	55
29-30 August	Hermine	23.8	90
31 August – 1 September	Hermine	22.8	87
22-23 September	Karl	24.0	82
24-25 September	Karl	22.8	81
5-6 October	Matthew	24.7	62
7-8 October	Matthew	23.7	43
9-10 October	Matthew	24.8	63

6.1.1 2016 SHOUT HRR Campaign – Mission 1

The first two 2016 SHOUT HRR flights studied Tropical Storm/Hurricane Gaston. The first mission was conducted on 24-25 August. Gaston was declared a tropical storm by NOAA NHC on 23 August and was forecast to further intensify to hurricane strength over the next couple of days. The storm was expected to remain over open water, but its potential for notable intensification made it a target of interest. Forecast models showed reasonably good agreement in the near term (i.e., 0-72 h) but increased uncertainty beyond about three days surrounding its expected recurvature. The lack of initial uncertainty caused some concern regarding its early targeting, but sampling was desirable over several model cycles leading up to the period of greater uncertainty. The Global Hawk flight plan included large and small butterfly elements centered over the storm, as well as sampling of an upstream trough region on the inbound and outbound legs that was specifically requested by NOAA NHC. Sampling of the system proceeded as planned with minor deviations to avoid overflying peak convection with high cloud top heights during some center crossings. GPS dropsonde data from the Global Hawk was explicitly cited in three consecutive NOAA NHC real-time forecast discussions (Table 6.2) and Gaston was upgraded to hurricane status based directly on observations from the last Global Hawk center overpass. All instrumentation performed well throughout the flight with the exception of an issue loading GPS dropsondes from the final AVAPS dispenser bin during the transit back to WFF. HIWRAP reflectivity data provided detail on convective and stratiform precipitation structure and cloud top heights from the Gaston center crossings.

6.1.2 2016 SHOUT HRR Campaign – Mission 2

The second Gaston mission was conducted on 26-27 August, completing a back-to-back flight sequence. Gaston had weakened, returning to tropical storm strength prior to the start of the mission. Model forecast uncertainty with Gaston had increased, particularly regarding the location of potential recurvature. During the day prior to the mission, there was also concern about the potential development of disturbance AL99, which later became Hurricane Hermine, and its potential risk to the southeast U.S. coastline. In addition to small and large butterfly elements over Gaston, the flight plan included environmental sampling of a potential vorticity streamer which showed sensitivity for impacting the forecasts of AL99. During initial transit, the NOAA NHC also identified a new disturbance, AL91, south of Bermuda, and requested that the environmental sampling be altered to transect AL91 and include deployment of six GPS dropsondes.

The mission achieved sampling of AL91, the environment influencing AL99, and Gaston, demonstrating how the long endurance capability of the Global Hawk can be used to optimize sampling of tropical cyclone targets. After completion of the small butterfly pattern, with a large deviation on the first leg to avoid strong convection, and the first leg of the large butterfly, the AVAPS primary electronics board ceased functioning after the 55th drop. Options to return early or alter the flight pattern were considered, but the 2016 SHOUT HRR science leads decided to complete the large butterfly as planned. The next-to-last center crossing had to be displaced slightly to avoid convection, but the final leg provided excellent data from HIWRAP and HAMSR over the storm center. HIWRAP and HAMSR again performed well, although a minor anomaly prevented the real-time return of HAMSR data through much of the flight.

6.1.3 2016 SHOUT HRR Campaign – Mission 3

Initially, a third Gaston mission had been planned for takeoff on 28 August, but AVAPS repairs required more time and the day was allotted to returning AVAPS to operational status. During this period, AL99 intensified into Tropical Depression Nine (TD 9) and forecasts indicated the system could potentially impact the U.S. as a tropical storm. Gaston also intensified and appeared likely to reach major hurricane status, but forecasts indicated relatively low uncertainty. There was substantial discussion amongst the 2016 SHOUT HRR science team of whether to conduct a third mission into Gaston, collecting observations of a strong, mature storm, or change focus to a system with greater potential societal impact and more forecast uncertainty. The 2016 SHOUT HRR science leads decided that sampling TD 9 was more consistent with SHOUT objectives centered on improving forecasts of high-impact weather events. In a future operational framework where NOAA NHC watches and warnings for U.S. coastal populations are critical, priority for Global Hawk operations would likely be given to storms threatening the U.S. Along with the development of TD 9, AL91 also strengthened into Tropical Depression Eight (TD 8) and moved towards the U.S. east coast near the Carolinas. While the system posed little significant threat to the US, its forecasts exhibited uncertainty and some model runs strengthened it to a tropical storm just off the coastline. While not viewed as a system worthy of a dedicated mission, its position close offshore lent itself to joint sampling during a transit to either TD 9 or Gaston.

