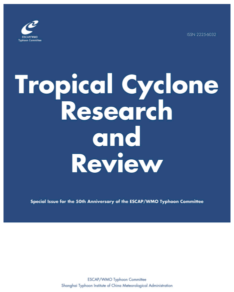

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Recent Advancements in Aircraft and In Situ Observations of Tropical Cyclones

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Abstract

Observations of tropical cyclones (TC) from aircraft and in situ platforms provide critical and unique information for analyzing and forecasting TC intensity, structure, track, and their associated hazards. This report, prepared for the tenth International Workshop on Tropical Cyclones (IWTC-10), discusses the data collected around the world in TCs over the past four years since the IWTC-9, improvements to observing techniques, new instruments designed to achieve sustained and targeted atmospheric and oceanic observations, and select research results related to these observations.

In the Atlantic and Eastern and Central Pacific basins, changes to operational aircraft reconnaissance are discussed along with several of the research field campaigns that have taken place recently. The changes in the use and impact of these aircraft observations in numerical weather prediction models are also provided along with updates on some of the experimental aircraft instrumentation. Highlights from three field campaigns in the Western Pacific basin are also discussed. Examples of in-situ data collected within recent TCs such as Hurricane Ian (2022), also demonstrate that new, emerging technologies and observation strategies reviewed in this report, definitely have the potential to further improve ocean-atmosphere coupled intensity forecasts.

Keywords: Tropical cyclones, Aircraft observations, In situ observations, IWTC-10

1. Introduction

Aircraft reconnaissance and in situ observations of tropical cyclones (TCs)[1] continue to play an important role in determining the intensity and structure of TCs and contribute to improvements in their forecasts. Since the IWTC-9 in 2018, additional advancements have been made in the strategies for collecting data with reconnaissance aircraft around the world, new instruments and technologies, and use of the data in forecast models. Research field campaigns have conducted experiments to gain a better understanding of key processes that impact TC genesis, intensity change, and associated hazards. Uncrewed autonomous vehicles, advanced weather balloons, ocean expendables, new autonomous profiling floats (APEX), as well as new approaches such as animal-borne ocean sampling also represent advanced observing technologies that are revolutionizing both our understanding of and ability to forecast TC track and intensity. To realize their full potential these technologies will continue to be more closely integrated with established regional and global ocean and atmosphere observing platforms.

Future TC observations will probably encourage more closely coordinated deployments of underwater, near surface, and airborne observations in order to better understand air-sea fluxes during intense TCs. As ocean, atmosphere, and coupled model architecture and data assimilation capabilities continue to co-evolve and improve, these autonomous observing platforms and their shoreside cyber-infrastructure will increasingly become critical components of operational forecasting systems. All these topics are discussed in more depth in the following sections.

2. Aircraft Observations

2.1 Operational Reconnaissance

2.1.1 North Atlantic, East Pacific, and Central Pacific

The United States government regularly deploys aircraft reconnaissance operated by the Air Force Reserve and National Oceanic and Atmospheric Administration (NOAA) to

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[1] The term tropical cyclone or TC will be used throughout this manuscript to denote the general category of cyclonic storms of sufficient strength with tropical characteristics. When referring to specific storms, the appropriate terms, such as Hurricane or Typhoon, will be used based on the convention used in the basin the storm occurred in.

Abbreviations: ALAMO: Air-Launched Autonomous Micro Observer; AOML: Atlantic Oceanographic and Meteorological Laboratory; APEX: Autonomous Profiling Explorer; APEX-EM: Electromagnetic Autonomous Profiling Explorer; APHEX: Advancing the Prediction of Hurricanes Experiment; AXBT: Airborne Expendable Bathythermograph; AXCTD: Airborne Expendable Conductivity Temperature Depth profiler; AXCP: Airborne Expendable Current Profiler; BUFR: Binary Universal Form for the Representation of meteorological data; CPHC: Central Pacific Hurricane Center; CPEX-AW: Convective Processes Experiment – Aerosols and Winds; CPEX-CV: Convective Processes Experiment – Cabo Verde; CRL: Compact rotational Raman Lidar; CTD: Conductivity, Temperature, Depth; ECMWF: European Center for Medium-Range Weather Forecasts; EnKF: Ensemble Kalman Filter; ESA: European Space Agency; EXOTICCA: Experiment of Typhoon Intensity Change in Coastal Area; FV3: Finite Volume Cubed Sphere: GFS: Global Forecast System; G-II: Gulfstream II; G-IV: Gulfstream IV-SP; GPS: Global Positioning System; GTS: Global Telecommunications System; HDOBs: High-Density Observations; HKO: Hong Kong Observatory; HRD: Hurricane Research Division; HWRF: Hurricane Weather Research and Forecasting; IFEX: Intensity Forecasting Experiment; IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer; ITCZ: Intertropical Convergence Zone; IWRAP: Imaging Wind and Rain Airborne Profiler; IWTC: International Workshop on Tropical Cyclones; JATAC: Joint Aeolus Tropical Atlantic Campaign; KaIA: Ka-band Interferometric radar Altimeter; LACy: Laboratoire de l’Atmosphère et des Cyclones; NASA: National Aeronautics and Space Administration; NCAR: National Center for Atmospheric Research; NCEP: National Centers for Environmental Prediction; NESDIS: National Environmental Satellite Data and Information Service; NHC: National Hurricane Center; NHOP: National Hurricane Operations Plan; NOAA: National Oceanic and Atmospheric Administration; NSF: National Science Foundation; ONR: Office of Naval Research; OTREC: Organization of Tropical East Pacific Convection; P-3: Lockheed WP-3D Orion; RSMC: Regional Specialized Meteorological Center; SFMR: Stepped-Frequency Microwave Radiometer; STORM: Sea Turtle for Ocean Research and Monitoring; sUAS: Small Uncrewed Aircraft System; TAFB: Tropical Analysis and Forecast Branch; TC: Tropical Cyclone; TCRI: Tropical Cyclone Rapid Intensification experiment; TDR: Tail-Doppler Radar; T-PARCII: Tropical Cyclone-Pacific Asian Research Campaign for Improvement of Intensity Estimation/Forecasts; VASCO: Validation of the Aeroclipper System under Convective Occurrence; WMO: World Meteorological Organization; WSRA: Wide Swath Radar Altimeter investigate TCs or their incipient disturbances that are a potential threat to populated islands and coastal areas within the North Atlantic, East Pacific, and Central Pacific regions. The data collected during these missions are critical for a real-time assessment of the systems and assimilation into various numerical models used for operational forecasting.

The National Hurricane Center (NHC; RSMC Miami) and Central Pacific Hurricane Center (CPHC; RSMC Honolulu) are responsible for tasking either the Air Force Reserve 53rd Weather Reconnaissance Squadron or NOAA's Aircraft Operations Center to investigate TC activity in their areas of responsibility. The requirements of the missions range from locating the circulation center and information related to the intensity and wind field size (fix missions), determining the existence, structure and location of the surface circulation (invest missions), and targeted environmental surveys and near-inner core sampling (synoptic surveillance missions). The details are documented in the National Hurricane Operations Plan (NHOP) that is updated on an annual basis. In addition, NOAA's Environmental Modeling Center can also task the NOAA Aircraft Operations Center for operational data collection to aid with model initialization and data assimilation.

The Air Force Reserve is equipped with ten WC-130J (C-130) aircraft capable of flying into the core of a TC. The planes are all equipped with standard operational instruments including dropsondes, flight-level probes, and Stepped-Frequency Microwave Radiometers (SFMRs) used to measure winds, temperature, moisture and pressure. In recent years, dropsondes have been released at the end points of a flight path that intercepts the center of a cyclone (this is in addition to dropsondes released at the radius of maximum winds and center) for use in numerical models and situational awareness of environmental features such as dry-air intrusions.

