2022 NOAA/AOML/HRD Hurricane Field Program - APHEX

MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Surface Wind and Wave Validation Module

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Requirements: Categories 2–5

Plain Language Description: This module will collect data in mature hurricanes to continue improving surface wind speed and rain rate estimates from the Stepped-Frequency Microwave Radiometer (SFMR) and understand how the wind speed observations from the SFMR, flight-level winds, dropsondes, tail-Doppler radar (TDR) and, Imaging Wind and Rain Airborne Profiler (IWRAP) relate to each other and to a 1-minute mean (or sustained) wind. It will also aid the development of surface wind products from synthetic aperture radar (SAR) satellites. Additionally, surface wave observations will be verified and the extent of 8 ft significant wave height waves will be identified. Improved measurements from the SFMR and understanding how the various aircraft-based wind observations relate to each other and to a 1-minute mean wind along with improving surface wind products from SAR and our knowledge of the surface wave field have numerous implications for forecasting and research efforts, such as providing more accurate observations to estimate tropical cyclone (TC) intensity and size along with improved estimates of marine hazards and comparisons for satellite observations. These improvements allow for better watches and warnings for a TC's potential impacts to be provided to emergency managers and the general public and leads to more accurate research results.

Mature Stage Science Objective(s) Addressed:

3) Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in mature hurricanes. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds and underlying oceanic conditions [*APHEX Goal 2*]

Motivation: Surface winds in a TC are essential for determining its intensity and size. Over the past several hurricane seasons, surface wind speed estimates from the SFMR, dropsondes, and surface-adjusted flight-level winds in major hurricanes have not been consistent. By obtaining better collocated SFMR, dropsonde, IWRAP, surface wave, and flight-level measurements in major hurricanes we will be able to determine the cause of the inconsistency. Better collocations of the SFMR and dropsondes will lead to improved calibration of the SFMR algorithm for high wind speeds by removing spatial collocation errors related to dropsonde drift

Currently, the SFMR is used for obtaining surface wind measurements at nadir. Due to poor knowledge about sea surface microwave emission at large incidence angles in high wind speed conditions, SFMR winds are only retrieved when the antenna is pointed directly downward from the aircraft during level flight. Understanding the relationship between the SFMR measured brightness temperatures, surface wind speed, wind direction, and the ocean surface wave field at off-nadir incidence angles would allow for the retrieval of wind speed measurements when the aircraft is not flying level. At off-nadir incidence angles the distribution of foam on the ocean surface from breaking waves impacts the SFMR measurements differently than at nadir and is dependent on polarization (Holbach et al. 2018). Therefore, by analyzing the wind-induced brightness temperature at various wind speeds and locations within the TC environment at various off-nadir incidence angles, the relationship between the ocean surface characteristics and the SFMR measurements will be quantified as a function of wind direction relative to the SFMR look angle and polarization.

In addition, there is very little understanding of how the wind data from the SFMR, flight-level, dropsondes, and TDR relate to each other and more specifically how they all relate to a 1-minute mean (or sustained) wind. Some of the discrepancies noticed recently in comparisons of the SFMR, flight-level, and dropsonde winds are likely related to not understanding the time-averaging inherent in the different observations. This lack of knowledge provides a significant barrier to forecasters analyzing the data to produce the most accurate analyses and forecasts of TC intensity and structure.

Satellite SAR provides ultra-high resolution (~25 m) measurements of microwave normalized radar backscatter cross-section (NRCS) off the ocean surface in either (or both) co-polarization or cross-polarization imaging with swath widths of 250 km or 400 km depending on imaging mode. This module will improve our understanding of C-band microwave radar backscatter off the sea surface in extreme wind conditions, improve fine resolution TC wind vector retrievals, explore the capabilities and limitations of high-resolution microwave radar to make quantitative measurements of TC atmospheric boundary layer (ABL) roll eddy characteristics, and, to provide the necessary measurements to further develop methods for SAR-based TC sea-level pressure and mean ABL wind profile retrievals.