The third 2016 SHOUT HRR mission, conducted on 29-30 August, was the first of two flights to study TD 9, which subsequently became Hurricane Hermine. Forecast uncertainty in the track of TD 9 was substantial, showing wide differences in potential landfall locations in Florida. The flight plan included sampling of TD 8 along the U.S. mid-Atlantic coast during transit, adaptive aircraft sampling of the environment both off the east Florida coast and over the Gulf of Mexico in support of forecast uncertainty associated with TD 9, and two figure-four patterns over TD 9. While air traffic control and airspace issues necessitated several modifications to the Global Hawk track during the flight, elements of each component were maintained. The instrument performed very well throughout the flight and the entire capacity of 90 GPS dropsondes were deployed. This represented a new record for GPS dropsondes deployed from the Global Hawk in a single flight. GPS dropsonde data were again cited in a NOAA NHC forecast discussion of TD 9 and were used to help justify maintaining the system at tropical depression strength (Table 6.2).

Table 6.2. National Hurricane Center tropical cyclone forecast discussions that included mention of Global Hawk data during the 2016 SHOUT HRR campaign, where UTC = Coordinated Universal Time and TD= Tropical Depression.

Date/Time (2016)	Target	NOAA National Hurricane Center URL
24 Aug 2100 UTC	Gaston	http://www.nhc.noaa.gov/archive/2016/al07/al072016.discus.009.shtml?
25 Aug 0300 UTC	Gaston	http://www.nhc.noaa.gov/archive/2016/al07/al072016.discus.010.shtml?
25 Aug 0900 UTC	Gaston	http://www.nhc.noaa.gov/archive/2016/al07/al072016.discus.011.shtml?
30 Aug 0900 UTC	TD 9	http://www.nhc.noaa.gov/archive/2016/al09/al092016.discus.007.shtml?
1 Sep 1500 UTC	Hermine	http://www.nhc.noaa.gov/archive/2016/al09/al092016.discus.016.shtml?
25 Sep 0300 UTC	Karl	http://www.nhc.noaa.gov/archive/2016/al12/al122016.discus.043.shtml?
25 Sep 0900 UTC	Karl	http://www.nhc.noaa.gov/archive/2016/al12/al122016.discus.044.shtml?
25 Sep 1500 UTC	Karl	http://www.nhc.noaa.gov/archive/2016/al12/al122016.discus.045.shtml?

Date/Time (2016)	Target	NOAA National Hurricane Center URL
9 Oct 1500 UTC	Matthew	http://www.nhc.noaa.gov/archive/2016/al14/al142016.discus.046.shtml?
9 Oct 2100 UTC	Matthew	http://www.nhc.noaa.gov/archive/2016/al14/al142016.discus.047.shtml?

6.1.4 2016 SHOUT HRR Campaign – Mission 4

The fourth flight and second in a back-to-back sequence into TD 9/Tropical Storm Hermine was conducted on 31 August to 1 September after the storm had strengthened to a tropical storm. The objectives, motivated by the extent and magnitude of forecast sensitivity calculations, included sampling directly over Hermine in an aircraft reconnaissance mode (i.e., storm sampling focus) prior to its predicted landfall as well as additional environmental sampling off the east Florida coast in an aircraft TC surveillance mode (i.e., environmental sampling focus). Initial sampling had to circumnavigate portions of the storm due to intense convection while the Global Hawk was still at a relatively low altitude early in flight. Later legs of subsequent butterfly patterns provided multiple good storm overpasses. Hermine increased to hurricane strength during the latter portion of the flight just after direct Global Hawk sampling of the storm had concluded. The only instrumentation issue encountered was a partial outage of HAMSR real-time data transmission, but the data collected on the aircraft was not affected.

Subsequent operations from WFF were hampered by poor local weather and the requirement for a chase plane during Global Hawk takeoff and landing. A single mission was planned for Tropical Storm Ian with a takeoff on 15 September, but the flight had to be cancelled due to forecasts for poor local weather at the planned landing time.