NOAA has two recently refurbished Lockheed WP-3D Orion (P-3) aircraft capable of performing inner-core TC reconnaissance and one Gulfstream IV-SP (G-IV) jet typically used to sample the near-storm environment and deep-layer steering synoptic features. In addition to the standard operational instruments, the NOAA aircraft are equipped with tail-Doppler Radars (TDRs). Recently, the use of TDR data for operational real-time assessment has increased. The 3-dimensional TDR analyses are particularly helpful to forecasters diagnosing TC structural changes that could impact short-term forecasts (Zawislak et al. 2022). Examples include finding signs of TC rapid intensification (Rogers et al. 2013) and eyewall replacement cycles (Didlake et al. 2017, 2018, Cha et al. 2021). These observations are also quite impactful when assimilated in the NOAA regional operational model, which will be discussed in Section 2.4.

2.1.1.1 *Updates to Strategic Use of Operational Reconnaissance Missions*

Traditionally, aircraft reconnaissance missions are tasked to investigate a system when a TC becomes a tropical storm or stronger (Fig. 1). However, recent years have seen an increase in the number of flights in disturbances below tropical storm strength. The benefit of this method is two-fold: 1) the data provided gives forecasters reliable information needed to classify and forecast a system and 2) an increase in more in-situ observations available for numerical model assimilation. Flight pattern strategies have also been formalized to optimize how the aircraft collect data in genesis cases.

In 2020, the NHOP was updated to include a "System Survey" operational mission type that is designed to investigate areas of disturbed weather that could become a TC in the future (OFCM, 2020). This pattern involves sampling the region in a gridded manner, as opposed to a storm-centric approach, and flying at a higher altitude than a low-level invest mission, which must be flown during daylight hours. Though flown in research taskings for several years, this was first flown operationally as a trial in 2020 in the disturbance that became Hurricane Teddy (2020) and as an official tasking in 2022 where a lawnmower flight pattern was used to release dropsondes every 0.5 degree over the tropical wave that would eventually become Hurricane Ian (2022).

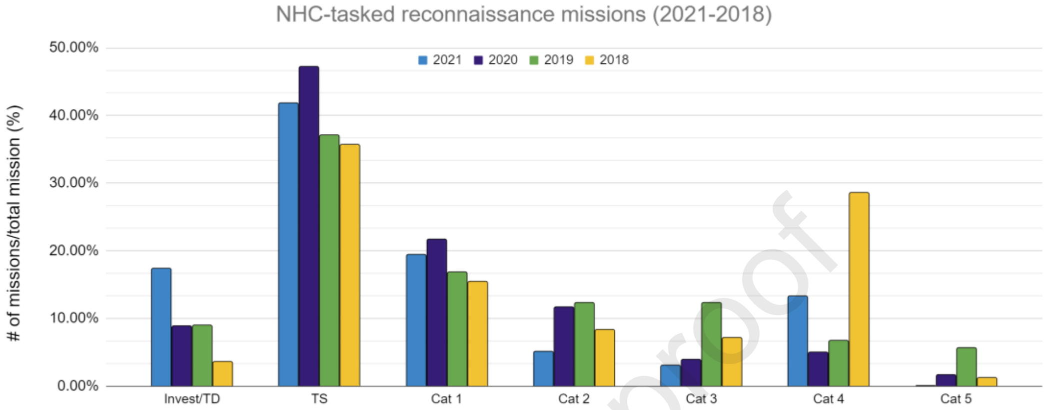


Figure 1: *Percent of NHC-tasked missions out of total NHC-tasked missions categorized by intensity of the system. Missions include both Air Force Reserve and NOAA aircraft and from both Atlantic and East/Central Pacific basins.*

In 2017, a new G-IV dropsonde strategy was implemented operationally to sample, and potentially reduce, regions designated with a large ensemble variance (Torn et al. 2014, 2018, 2020, 2021a, 2021b; Wick et al. 2018, 2020). Another update to the G-IV flight pattern came with the addition of an inner circumnavigation around the TC at 1.5 degrees (~167 km) from the center which was first tested in Hurricane Florence (2018). Prior to this addition, the G-IV would fly one circumnavigation at a fixed radius of 3 degrees (333 km). Ryan et al. (2018) suggested forecasts could be improved if the ring were scaled to the size of the radius of tropical-storm-force wind radii. However, prediction of the storm size remains a particularly difficult aspect of the TC to forecast. Operations added the inner circumnavigation as a compromise until future studies can provide updated guidance.

2.1.2 *Western Pacific Operational Reconnaissance by the Hong Kong Observatory*

The Hong Kong Observatory (HKO) continues to conduct operational reconnaissance over the South China Sea in collaboration with the Hong Kong Government Flying Service. The program, which started with boundary-layer flights in 2011 and switched to dropsondes in 2016, entered its 10th year in 2020 (Hon and Chan 2022). Available dropsonde observations are exchanged on the Global Telecommunications System (GTS) in near real-time, with recently streamlined processing for faster dissemination. In addition to supporting operational forecasting, HKO's aircraft reconnaissance data have contributed to studies on dynamical processes (Tang et al. 2021), assimilation (Qin et al. 2022) and regional collaboration (Chan et al. 2022).

2.2 Research

2.2.1 North Atlantic, East Pacific, and Central Pacific

Since the IWTC-9 in 2018, four main research projects have been launched to further improve our understanding of the processes that govern TC formation and intensification:

2.2.1.1 APHEX

In 2021, NOAA’s Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division’s (HRD) annual Hurricane Field Program transitioned from the Intensity Forecasting Experiment (IFEX) to the Advancing the Prediction of Hurricanes Experiment (APHEX). The goals of APHEX are not only to improve the understanding of processes important for intensity change of TCs over the duration of their life cycle, but also focused on TC formation, structure, and associated hazards. Other key components of the program are to improve the use of aircraft observations in numerical forecast models, improve existing or develop new airborne instrumentation, and develop observing strategies targeted at filling observation gaps and maximizing the impact of the aircraft data in model forecasts. Zawislak et al. (2022) highlights the advancements toward improving the understanding and prediction of TCs and the accomplishments of the 16-year IFEX program.

Since the IWTC-9 in 2018, NOAA, in collaboration with IFEX and APHEX, flew missions into 34 storms. A breakdown of the number of flights by the NOAA P-3 and G-IV between 2019 and 2022 is provided in Table 1 along with some of the notable storms flown each year. During this time period, storms have been sampled at all stages of their lifecycle from genesis through landfall, decay, or extratropical transition. There has been a particular focus on sampling storms in regions of moderate vertical wind shear (10-20 kt) to gain a better understanding of how shear impacts a storm's ability to intensify. Many periods of rapid intensification, secondary eyewall formation, and eyewall replacement cycles have also been sampled to further understand these intensity change processes. IFEX and APHEX have also collaborated with several other field campaigns during this time period, such as the National Center for Atmospheric Research/National Science Foundation’s (NCAR/NSF’s) Organization of Tropical East Pacific Convection (OTREC), NASA’s Convective Processes EXperiment (CPEX), and the Office of Naval Research’s (ONR’s) Tropical Cyclone Rapid Intensification (TCRI) experiment. Several new experimental instruments have also been tested and efforts to aid in satellite validation were accomplished.