The Tropical Analysis and Forecast Branch (TAFB) at the National Hurricane Center (NHC) provides forecasts for significant wave heights of 8 ft and greater in their High Seas product (https://www.nhc.noaa.gov/abouttafbprod.shtml#HSF). These forecasts are important for informing mariners on the sea state conditions they may encounter while traversing the open oceans. The goal of this module is to collect sea state measurements from the Wide Swath Radar Altimeter (WSRA; PopStefanija et al. 2020) to inform the analyses and forecasts produced by TAFB as well as to help calibrate the Wavewatch III and COAMPS-TC ocean wave models. Wave buoy overflights with the WSRA will also provide additional verification of the surface wave data.

Background: Historically, the SFMR served as a research instrument that measured surface wind speeds and rain rates in hurricanes. As early as 1980, data were collected to estimate surface wind speeds from the breaking waves on the sea surface, but they were used in a limited capacity due to various errors. Beginning in 1998-1999, SFMR data were regularly collected on the NOAA P-3 aircraft with reasonable estimates of surface wind speeds, but an algorithm upgrade in the mid-2000s significantly improved the data (Uhlhorn et al. 2007). The SFMR still struggled at the low wind regime and within rainy conditions, which prompted a second algorithm update that became operational in 2015 (Klotz and Uhlhorn 2014). Another algorithm update is under development to correct an overestimate at high wind speeds (≥ 100 kts).

Currently, if the aircraft pitch or roll angle exceeds a threshold of ± 10°, surface wind speed and rain rate are not reported by the SFMR. These thresholds result in surface wind speeds not being provided when the aircraft turns or if the aircraft exceeds the pitch threshold, for example, while flying a constant pressure surface through the eyewall where the highest wind speeds are usually measured. By improving our understanding of the physics of the air-sea interaction between the wind and sea surface in the extreme environment of TCs, it will be possible to develop corrections for the SFMR algorithm to obtain surface wind speed measurements when the aircraft is not flying level.

The different technologies and sampling volumes for the SFMR, flight-level, dropsondes, and TDR play a key role in the characteristics of wind they are responding to. For example, dropsondes are point measurements that are being advected by the wind: they respond relatively directly to wind gusts. Whereas the SFMR observes the brightness temperature of the ocean surface with a footprint of about 1 km in diameter and relies on the generation of whitewater on the ocean surface by the wind, integrating the impacts of gusts over that surface area. Even if the temporal averaging were identical and the instruments perfectly calibrated for longer-term averages, the larger spatial averaging makes SFMR observations effectively represent a point observation (like a buoy or dropsonde) at a different temporal averaging scale.

SAR experts Mouche and Chapron at IFREMER in Brest, FR established a *Satellite Hurricane Observations Campaign* (SHOC) that routinely requests all possible SAR images of tropical cyclones (TCs) worldwide from the two Sentinel-1 satellites. By 2019, SHOC had cataloged 200 TC eye images, including 103 from the year 2018. Because of the data demands due to very high resolution, SAR NRCS is not collected continuously. Foster (2017) developed a method for deriving km-scale resolution sea-level pressure patterns from TC SAR images using a simplified version of the similarity TC ABL model described in Foster (2009). When all possible surface pressure differences between pairs of dropsonde observations were compared to those derived from five co-pol SAR images with near-in-time aircraft observations, the RMS error was approximately 3 mb. Similar agreement is found when comparing aircraft flight level estimates of the surface pressure with the SAR images. The available SAR imagery was all co-pol. Hence, the method has not yet been tested for strong TCs.