6.1.5 2016 SHOUT HRR Campaign – Mission 5

The fifth and sixth 2016 SHOUT HRR missions targeted Tropical Storm Karl with the first flight taking place on 22-23 September. The first flight was originally planned to start on 21 September, but the mission had to be delayed a day due to low cloud ceilings at WFF at takeoff time. Forecasts of Karl were particularly challenging with model disagreement on the time and amount of potential intensification. The Global Hawk flight plan included a lawnmower pattern to the northwest of the storm sampling a region of computed track sensitivity and then small and large butterfly elements centered over the storm. The flight incorporated significant coordination with NOAA and Air Force aircraft and a coordinated transect was flown with the NOAA WP-3D to directly compare coincident GPS dropsonde data from the WP-3D and Global Hawk and collocated retrievals from HIWRAP and the WP-3D NOAA National Environmental Satellite Data and Information Service (NESDIS) Imaging Wind and Rain Profiler (IWRAP). Global Hawk instrumentation performed well until AVAPS had a failure loading from the final bin during the last leg of the large butterfly pattern. The path of the leg was modified to optimize the HIWRAP sampling of convection which had increased during the latter portion of the flight. Following landing, the crew performed a rapid turn-around of the aircraft enabling a second flight over Karl. While normal crew cycles dictate a takeoff approximately 24 hours after a landing, the aircraft was prepared for takeoff just 20.5 hours after completion of the first flight. The rapid reset was critical because local weather was forecast to degrade later in the afternoon and the storm was rapidly accelerating to the northeast making sampling increasingly difficult.

6.1.6 2016 SHOUT HRR Campaign – Mission 6

The second flight into Tropical Storm Karl on 24-25 September chased the storm while it rapidly accelerated to the northeast as was forecast to begin undergoing extratropical transition. The flight was highly significant for its international coordination with the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX) and other NOAA aircraft conducting Intensity Forecasting EXperiment (IFEX) missions (i.e., a WP-3D and the G-IV jet; Rogers et al. 2013). The Global Hawk flight pattern provided continuity in observations of the storm leading up to further downstream sampling by NAWDEX that was operating aircraft south of Iceland. Together, the observations from all the aircraft involved provided unique sampling of the full lifetime of a complex storm. Forecasts of the storm's extratropical transition exhibited notable downstream predictability issues and analysis of observations from the entire storm should enable a good assessment of the value of targeted observations. Global Hawk reconnaissance sampling strategies included multiple butterfly elements while following the storm motion. A coordinated leg was flown with the NOAA G-IV aircraft early in the mission. Strong convection and very high cloud tops reflected the storm intensity early in the flight but posed sampling challenges for the Global Hawk. By the end of the flight, the cloud top heights had dropped significantly. Observations from the Global Hawk were acknowledged in two consecutive NOAA NHC discussions for Karl, providing documentation of the evolution of the intensity and character of the system. Continued anomalies were anticipated with one of the AVAPS dispenser bins, and usage of that bin was deferred to the end of the mission where a load failure did again occur.

6.1.7 2016 SHOUT HRR Campaign – Mission 7

The 2016 SHOUT HRR operations were extended for an additional week enabling a three-consecutive flight sequence targeting forecasting of the high-profile Hurricane Matthew. The extension was made possible by operational flexibility and tremendous interagency coordination. Because of cost constraints and end of the fiscal year travel limitations, the Global Hawk was first transited back to AFRC and the Matthew missions were flown from there. Science operations used the control rooms at both AFRC and WFF to reduce costs and simplify travel.

The first Hurricane Matthew mission was flown on 5-6 October while the storm was located near the Bahamas. Because of restrictions on flight of the Global Hawk over land, the mission was constrained solely to environmental sampling which was planned over the Gulf of Mexico and east of the Florida, Georgia, and Carolina coasts. The corresponding computed track uncertainty used in the planning was shown in Figure 6.1. The flight was still deemed highly valuable because of the significant forecast track uncertainty and associated questions of whether the storm would directly impact the U.S. Actual sampling included only 11 of 16 planned drops over the Gulf of Mexico due to airspace and air traffic issues. Operations during the remainder of the mission went very well with no instrumentation anomalies and the addition of rapid deployment of a couple of GPS dropsondes to sample Matthew's upper-level outflow.