Year	Number of P-3 Missions	Number of G-IV Missions	Notable Storms
2019	38	17	Pre-Ivo (East Pacific), Dorian, Lorenzo
2020	58	28	Laura, Sally, Teddy, Delta
2021	35	17	Ida, Larry, Sam
2022	49	19	Earl, Fiona, Ian

Table 1: *Summary of NOAA P-3 and G-IV missions from 2019 to 2022.*

2.2.1.2 TCRI Experiment

The Tropical Cyclone Rapid Intensification *(*TCRI) experiment, sponsored by the Office of Naval Research (ONR), is a multi-year program focused on improving our understanding of rapid intensification of TCs, through insight gained from new observations and high-resolution numerical model simulations. Although the ingredients for and basic mechanisms of TC intensification are well-understood, the key processes governing the transition from genesis to rapid intensification remain unclear. Additionally, TC prediction models have great difficulty accurately forecasting the onset of rapid intensification and subsequent rate of intensification for such post-genesis, weak TCs.

Motivated by these deficiencies in our understanding and prediction of rapid intensification, the ONR TCRI observing program has been closely coordinated with the NOAA/AOML/HRD APHEX program. The TCRI science team coordinates with APHEX scientists to design flight patterns and expendable drop points to observe processes thought to be important to rapid intensification and its onset. During the 2020 and 2021 Atlantic seasons, rapid intensification events were observed in Hurricanes Ida (2021) and Delta (2020). In 2022, two distinct periods of rapid intensification were observed for Hurricane Ian, including one immediately preceding Florida landfall.

The TCRI team has been investigating the processes governing the onset of rapid intensification from both an observational and modeling perspective. One key finding is that rapid intensification often begins earlier in the TC lifecycle than may have previously been understood. Surprisingly, the most frequent rapid intensification onset time is coincident with genesis, and almost half of all TCs which undergo rapid intensification begin to do so within the first 24 h after genesis. This indicates that the processes leading up to rapid intensification are often difficult to observe unless sampling is done prior to and during genesis. Thus far, we were able to observe a number of storms early in the life cycle prior to and during the onset of rapid intensification, including Hurricanes Grace (2020), Ida (2021), and Ian (2022).

2.2.1.3 CPEX Field Campaigns

In 2021, the National Aeronautics and Space Administration’s (NASA’s) Weather program carried out the Convective Processes Experiment – Aerosols and Winds (CPEX-AW) out of St. Croix, U.S. Virgin Islands, between the middle of August and early September with NASA’s DC-8 aircraft. The DC-8 was equipped with active and passive remote sensors, as well as dropsondes, permitting profiling measurements of tropospheric winds, water vapor, temperature, aerosols (dust), clouds, and precipitation. NASA CPEX-CV (CPEX – Cabo Verde), flown in September of 2022, was a continuation of CPEX-AW, but operated out of Sal Island, Cabo Verde.

The goals of these projects were to observe convective life cycles and processes in a variety of dynamic, thermodynamic, and aerosol environments, such as within persistent (Intertropical Convergence Zone (ITCZ)) and periodic (African Easterly Waves, TCs) large-scale environmental forcing, local terrain effects (e.g., land-ocean transition off western Africa), and aerosol-cloud interactions within the Saharan Air Layer, as well as the interactions with the boundary layer (e.g., in cold pools). Also prioritized was the validation of the NASA-European Space Agency (ESA) collaborative satellite mission ADM-Aeolus, which hosts the first wind profiling lidar in space. Aeolus validation underflight legs with the DC-8 were NASA’s contribution to the Joint Aeolus Tropical Atlantic Campaign (JATAC), a cooperative sampling and validation effort of Aeolus between NASA and ESA-partner agencies, and universities, the latter of which hosted observing platforms in Cabo Verde.

As CPEX-AW was flown from the Caribbean during the heart of the North Atlantic TC season, the program flew 5 missions (of the 7-total flown, Fig. 2a) within and around TCs. Thirteen missions were flown during CPEX-CV (Fig. 2b), with several of the missions targeting African Easterly Waves (and accompanying Saharan Air Layer) moving off western Africa that likely eventually developed into Hurricanes Fiona and Ian – though the genesis of these storms generally happened downstream several days after the flights. One mission, though, was flown during the genesis of Tropical Storm Hermine between the west coast of Africa and Cabo Verde. Quality-controlled dropsonde data was transmitted from the DC-8 into the GTS for delivery to NHC and for assimilation into global forecast models, which included National Centers for Environmental Prediction (NCEP) and European Center for Medium-Range Weather Forecasts (ECMWF) during CPEX-CV. CPEX-AW and -CV met recommendations *13* and *31* from the IWTC-9.

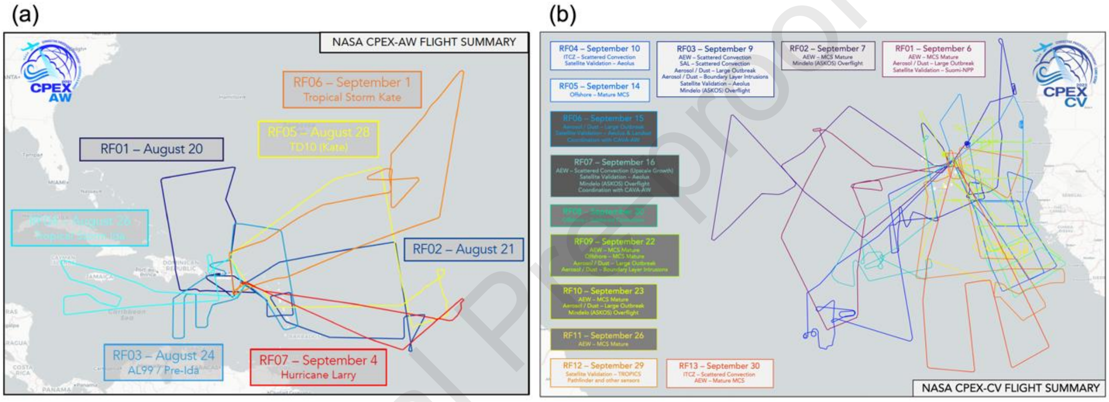


Figure 2: *A summary of DC-8 flight tracks from NASA's 2021 CPEX-AW (a) and 2022 CPEX-CV (b) field programs.*

2.2.1.4 NESDIS Ocean Winds

The National Environmental Satellite Data and Information Service (NESDIS) Ocean Winds Flight Project has two advanced radar systems that it installs and operates on the NOAA P-3 aircraft. These are a profiling Doppler radar/scatterometer (IWRAP) that provides 3-D wind and reflectivity profiles below the aircraft to just above the surface and surface winds (scatterometry), and a Ka/Ku-band altimeter (KaIA) that provides significant wave height and relative ocean height. The program has several objectives, which includes (1) testing new remote sensing methodologies and technologies for future satellite instruments; (2) characterizing the air-sea interface in extreme conditions (TCs and winter storms) to improve and calibrate/validate existing satellite observations (i.e., ASCAT, SCA, OceanSat3, AMSR2, AMSR3, etc.) and advance the state of knowledge of the physics at the air-sea interface; and (3) providing real-time actionable wind and wave information to the National Weather Service (forecasters and models) to support the TC forecast and warning mission.

2.2.2 Western Pacific

In addition to research activities conducted in the North Atlantic, East Pacific, and Central Pacific basins, two campaigns are also ongoing in the Western Pacific basin.