NHC/TAFB has been producing High Seas forecasts since 2003. The lowest threshold used in the forecasts is a significant wave height of 8 ft. This 8 ft threshold is used by cruise ships to identify areas to avoid. Navy vessels generally tend to avoid 12 ft seas and very large cargo ships often will continue traversing seas up to 20 ft. Observations of the sea state are quite sparse in the open ocean, especially in TCs, and are generally limited to observations by buoys. Sea state observations from the WSRA will provide much needed measurements for informing and validating the High Seas forecasts and improving the Wavewatch III and COAMPS-TC ocean wave models.

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Goal(s): Improve the wind speed and rain rate estimates obtained by the P-3 SFMRs and understand how the wind speed observations from the SFMR, flight-level winds, dropsondes, and tail-Doppler radar (TDR) relate to each other and to a 1-minute mean (or sustained) wind. In addition, improve surface wind products from SAR satellites and NHC/TAFB's High Seas analyses and forecasts and NOAA's Wavewatch III and COAMPS-TC ocean wave models by collecting and validating WSRA significant wave height data in the environment of TCs.

Hypotheses:

1. Collecting directly collocated SFMR and dropsonde data will reduce errors in the high wind speed portion of the SFMR algorithm, which will then translate to reduced errors in SAR satellite surface wind speed estimates.
2. Collecting high-incidence angle SFMR data will allow for quantification of the changes in the SFMR brightness temperatures at off-nadir incidence angles that are related to the wind direction relative to the SFMR look angle and polarization.
3. Collecting SFMR, flight-level, dropsonde, and TDR data over a buoy with a reliable anemometer will allow us to determine the spatial and/or temporal averaging needed to match 1-minute mean winds from buoys.
4. Determining the relationship between the SAR-observed orientations of organized TC boundary layer large eddies and the surface wind directions will improve surface wind vector retrievals. SAR observations and derived products can be used to estimate mean wind profiles in the TC ABL.
5. Collecting and validating WSRA significant wave height data will improve TAFB's High Seas analyses and forecasts as well as help improve the Wavewatch III and COAMPS-TC ocean wave models.

Objectives:

1. Collect collocated SFMR and dropsonde data in high wind regions (surface wind speeds ≥ 100 kts).
2. Collect off-nadir SFMR observations at several different incidence angles in several different storm-relative locations.
3. Collect SFMR, flight-level, dropsondes, and TDR data over buoys.
4. Collect SFMR, dropsonde, flight-level, WSRA (when available), IWRAP (when available), and/or DWL (when available) coincident with SAR data acquisition.
5. Collect WSRA significant wave height data for all regions of the storm with significant wave heights ≥ 8 ft or over wave buoys.

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Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): The goal of the P-3 SFMR validation module is to collect collocated high wind speed (≥ 100 kts) SFMR and dropsonde data. For the single aircraft P-3 SFMR validation module (P-3 Pattern #1), either P-3 (NOAA42 or NOAA43) can be used, but the P-3 with the WSRA is preferred. The P-3 will fly inbound through the eyewall releasing a dropsonde targeting the surface wind speed maximum or a sequence of 3 dropsondes released in rapid succession to increase the odds of observing the surface wind speed maximum. The P-3 will then enter the eye and turn outbound approximately 30–40° azimuthally downwind of the inbound leg to overfly the splash point of the dropsonde. It may be necessary to adjust the azimuthal separation of the inbound and outbound legs to account for eye size, storm strength, and flight altitude. Dropsondes released in hurricanes with smaller eyes tend to drift further downwind than those released in larger eyes. Dropsondes will also drift further downwind in stronger winds, especially if the layer of strong winds is deeper, and dropsondes released from higher altitudes will have more time to drift further downwind. Another option is to wait for the dropsonde(s) to splash, determine the splash location(s), and overfly the exact splash location(s). This will allow for the best spatial collocation; however, the temporal collocation will not be as close.