6.1.8 2016 SHOUT HRR Campaign – Mission 8

The second Matthew mission was conducted on 7-8 October and included extensive observations over and around Matthew while it was located just off the Florida coast. Multiple legs were flown directly over the storm center. A recurrence of AVAPS launcher anomalies prevented GPS dropsonde deployments through much of the flight, but operations were restored by the end of the mission when GPS dropsonde were successfully dispensed in both the eyewall and over the center of the storm during the course of the flight. The HAMSR and HIWRAP instruments both performed very well, collecting valuable over-storm data.

6.1.9 2016 SHOUT HRR Campaign – Mission 9

The final Matthew mission was flown on 9-10 October. At takeoff, Matthew was located just off the coast of North Carolina and had weakened significantly since the previous flight. While still classified a hurricane with tropical characteristics at departure, the storm became post-tropical, with hurricane force winds, during the flight. The flight included abbreviated environmental sampling over the Gulf of Mexico and butterfly elements tracking the storm motion. Global Hawk observations were again cited in two consecutive NOAA NHC discussions and used to help characterize the storm's intensity (Table 6.2). All instrumentation performed without error during the mission, though targets for HIWRAP were more limited than in the previous mission.

Data Delivery and Utilization

While the primary objective of the 2016 SHOUT HRR flights was to collect observations to support forecast impact and data denial studies, real-time data from the Global Hawk was used significantly by operational forecasting and modeling groups. The Global Hawk GPS dropsonde data were again assimilated operationally in the HWRF model by NCEP/EMC and in the global ECMWF model. The data were made available to the operational centers through normal real-time submission to the GTS. Assimilation of the data within HWRF began with the 2015 SHOUT Hurricanes flights and was exercised more extensively during the 2016 SHOUT HRR field campaign with the larger number of flights. A preliminary analysis by Jason Sippel from NOAA of the impact of the data from one storm on the operational HWRF model at NCEP/EMC is reviewed in Wick et al. (2018). Informal communication between SHOUT project members and personnel from ECMWF during the mission confirmed that the Global Hawk GPS dropsonde data were being successfully assimilated into the ECMWF model.

Data from the NRD-94 GPS dropsondes used on the Global Hawk were not assimilated operationally in the NOAA GFS model during the 2016 SHOUT HRR campaign. The issue is tied to the GPS dropsonde type and not specifically their deployment from the Global Hawk platform. The importance of this problem was emphasized when the NOAA G-IV experienced mechanical problems and was unable to fly for a portion of the season. The National Science Foundation (NSF) NCAR G-V was enlisted to fly replacement missions, but that platform had most recently utilized the NRD-94 GPS dropsondes as on the Global Hawk. The aircraft had to be retrofitted to accommodate the larger, operational, RD-94 dropsondes again, at the expense of both time and money (note that both dropsonde types use the identical sensor modules). Based upon initial positive impact studies described in Wick et al. (2018), additional efforts have been exercised to facilitate the assimilation of the NRD-94 data within GFS during the 2017 hurricane season. Approximately 30 NRD-94 GPS dropsondes were deployed from the NOAA WP-3D aircraft during Hurricane Matthew flights, interspersed with normal RD-94 dropsondes to compare their data. While intercomparisons between data from the NRD-94 and RD-94 deployed from the Global Hawk and NOAA G-IV, respectively, during the NASA HS3 field campaign showed the dropsondes to respond very similarly in clear air conditions, the new comparisons should further verify their similar performance in a storm environment. The SHOUT-supported data impact studies described by Wick et al. (2018) provides other critical evidence that use of the data within the GFS does have a positive impact on model performance and in addition, a positive impact upon HWRF, which uses GFS boundary conditions.

Real-time data from the Global Hawk was also shared with and used by forecasters at NOAA NHC. Observations from the GPS dropsondes made available through the GTS were accessed and cited frequently by NHC forecasters in their regular forecast discussions as noted in Table 6.2. In total, ten different forecast discussions spanning each of the storms studied made explicit mention of the Global Hawk GPS dropsonde data, including the case where Gaston was upgraded to a hurricane based on the data. Real-time graphics of products from HAMSR and HIWRAP of interest to NHC were also made available via a dedicated web page, but those products were not extensively utilized. A post-mission discussion with NHC forecasters emphasized the need to have data made available through their Advanced Weather Interactive Processing System (AWIPS) for rapid and integrated access, because of the very tight time constraints on the forecasters during their shifts.