2.2.2.1 T-PARCII

For disaster prevention related to TCs, accurate estimation and prediction of their intensities are very important. The 5-year Tropical cyclone-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII) project aims to improve estimations and forecasts of TC intensity in the western North Pacific between May 2016–March 2021. The success of this project led to the second phase of the T-PARCII project, which started in July 2021 and will be continued until March 2026. In the second period, more focus is given to observing rapid intensification and concentric eyewalls.

The T-PARCII flights were carried out using a Gulfstream II (G-II) jet operated by Diamond Air Service until 2018. Because of the retirement of the G-II jet, in 2021, a dropsonde observing system was installed on a G-IV jet operated by Diamond Air Service. A Meisei Electric iMDS-17 dropsonde is released from a high altitude of 43,000–45,000 ft. It enables observations of wind speed, wind direction, temperature, height, humidity, and pressure throughout the deep troposphere. The observed data have been transferred to the GTS by way of the Japan Meteorological Agency in near-real-time. The dropsonde data are open to the public upon request one year after the data were collected.

During the period from 2017 to 2022, penetration observations into the eyes of TCs through eyewalls of Typhoons Lan (2017, Fig. 3), Trami (2018), Mindulle (2021), and Nanmadol (2022) were performed 16 times in total without experiencing any moderate or severe turbulence when their minimum sea-level pressures were 910–950 hPa. In total, 169 dropsondes have been successfully deployed. During the projects, rapid weakening and concentric eyewall formation were observed for Typhoon Trami. Very recently, rapid intensification and concentric eyewalls were successfully observed for Typhoon Nanmadol in September 2022. A so-called butterfly pattern is employed to observe the deep troposphere in many quadrants, if possible. Thanks to the T-PARCII observations, important findings have been coming out recently (Ito et al. 2018; Tsukada and Horinouchi 2020; Yamada et al. 2021; Tsujino et al. 2021a; Tsujino et al. 2021b; Hirano et al. 2022; Chang et al. 2022).

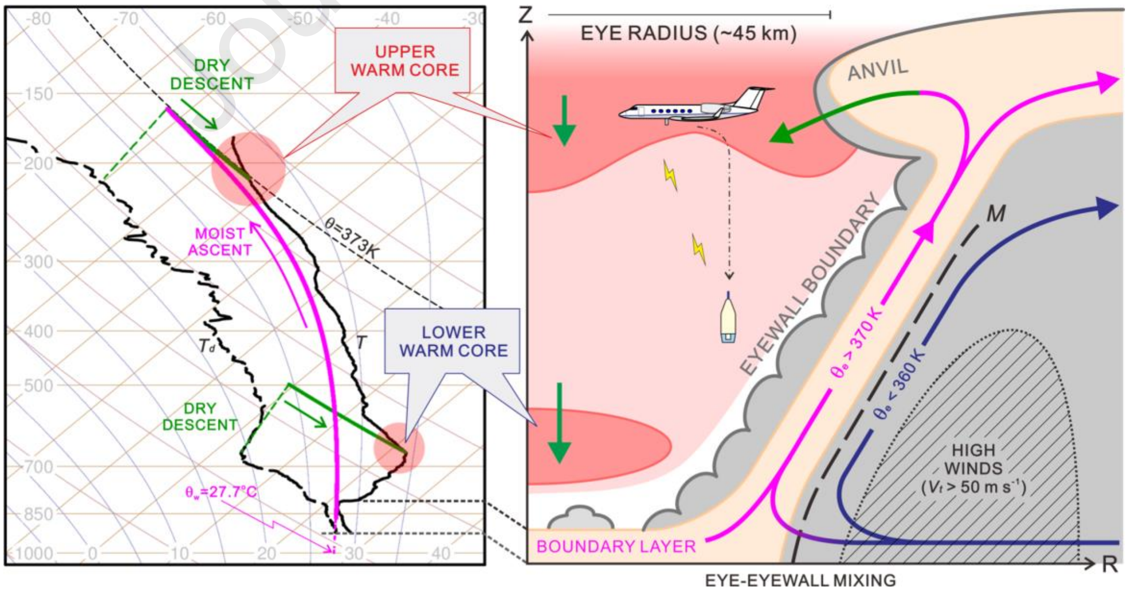


Figure 3: *Schematic view of the double warm cores observed for Typhoon Lan (2017). Reproduced from Yamada et al. (2021).*

2.2.2.2 EXOTICCA

During the past four years, the Experiment on Typhoon Intensity Change in Coastal Area (EXOTICCA) entered its second phase in which different kinds of uncrewed aerial vehicles and uncrewed aircraft systems have been tested in several TC cases in cooperation with the crewed aircraft of the HKO. Observations were collected in Typhoons “Nangka” (No. 2016), “Sinlaku” (No. 2002), “Wipha” (No. 1907), “Conson” (No. 2113) and “Chanthu” (No. 2114), and “In-fa” (No. 2106).

Typhoon “Nangka” (No. 2016) was observed from October 12-14, 2020 with a multi-platform coordinated three-dimensional effort to provide full coverage of the "earth-sea-air-sky" (Fig. 4 left panel). During the test, the second sounding observation of the typhoon was also successfully carried out for the first time and flights with the HKO’s crewed aircraft were carried out in the adjacent area. Observation sensitivity regions were also determined and sampled every 6 hours.

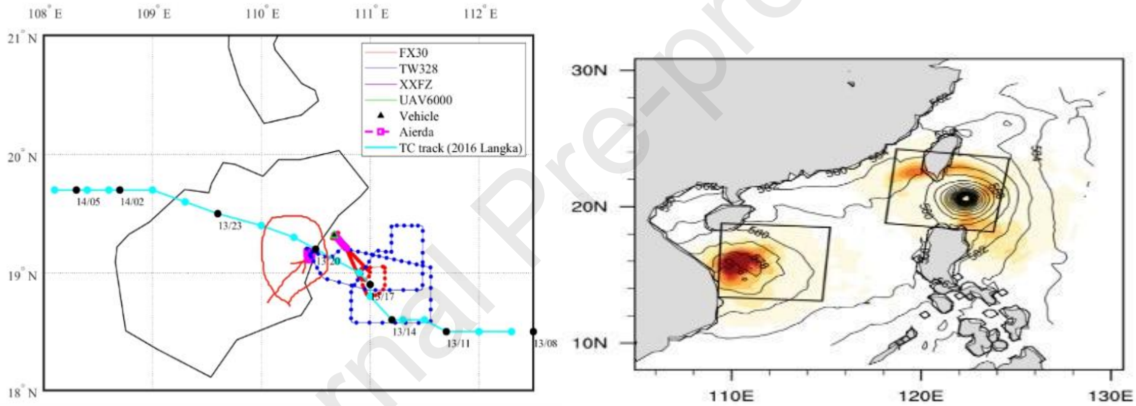


Figure 4: *(left panel): Typhoon "Nangka" (No. 2016) multi-platform collaborative observation drone detection route and typhoon path. (right panel): The target observation sensitive areas of Typhoons "Conson" and "Chanthu", which are shown in the black box near the center of the typhoon.*

On August 2, 2020, a coordinated "sea-air-sky" observation test for Typhoon “Sinlaku” (No. 2002) was carried out. The uncrewed aerial vehicle, which was equipped with instruments such as millimeter-wave radar, carried out the first high-altitude uncrewed aerial vehicle drop sounding operation in China (30 dropsondes were successfully dropped from an altitude of about 10km). An uncrewed boat entered the typhoon core area for the first time for China.

On July 31, 2019, EXOTICCA-II and the HKO carried out a "sea-air" joint observation experiment for Typhoon "Wipha" (No. 1907). The HKO's crewed aircraft flight observation and drop sounding over the typhoon were carried out while a wave glider was used to continuously observe the sea surface meteorological elements and waves before and after the typhoon (June 15-August 30) for a long time period.