For the two aircraft P-3 SFMR validation module (P-3 Pattern #2), one P-3 (preferably the P-3 with the WSRA) will fly inbound and release a dropsonde targeting the surface wind speed maximum or a sequence of 3 dropsondes released in rapid succession to increase the odds of observing the surface wind speed maximum. The second P-3 (preferably the P-3 with IWRAP) will fly inbound 30°–40° downwind of the first P-3 and approximately 5-6 min later (or the closest temporal spacing possible for safe operations) to overfly the splash location of the dropsonde(s). The two aircraft can be at different altitudes. As in the single P-3 module, it may be necessary to adjust the azimuthal separation of the two P-3s to account for eye size, storm strength, and flight altitude or to identify the actual splash location of the dropsonde(s).

For the SFMR high-incidence angle module (P-3 Pattern #3), preferably, two down-looking SFMRs should be mounted on the P-3 aircraft. The operational wing-pod mounted SFMR should be operating as usual. A second SFMR or the USFMR is to be mounted parallel to the latitudinal axis of the airframe (rotated 90° from the operational position). When the aircraft rolls, the operational SFMR will be collecting off-nadir data at H-pol and the second SFMR will be collecting off-nadir data at V-pol, simulating the data that the SFMR would collect when the aircraft pitches. The high-incidence angle modules can be flown during any mission with any flight pattern and are designed to obtain SFMR measurements in various locations of the TC environment at several different wind speeds during constant banked aircraft turns at several different roll angles, specified below. A full pattern for each module consists of three complete circles for each specified roll angle. *It is important to maintain as constant of a roll angle, pitch angle, and altitude and to stay within an area of similar surface conditions (i.e., constant surface wind speed, surface wind direction, and swell direction) as possible.* A dropsonde and AXBT pair should be released at the beginning of the pattern. The WSRA, if available, should also be obtaining measurements before, during, and after the pattern for analysis of the ocean surface characteristics. The wave spectra obtained by the WSRA will allow for a more accurate investigation of the sensitivity of the SFMR to the surface wave characteristics. It is ideal to fly these modules in rain-free areas as to reduce the impact of the atmospheric emission on the SFMR measurements and to obtain measurements in regions of moderate to heavy precipitation, as deemed safe by the aircraft pilots, to understand the impact of varying the path length of the precipitation.

Module Options:

1. Zero wind, high incidence angle response
    - This module is designed to determine the antenna pattern corrections and possible impacts of sun glint
    - Fly circles at roll angles of 15, 30, 45, and 60 degrees

2. Moderate wind response (~15 m s^{-1}, 30 kts)
    - This module is designed to understand the mixed "phase" (i.e., foam vs roughness contributions to brightness temperature)
    - Fly circles at roll angles of 15, 30, and 45 degrees

3. Moderate winds (~15 m s^{-1}, 30 kts) and substantial swell or varying fetch length response
    - This module is designed to determine the sensitivity to stress
    - This can be performed on the way to the storm or in different sectors of the storm
    - Fly circles at roll angles of 15, 30, and 45 degrees

4. Strong wind response (>30 m s^{-1}, 60 kts)
    - This module should be flown in multiple storm quadrants (motion relative)
    - Fly circles at roll angles of 15, 30, and 45 degrees

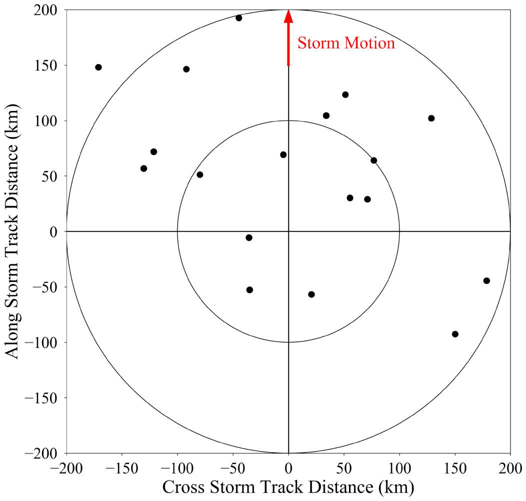

Figure 1: *Storm-relative locations of high-incidence angle SFMR observations obtained in previous seasons.*

Thus far, measurements have been obtained in all storm-relative quadrants (Figure 1). However, there is a lack of observations in the rear storm-relative quadrants. To develop a more complete composite picture, *we are particularly interested in obtaining measurements in the rear quadrants* of storms (motion relative) this season. We would also like to focus on regions with wind speeds greater than 20 m s^{-1} and regions of stratiform precipitation.