U.S. and International Collaborations

The 2016 SHOUT HRR mission coordinated closely with U.S. research and operational TC monitoring missions as well as two international programs. Daily coordination calls were held with representatives from NOAA IFEX and the Air Force Reserve Command 53rd Weather Reconnaissance Squadron discussing joint sampling opportunities and any potential deconfliction with planned GPS dropsonde locations and frequencies. Several coordinated sampling legs were flown between the Global Hawk and other NOAA aircraft. As was the case during the 2015 SHOUT Hurricanes campaign, participants from the ONR TCI project were embedded in the group of SHOUT mission scientists under TCI funding and provided key input on potential observations of interest to the TCI objectives as well as essential mission support.

International coordination occurred with the international Next Generation Aircraft Remote-Sensing for Validation Studies (NARVAL) and North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX). The Deutsches Zentrum für Luft- und Raumfahrt (DLR) Falcon and High Altitude, Long Endurance (HALE) aircraft were deployed from Bridgetown, Barbados from 20 June to 31 August as part of NARVAL with the goal of analyzing organized convection in the deep tropics (see, e.g., http://www.halo.dlr.de/science/missions/narval2/narval2.html). The same aircraft were then deployed to Keflavik, Iceland from 19 September to 16 October for NAWDEX with the overarching goal of understanding disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather events in Europe (http://www.pa.op.dlr.de/nawdex/). Clearly, important overlap exists between the SHOUT and NAWDEX objectives. While individual mission plans were shared and discussed with the NARVAL investigators, operational constraints and differing mission priorities limited direct flight coordination. Significant, mutually beneficial collaboration was achieved with NAWDEX, particularly associated with observations of Tropical Storm Karl. Karl was sampled at multiple stages of its lifecycle by the Global Hawk and NAWDEX aircraft (see Section 6.3), and joint analysis of the data will be valuable for evaluation of forecasts of its evolution and impacts.

7 CONCLUDING ASSESSMENT

The NOAA UAS program office successfully conducted three Global Hawk field campaigns consisting of 15 total missions from 2015 to 2016 in support of its SHOUT project. SHOUT's overarching goal was to demonstrate and test a prototype UAS concept of operations that could be used to mitigate the risk of diminished high impact weather forecasts and warnings in the case of polar-orbiting satellite observing gaps. Using this goal as a guide, the NOAA UAS Program focused on two operational forecast-related goals: 1) assess the impact and optimization of UAS data on model forecasts of high impact weather; and 2) perform a cost-operational benefit analysis that quantifies the cost and operational benefit of UAS observing technology for high impact weather prediction. During the three field campaigns, the Global Hawk aircraft proved to be an effective platform for addressing the various SHOUT scientific objectives, instrument performance was generally quite reliable, and the adaptive sampling techniques for targeting GPS dropsonde sampling that were employed proved effective in helping to guide missions and optimize SHOUT goals. Data that was collected during SHOUT has been extensively used in formal impact studies as documented by Wick et al. (2018) and was also extensively utilized in real time by forecasters at NOAA NHC. NOAA/EMC's analyses of the impact of Global Hawk GPS dropsondes on the GFS model were particularly significant, demonstrating multi-storm average track skill improvements exceeding 10% and improvements for individual storms of over 20% depending on forecast lead time. The results also showed improvements in the track forecasts of concurrent Pacific cyclones based on observations of the Atlantic storms, suggesting that the observations could have positive larger- scale impacts. These results indicate that the SHOUT field campaigns and Global Hawk missions that were flown have provided significant advancements for optimizing the Global Hawk UAS to study and improve forecasts of high impact weather. The wealth of lessons learned from those missions have helped provide operational experience applicable to potential future NOAA field campaigns.

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REFERENCES

Aberson, S. D., 2002: Two years of operational hurricane synoptic surveillance. *Wea. Forecasting*, **17**, 1101–1110.

Aberson, S.D and J. L. Franklin, 1999: Impact on hurricane track and intensity forecasts of GPS dropwindsonde observations from the first-season flights of the NOAA Gulfstream-IV jet aircraft. *Bull. Amer. Meteor. Soc*., **80**, 421–427.

Bishop, C. H. and Z. Toth, 1996: Using ensemble to identify observations likely to improve forecasts, Preprints*, 11th Conf. on Numerical Weather Prediction*, Norfolk, VA, Amer. Meteor. Soc., 72–74.