From September 11 to 13, 2021, a coordinated observation of the FY-4A satellite and aircraft were carried out on the twin Typhoons "Conson" (No. 2113) and "Chanthu" (No.

2114). The crewed typhoon detection aircraft of the HKO was equipped with a drop sounding system. The twice-a-day observation period of the HKO was informed by targeted observations of sensitive areas of Typhoon “Conson” (No. 2113). Figure 4 (right panel) shows the observation sensitive areas of twin typhoon targets calculated according to the conditional nonlinear optimal disturbance. The same "air-sky" collaborative observation experiment was also carried out for Typhoon “Higauss” in 2007.

From July 23 to 26, 2021, "ground-based" observation platforms and "sea-based" wave gliders on the coast of Zhoushan, Zhejiang collected targeted coordinated observations of the landfalling Typhoon “In-fa” (No. 2106). The experiment collected vehicle-borne raindrop spectra and wind profiles, GPS soundings (including ozone soundings), wind profiles, eddy fluxes, microwave radiometers, laser wind radars, Raman radars, and strong winds from typhoon observation bases.

2.3 Advancements in Aircraft Instrumentation

One of the unique capabilities of the NOAA P-3 aircraft is to test experimental instrumentation. Several of the instruments currently operational on the Air Force Reserve C-130 reconnaissance aircraft, such as the SFMR and dropsondes, were first tested on the P-3s before transitioning to operations on the C-130s. A few of the instruments currently being tested on the P-3s are discussed briefly hereafter:

2.3.1 Imaging Wind and Rain Airborne Profiler (IWRAP)

The Imaging Wind and Rain Airborne Profiler (IWRAP) is a downward-pointing, conically scanning, dual-frequency, dual-polarization Doppler radar capable of measuring surface backscatter and intervening volume reflectivity and Doppler velocity at 30 m range resolution. During the 2021 TC season, IWRAP was configured to acquire vertically polarized measurements at Ku and C-band frequencies and 30–50° angles of incidences. The signal transmission characteristics result in a blind range of approximately 120 m at the inner angle and 1.5 km at the outer angle. A unique aspect of the IWRAP data acquisition system is in its ability to collect both in-phase and quadrature signals for the entire observational profile. This allows for the full spectrum to be derived by utilizing a series of fast Fourier transforms on every single range gate. Spectral processing allows IWRAP wind retrievals to within one range gate (30 m) above the ocean surface. Figure 5 shows an IWRAP wind profile below the P-3 measured during an inbound pass into Hurricane Ida (2021).

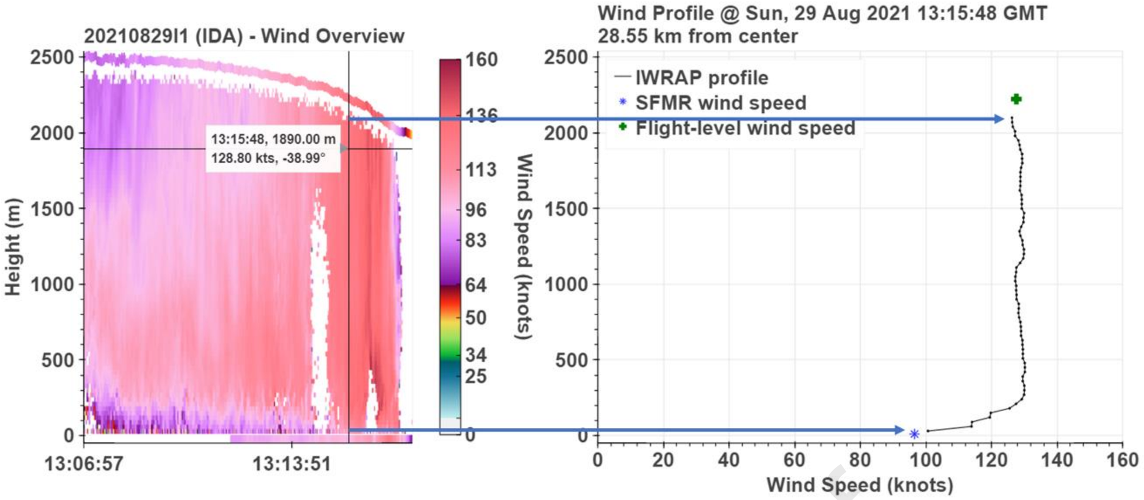


Figure 5: *(left): IWRAP wind profile below the P-3 measured during an inbound pass into Hurricane Ida on August 29, 2021. Corresponding flight level and SFMR surface wind speeds are shown above and below the IWRAP profile, respectively. (right): Example IWRAP vertical wind speed profile.*

2.3.2 Wide Swath Radar Altimeter (WSRA)

The WSRA provides continuous real-time reporting of significant wave height, ocean wave height, wavelength, and direction of propagation of the primary and secondary wave fields, directional ocean wave spectra, and sea surface mean square slope (PopStefanija et al. 2021). It has been flown on one of the NOAA P-3 aircraft since 2008 and recently received a significant hardware upgrade to improve its reliability for collecting these important observations. The wave data collected by the WSRA and KaIA (discussed below) have been used by the NHC Tropical Analysis and Forecast Branch (TAFB) in their analyses of wave heights, which are used to issue high seas warnings. In 2022, ocean wave spectra observations were added as a new operational requirement in the NHOP, which further motivates the importance of continued testing of these wave observing instruments.

2.3.3 KaIA

KaIA is a nadir-looking Ka-band interferometric radar altimeter capable of centimetric altimetry (500 MHz bandwidth). Starting in the 2020 TC season, real-time significant wave height retrievals have been provided to the NHC and Ocean Prediction Center in support of wind and wave forecasting products. Near-real-time KaIA wave products are posted at https://manati.star.nesdis.noaa.gov/datasets/AircraftData.php together with IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) wave model and available buoy and altimeter wave data during the flights, which allows for real-time validation of both KaIA observations as well as model outputs. KaIA also has the capability of retrieving mean squared slope, relative ocean height, and wind speed estimates at low to moderate wind speeds. A Ku-band channel was added for the 2021 winter storm season, and the two frequencies will allow for rain rate retrieval, correction of rain effects on the surface, and freeboard sea ice measurements. Figure 6 shows the significant wave height from KaIA collected during a flight into Hurricane Ida on August 28, 2021.

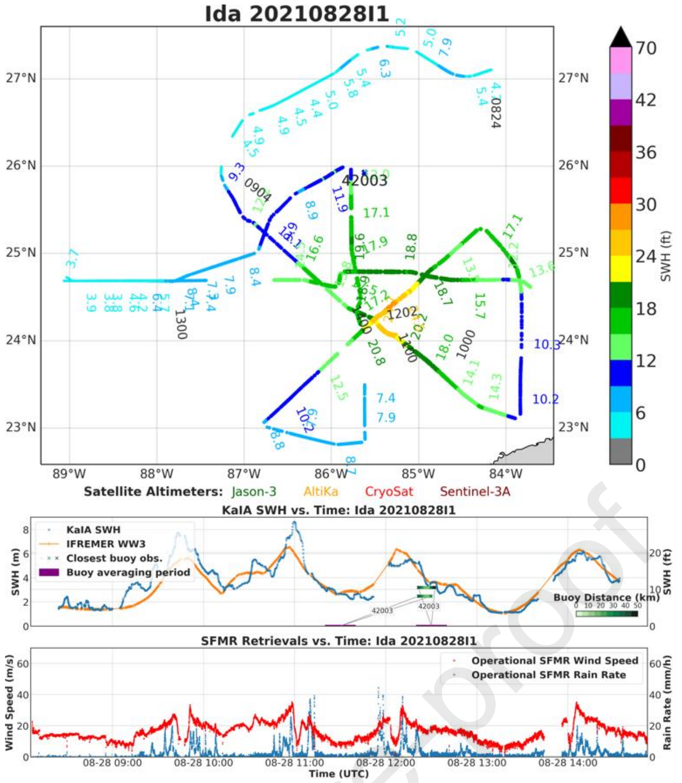


Figure 6: *KaIA* significant wave height *data collected during a flight into Hurricane Ida on August 28, 2021 plotted along the flight track (top) and as a time series (middle) as well as the corresponding IFREMER forecast* significant wave height *and SFMR wind speed and rain rate (bottom).*