The wind buoy overflight module (P-3 Pattern #4) will collect SFMR, flight-level, dropsonde, and TDR data over a buoy with a reliable anemometer. The aircraft will fly parallel to the flight-level wind direction in a region of homogenous wind conditions upwind and downwind centered on the buoy's location for approximately 30 minutes, releasing a dropsonde during each pass over the buoy's location. Performing this module in various storm-relative regions of a TC and at different wind speeds would provide insight into the variability of the relationships, allowing us to determine the spatial and/or temporal averaging of aircraft and dropsonde data needed to match 1-minute mean winds from buoys. This module would preferably be performed in a region of stratiform precipitation to obtain wind speeds from the TDR.

The SAR overflight module (P-3 Pattern #5) is designed to collect aircraft data (SFMR, dropsonde, flight-level, WSRA, IWRAP, and/or DWL) coincident with SAR satellite (Sentinel-1 A & B and RadarSAT-2) image acquisition. No modifications to the flight track are required. SAR image acquisitions will be requested when the swath is forecast to intersect the storm. There will usually be a 24-to-48-hour notice. The ascending passes occur near 1800 local time and descending passes occur near 0600 local time. Ascending SAR acquisitions are eastward of the sub-satellite point approximately 230 to 600 km (125 to 325 nm). Descending SAR acquisitions are westward of the sub-satellite point approximately 230 to 600 km (125 to 325 nm). There are no particular SAR image "sweet spots" to consider.

The wave validation module (P-3 Pattern #6) can be conducted with any of the standard P-3 patterns. Data collection for the WSRA requires a flight radar altitude between 8 and 12 kft. It may be necessary to descend prior to reaching the planned IP to capture the extent of the 8 ft significant wave height waves. Guidance will be provided by the PIs prior to and during the flight on the estimated extent of the 8 ft significant wave height waves. Ideally, the 8 ft threshold would be captured by the WSRA in each quadrant of the storm. However, if it is not possible to observe the 8 ft threshold in each quadrant due to time constraints then it would be preferred to obtain those estimates in at least the front right (storm-relative) quadrant.

Wave buoy overflights (P-3 Pattern #7) should also occur at a flight radar altitude between 8 and 12 kft. The ideal pattern for overflying the buoy is to fly straight and level for 250 seconds (4 minutes and 10 seconds) on the approach to the buoy. Upon reaching the buoy, the aircraft would make a 90° turn (either direction) and fly straight and level for an additional 250 seconds away from the buoy. The 90° turn provides a test for any dependencies of the ocean surface wave data on the aircraft heading and propagation direction of the dominant wave. While the 90° turn is preferred, it is not necessary to provide valuable data for wave validation efforts. The maximum distance from a buoy for good comparison is estimated to be about 50 km. However, this is dependent on the buoy's relative location within the TC.

Links to Other Mature Stage Experiments/Modules: The Surface Wind and Wave Validation Module can be flown in conjunction with the following Mature Stage experiments: Gravity Wave, Ocean Winds, Rainband Complex Survey, RICO SUAVE, and TC Diurnal Cycle.