Cecil, Daniel J. and Sayak K. Biswas, 2017: Hurricane Imaging Radiometer (HIRAD) Wind Speed Retrieval Assessment with Dropsondes, *OFCM, TCORF/ 71st IHC*, Session 4, Rosenstiel School of Marine and Atmospheric Science, U. Miami, Virginia Key, FL, 13-16 March.

Doyle, J.D., C.A. Reynolds, C. Amerault, and J. Moskaitis, 2012: Adjoint Sensitivity and Predictability of Tropical Cyclogenesis. *J. Atmos. Sci.*, **69**, 3535–3557.

Doyle, J.D., C. Amerault, C.A. Reynolds, and P.A. Reinecke, 2014: Initial Condition Sensitivity and Predictability of a Severe Extratropical Cyclone Using a Moist Adjoint. *Mon. Wea. Rev.*, **142**, 320–342, https://doi.org/10.1175/MWR-D-13-00201.1

Doyle, J.D., J. R. Moskaitis, J. W. Feldmeier, R. J. Ferek, M. Beaubien, M. M. Bell, D. L. Cecil, R. L. Creasey, P. Duran, R. L. Elsberry, W. A. Komaromi, J. Molinari, D. R. Ryglicki, D. P. Stern, C. S. Velden, X. Wang, T. Allen, B. S. Barrett, P. G. Black, J. P. Dunion, K. A. Emanuel, P. A. Harr, L. Harrison, E. A. Hendricks, D. Herndon, W. Q. Jeffries, S. J. Majumdar, J. A. Moore, Z. Pu, R. F. Rogers, E. R. Sanabia, G. J. Tripoli, and D. Zhang, 2017: A View of Tropical Cyclones from Above: The Tropical Cyclone Intensity Experiment. *Bull. Amer. Meteor. Soc*., **98**, 2113–2134.

Hock, T. F. and J. L. Franklin, 1999: The NCAR GPS dropwindsonde. *Bull. Amer. Meteor. Soc*., **80**, 407–420.

Hood, R.E., D.J. Cecil, F.J. LaFontaine, R.J. Blakeslee, D.M. Mach, G.M. Heymsfield, F.D. Marks Jr., E.J. Zipser, 2006: Classification of tropical oceanic precipitation using high-altitude aircraft microwave and electric field measurements, *J. Atmos. Sci*., **63**, 218-233.

Kenul, P., J. Coffey, J. Walker, A. Roberts, and J. Huning, 2018: Sensing Hazards with Operational Unmanned Technology: Cost Study of Global Hawk Unmanned Aircraft System Operations for High Impact Weather Observations, Final Report. NOAA Tech Memo. OAR-UAS-003, 43 pp.

Lambrigtsen, B., S. Brown, A. Braverman, H. Nguyen, and Y. Yaglovskaya, 2009: Measuring the three-dimensional structure of hurricanes with a microwave sounder, *Interdepartmental Hurricane Conference*, St. Petersburg, FL.

Langland, R. H., R.L. Elsberry, and R.M. Errico, 1995: Evaluation of physical processes in an idealized extratropical cyclone using adjoint sensitivity. *Q.J.R. Meteorol. Soc*., **121**: 1349–1386.

Lihua, L., G. Heymsfield, J. Carswell, D. Schaubert, M. Mclinden, M. Vega, and M. L. Perrine, 2011: Development of the NASA High-Altitude Imaging Wind and Rain Airborne Profiler, *2011 IEEE Aerospace Conference*, Big Sky, MT, pp. 1–8, https://doi.org/10.1109/AERO.2011.5747415.

Rogers, R., S. Aberson, A. Aksoy, B. Annane, M. Black, J. Cione, N. Dorst, J. Dunion, J. Gamache, S. Goldenberg, S. Gopalakrishnan, J. Kaplan, B. Klotz, S. Lorsolo, F. Marks, S. Murillo, M. Powell, P. Reasor, K. Sellwood, E. Uhlhorn, T. Vukicevic, J. Zhang, and X. Zhang, 2013: NOAA'S Hurricane Intensity Forecasting Experiment: A progress report. *Bull. Amer. Meteor. Soc.*, **94**, 859–882.

Wick, G., J. Dunion, and J. Walker, 2018: Sensing Hazards with Operational Unmanned Technology: Impact Study of Global Hawk Unmanned Aircraft System Observations for Hurricane Forecasting, Final Report. NOAA Tech Memo. OAR-UAS-002, 93 pp.