2.4 Aircraft Data Model Impacts

In 2021, NCEP's FV3-GFS began assimilating additional near-center dropsonde data as well as the first-time addition of high-density, flight-level reconnaissance observations (HDOBs). This additional reconnaissance data led to about 15% improvement in track forecasts on days 2–5 when reconnaissance was present (Sippel et al. 2022; their Fig. 4). Thus, assimilating additional reconnaissance data would likely improve TC forecasts in other global models.

Of the current operational regional TC models, only NCEP's HWRF has advanced data assimilation, including inner-core reconnaissance data (Christophersen et al. 2022). Recent changes to how reconnaissance data are assimilated into HWRF beginning in 2018 include (1) assimilation of TDR Doppler velocity from the G-IV as well as surface wind speed from the SFMR and (2) accounting for advection of dropsondes by the TC flow while falling (i.e., dropsondes drift; Aberson et al. 2017), which allows for accurately using inner-core dropsondes. Recent research has found that HWRF forecasts of maximum sustained 10-m wind speed forecast improve 10-15% due to assimilating this reconnaissance data (Zawislak et al. 2022; see their Fig. 4).

There have been four recent changes to how aircraft reconnaissance data are collected, mainly focused on the North Atlantic basin including additional dropsondes at endpoints and midpoints of the common patterns for the C-130s and P-3s, an inner ring circumnavigation at around 165 km (Sippel 2020; Sippel et al. 2021) by the G-IV when possible, and using ensemble sensitivity metrics described in Torn (2020, 2021a,b) to guide environmental sampling conducted by the G-IV. Given many of the changes related to dropsonde deployment, a number of studies (Ditchek et al. 2022; Ditchek et al. 2023a,b; Piper et al. 2022) have recently examined and are currently assessing the forecast impacts from dropsondes.

Other forecast improvements from reconnaissance data come from Raytheon’s small Uncrewed Aircraft System (sUAS) called Coyote, which was launched from P-3s between 2017–2018 to increase in-situ sampling capabilities (Cione et al. 2016). While not currently operational, recent peer-reviewed literature as well as ongoing work have shown that they lead to TC forecast improvement when assimilated into numerical weather prediction models (Cione et al. 2016, 2020; Christophersen et al. 2017, 2018a; Kren et al. 2018; Wick et al. 2020; Aksoy et al. 2022; Sellwood et al. 2023)

3. In Situ Observations

3.1 Oceanic measurements

One of the factors contributing to the lag in improvement of TC intensity forecasts relative to TC track forecasts may be the lack of a dedicated surface and subsurface ocean observing systems with sustained and targeted ocean observations that capture adequately, i.e. at appropriate spatio-temporal scales, the ocean component in ocean-atmosphere coupled intensity forecast models (Domingues et al. 2019). Examples of emerging technologies and observation strategies that have the potential to fill this gap are described below.

3.1.1 Underwater gliders

Underwater gliders are uncrewed vehicles that have emerged as a major component of the global ocean observing system. Gliders are unique in their underwater maneuverability, with the ability to profile through the water column as deep as 1000 m with vertical speeds of ~10 – 20 cm/s while traveling up to 24 km per day and collecting data up to 2 second intervals. Together with other uncrewed autonomous vehicles, gliders represent an advanced ocean observing technology that is revolutionizing both our understanding of and ability to forecast TC track and intensity (Miles et al. 2021, Fig. 7).

In the tropical Atlantic basin, targeted and sustained ocean observations with gliders for TC research and forecasts have been in place since 2014 with a network of 30 to 40 gliders operating during TC season, providing an excess of 100,000 profile observations in areas of the tropical Atlantic, Caribbean Sea, Gulf of Mexico and the US east coast, where TCs travel and intensify and/or weaken. A field campaign was also recently conducted in the Southwest Indian Ocean basin, with two underwater gliders deployed for the first time in this area during the TC season 2018-2019 (Bousquet et al. 2021).

Glider datasets are generally transmitted in real-time to national and international data centers for analysis and assimilation into operational ocean and ocean-atmosphere operational and experimental forecast models. Their integration allows for an improved representation of the ocean, particularly the vertical temperature and salinity structure, and the resolution of essential ocean features, in ocean forecast models used to initialize the coupled TC forecast models (Halliwell et al. 2020, Dong et al. 2017). Hindcast data impact studies during Atlantic TCs (e.g. Maria in 2018 and Michael in 2018) have also shown that, out of the suite of in-situ ocean observing platforms, underwater gliders locally have the largest impact to reduce error in intensity forecasts within NOAA experimental forecast models (Domingues et al., 2021; Lehenaff et atl, 2021). Additional model improvements were found when underwater glider data were used alongside other profile data, such as Argo and eXpendable BathyThermograph profiles (XBT), and satellite observations. In addition to their impacts on model forecasts, these uncrewed vehicles have also contributed to new understanding of TC-forced coastal ocean circulation (Miles et al., 2017), impacts on boundary currents (Todd et al., 2018), and impacts of these processes on TC intensity (Seroka et al., 2017).

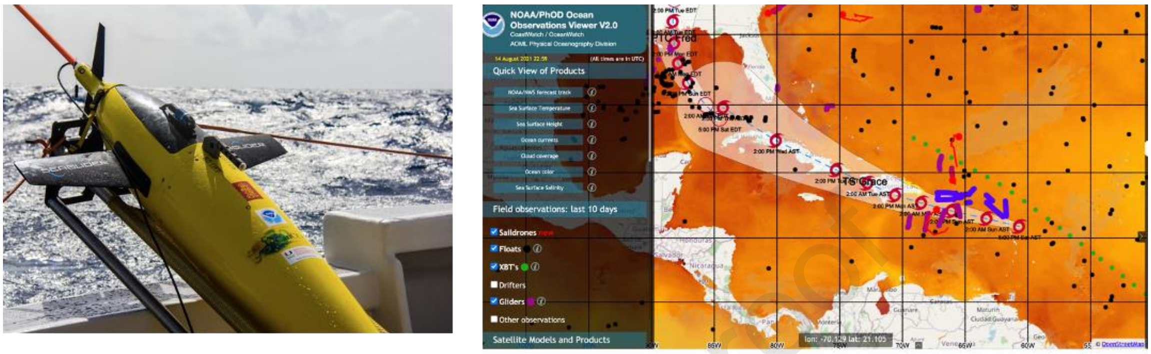


Figure 7: *(left): Underwater glider deployed in the Caribbean Sea in 2018. (right): Location of ocean observational assets in the tropical Atlantic during the passage of Hurricanes Fred and Grace in 2018, with gliders (purple circles), Argo floats (black), XBTs (green), and saildrones (red).*