Analysis Strategy: The SFMR and dropsonde data collected during the P-3 SFMR validation module will be directly compared to identify any inconsistencies in the SFMR algorithm at high wind speeds. These collocated pairs will also be compared to the SFMR and dropsonde data used for the previous algorithm development, which were not directly spatially collocated, to identify the errors that may be present when using those data. Any USFMR or IWRAP data collected with the overflight of the dropsondes will also be used to investigate the dropsonde and SFMR wind data. WSRA data collected in tandem will be used to analyze the surface wave field to identify any surface characteristics that may impact the SFMR observations. It is important that the aircraft maintain as straight and level of flight as possible when collecting the collocated data, so that no additional errors are introduced related to the conditions of flight.

The SFMR high-incidence angle data from these flights will be analyzed to quantify the double harmonic oscillation that is evident in high-incidence angle SFMR data collected during previous seasons (Holbach et al. 2018). The WSRA data will then be used to analyze the differences in the ocean surface characteristics to reveal any possible relationships between the double harmonic oscillation found in the SFMR measurements and the ocean surface characteristics. The surface wind direction from the dropsondes will be used to compute the relative look angle of the SFMR to the surface wind direction. Wind speed from the dropsondes will be used to quantify the differences in the SFMR brightness temperatures expected at nadir with the high-incidence angle measurements. SST from the AXBTs will be used as input to the brightness temperature algorithm.

The time series of wind observations collected for the aircraft instruments (flight-level, SFMR, and TDR) over the buoys will be long enough to decompose into averaging periods (e.g., 10-second, 1-minute, and 10-minute) and obtain information on the variability of the data. These different wind averages will then be compared to the 10-minute mean, maximum 1-minute mean, and 5-second gust winds provided by the buoy anemometer. Ideally, we would match histograms of the observations. This approach works very well for calibration when the noise is small compared to the standard deviation associated with the natural variability of the observations and when the noise in both observations is similar. It also works best with a large amount of comparison data. A less data intensive approach is to simply match the variances. This approach requires the same assumptions, but it is much easier to determine a variance than a distribution. Analysis of the variance as a function of averaging time will be used to determine which averaging scales are needed to convert each aircraft instrument to the same scale for gustiness, and which averaging scales match 1-minute mean winds estimated from the buoys. Note that this variance matching approach does not require that the exact same space be sampled for the buoy and the aircraft data. It simply requires that they are sampling air with similar properties, which is easily achieved. The dropsondes released over the buoys will serve as verification that the buoy anemometer is functioning properly by obtaining wind speeds in a similar range as the dropsonde. In addition, releasing multiple dropsondes throughout the duration of the module will allow for some analysis of the fluctuations in the dropsonde wind observations. We expect that since the dropsonde is advected by the wind, it should be responding to a shorter wind averaging timescale, have greater variance from a mean wind, and would thus fluctuate around the 1-minute and 10-minute mean buoy wind speeds.

New aircraft matchups will be used to further validate and/or improve the SAR surface wind speed retrievals at km-scale (or sub-km scale) resolution. The existing methodology for calculating sea-level pressure from SAR TC wind vectors will also be tested against new observations. Of particular interest are strong storms that will strain the model. In regions of the SAR image with clear ABL roll signatures, the SAR-derived surface pressure and surface wind boundary conditions will be combined with variations of the Obrien (1970) closure model to estimate mean ABL wind and eddy viscosity profiles and roll characteristics using updated versions of the Foster (2005, 2009, 2013) models.

The WSRA significant wave height measurements sampled at a 55-second rate are transmitted off the P-3 aircraft during flight to NHC/TAFB and incorporated into their High Seas analyses and forecasts. The data will also be analyzed to identify characteristics of the typical sea state for storms of various sizes, strengths, and translation speeds. The extent of various significant wave heights, starting at 8 ft, will be determined for each flight and compared to identify/validate relationships between significant wave height, storm size, strength, and translation speed. Data from any overflights of wave buoys will be directly compared to the WSRA surface wave data for validation of the observations. The results of the analysis will lead to a better understanding of the sea state in TCs, which will be used by forecasters and modelers to improve forecasts and coupling of the sea state in TCs.

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