3.1.2 Airborne Expendables

Observations of the ocean response to TC passages have been generally sparse over the global oceans as the community has had to rely on fortuitous encounters with buoys, drifters and moorings deployed in support of other experiments or ships crossing TC wakes. Thanks to the advent of new expendable probes (AXCPs, AXCTDs, AXBTs, ALAMOs, APEX-Ems, which can be released directly within or nearby TCs by NOAA reconnaissance and research aircraft, it is now possible to achieve direct samplings of the inner core of TCs without having to rely on fortuitous encounters with operational in-situ networks. A quick overview of the main available expendable probes is given hereafter:

3.1.2.1 Profilers

At altitudes of 1500-2000 m, airborne expendable profilers such as bathythermographs (AXBTs), conductivity–temperature–depth sensors (AXCTDs), and current profilers (AXCPs), require approximately a minute to arrive at the ocean's surface. Once in the seawater, a battery is activated that turns on a radio frequency transmitter to transmit data to the aircraft. During the period of active sampling (typically 6 to 8 minutes depending on profiler types), the aircraft traverses about 35 to 40 km down range as AXCPs and AXCTDs descend to 1000 to 1500 m compared to 350 to 800 m depths for shallow and deep AXBTs, respectively.

Although, airborne expendable profilers have been used for many years to investigate the vertical structure of the ocean as well as air-sea coupling in TC conditions (e.g., Jaimes et al. 2016), recent studies have further demonstrated their capabilities to investigate the inner core of TCs (e.g., Wadler et al., 2021), as well as to measure air-sea fluxes (Rudzin et al. 2020), and improve bulk air–sea heat flux functions (Jaimes et al. 2021).

3.1.2.2 APEX-EM floats

With nearly 8,000 units deployed as part of the global Argo Program, the Autonomous Profiling Explorer (APEX) float has been the workhorse for ocean temperature and salinity data collection for more than 15 years. In addition to temperature and salinity measurements, electromagnetic APEX floats (APEX-EM) can also measure temperature, conductivity, pressure and velocity profiles from the surface layer to as deep as 2000 m using motional induction (Shay *et al.*, 2019).

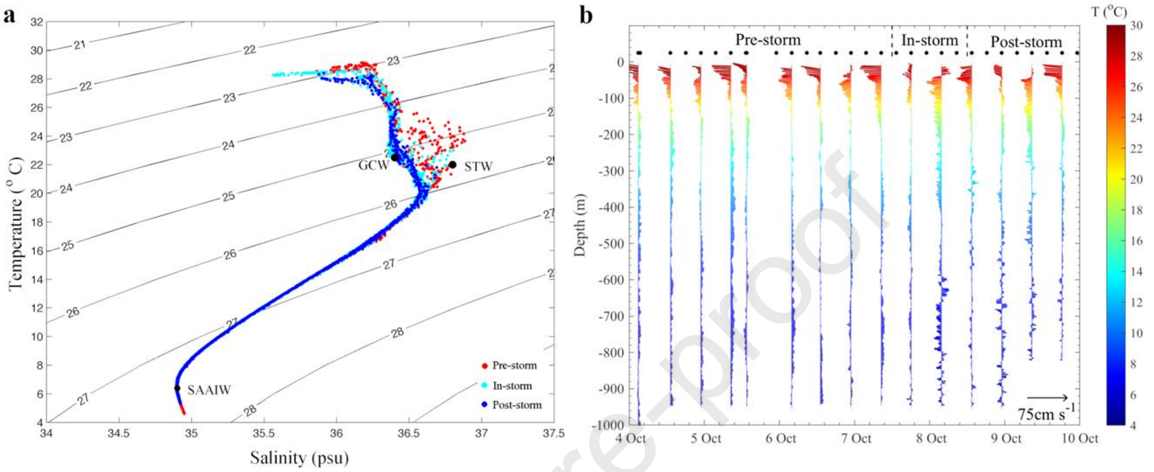


Figure 8: *Temperature and salinity measurements (left panel) and current profile measurements (right panel) from an APEX-EM float deployed in Hurricane Nate (2017) over a warm core eddy. Red, light blue, and dark blue profiles signify pre-, in-, and post-storm measurements, respectively. GCW, STW, and SAAIW stand for Gulf Common Water, Subtropical Water, and Sub Antarctic Intermediate Water in the left panel. Velocity profiles (color coded by temperature) were obtained at each black dot (for clarity in the presentation, every other profile is shown). Reproduced from Shay et al. (2019).*

During TC passage, APEX-EM floats repeatedly descend and ascend for a preset amount of time between a preset minimum and maximum depth to measure the oceanic response to the atmospheric forcing as quickly as possible. Figure 8 shows examples of temperature, salinity and current responses during Hurricane Nate (2017) as an APEX-EM float moved into a warm core eddy. Collected data shows that current shears across the base of the ocean mixed layer caused a deepening and cooling of the layer, while currents were also apparently excited at depth (suggesting downward propagation of near-inertially rotating internal wave currents). Other experiments to acquire data in the proximity of evolving APEX-EM float deployments, such as done during Hurricane Michael (Wadler et al., 2021), will allow further assessing APEX-EM measurements (including shear) in various storm conditions.

3.1.2.3 ALAMO floats

The Air-Launched Autonomous Micro Observer (ALAMO) is a versatile profiling float that can be launched from an aircraft to make temperature and salinity observations of the upper ocean for over a year with high temporal sampling (Jayne and Bogue 2017, Jayne et al. 2022). Similar in dimensions and weight to an AXBT, but with the same capability as Argo profiling floats, ALAMOs can be deployed from an A-sized (sonobuoy) launch tube, the stern ramp of a cargo plane, or the door of a small aircraft. Unlike an AXBT, however, the ALAMO float directly measures pressure, can incorporate additional sensors, and is also capable of performing hundreds of ocean profiles compared to the single temperature profile provided by an AXBT.

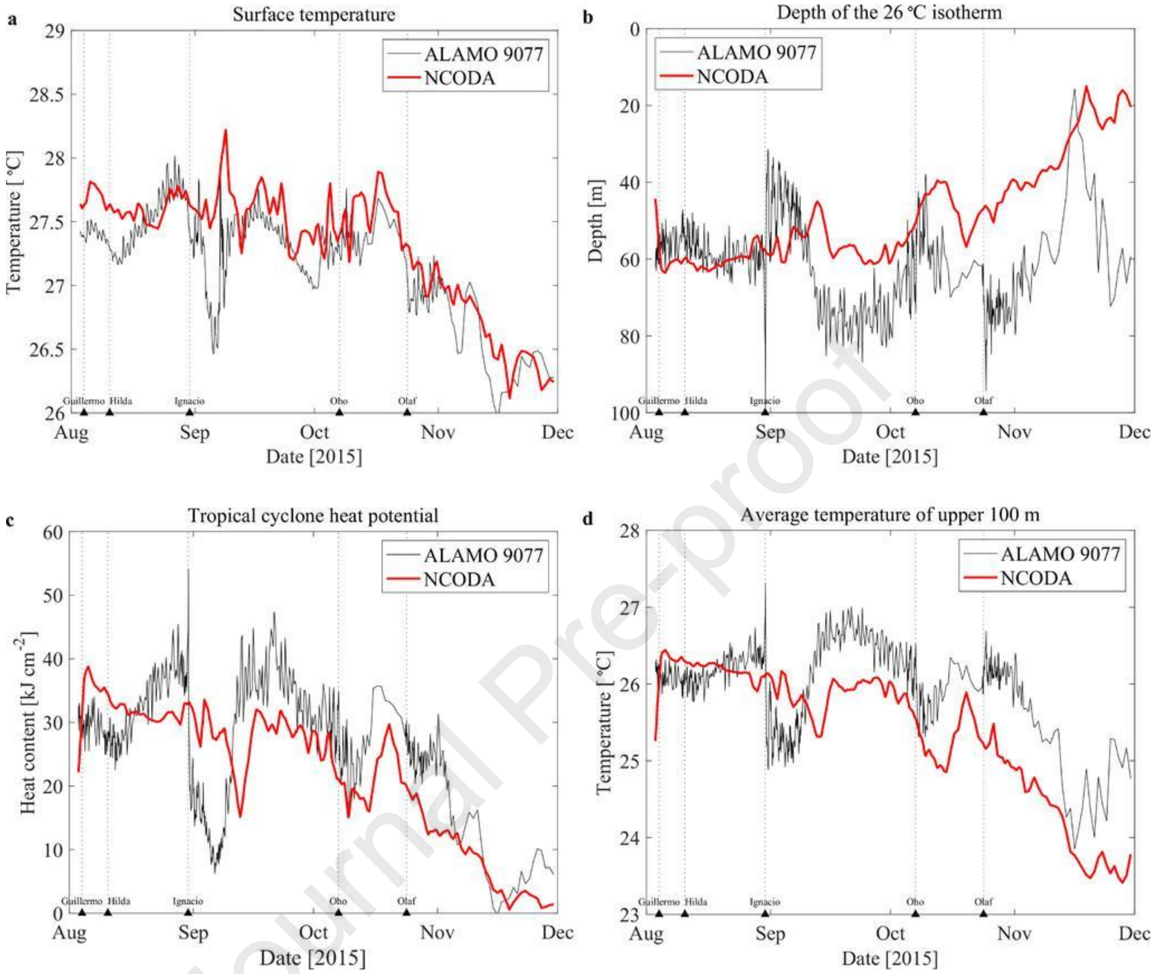


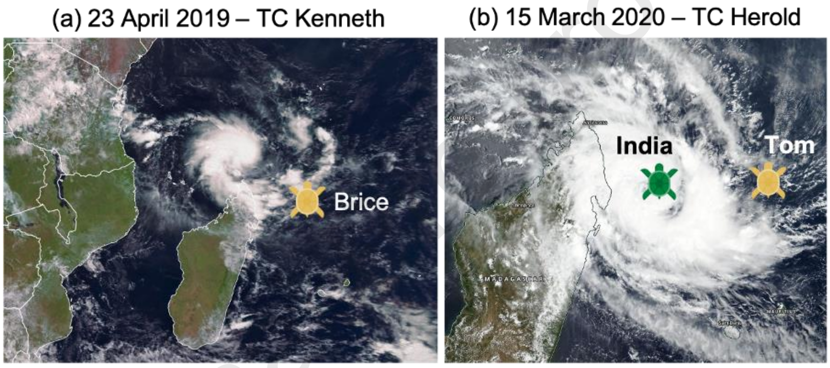
Figure 9: *Metrics comparing the NCODA analysis to observations from the ALAMO float 9077 deployed ahead of Hurricane Guillermo (Eastern Pacific) in 2015: (a) the sea surface temperature (°C), (b) depth of the 26°C isotherm (m), (c) TC heat potential (kJ cm^{-2}), and (d) average temperature of the upper 100 m (°C). Small triangles with gray dotted lines and TC names along the time axis indicate the time of closest point of approach between the float and each storm. Reproduced from Jayne et al. (2022).*

Beginning in 2017, ALAMO floats with pressure, temperature, and salinity sensors (CTDs) have been deployed and tested from operational reconnaissance flights in the Eastern Pacific Ocean (Fig. 9) as well as in the Arctic ocean and Northern Arabian Sea. Given its relative ease of deployment and its ability to provide targeted ocean observations around a TC that would be difficult to obtain otherwise, the ALAMO float is expected to rapidly find widespread use among the oceanographic community.

3.1.3 Biologging

Physical ocean data collected by animal-borne sensors (a.k.a biologging) have been used for many years for understanding animal movements, behavior and social interactions. The sophistication and precision of current sensor technology now further enables the use of animals equipped with satellite tags to also collect reliable in situ environmental information that can complement data collected from traditional Earth observing platforms (McMahon et al., 2021).

Marine animals equipped with biological and physical electronic sensors have already produced long-term data streams on key marine environmental variables, hydrography, animal behavior and ecology in polar areas, but using this approach to collect oceanographic observations in other regions of the world remains less frequent. There is, however, growing recognition of the value of animal borne sensors in delivering key oceanographic observations to improve ocean model forecasts in tropical and subtropical areas. Recently, Temperature-Depth profiles collected by sea turtles in both the Kuroshio-Oyashio Confluence region and the Arafura Sea have for instance been integrated in ocean nowcast/forecasts (Miyazawa et al., 2018) and assimilated into an operational seasonal prediction system (Doi et al., 2019), respectively.



(c) SST India 13-19 March 2020

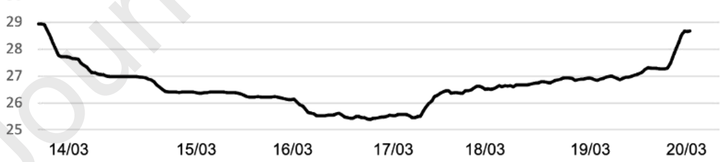


***Figure 10**: Sea turtles trapped in the vicinity of TCs Kenneth and Herold in the* Southwest Indian Ocean*. Satellite images of (a) TC Kenneth on 15 April 2019 and (b) TC Herold on 15 March 2020. Animal symbols show the location of the sea turtle “Brice” during the cyclogenesis of TC Kenneth (left panel) and of the sea turtles “India” and “Tom” during the intensification phase of TC Herold (right panel). (c) Evolution of the sea surface temperature (°C) near the center of TC Herold, as measured by the sea turtle “India” between 14-20 March 2020 within the area [51.93-52.62°E; 13.9/14.67°S]. Reproduced from Bousquet et al. (2021).*

Because sea turtles typically dive between 25 m to 200 m, these animals are able to collect important information on the physical properties of the water column (particularly temperature, salinity and density) in the ocean mixed layer and, as such, to potentially provide crucial observations to assess and better forecast TC properties. Recent research initiatives like the Sea Turtles for Ocean Research and Monitoring (STORM, Bousquet et al., 2020) further illustrate the vast potential of animal-borne ocean observations to both complement and augment current observing capabilities during TC seasons. During the first two STORM experimental campaigns (2019-2021; 2022), many sea turtles have for instance been caught in the immediate vicinity of TCs (Fig. 10), providing key data to investigate the impact of the storms on the surface and subsurface structure of the ocean (Bousquet et al. 2021), but also to evaluate coupled ocean-atmosphere model forecasts (Barthe et al. 2021), and potentially improve TC forecasts through assimilating sea turtle-borne observations into ocean models.

3.2 Atmospheric measurements

Recent surveys of operational meteorologists in the United States have pointed to the need for increased observation of the lower atmosphere, especially to improve the accuracy of short-term (<24 h) forecast guidance products (e.g., Houston et al. 2020, 2021) during periods of rapidly changing conditions. While small uncrewed airborne systems (sUAS), appear to be a particularly relevant option to quickly fill these gaps (McFarquhar et al. 2020), a number of other emerging systems can also collect priceless in-situ data in this critical layer. The most promising devices are described in the following.

3.2.1 sUAS

Applications for atmospheric sampling with land-based and airborne sUAS have included sensing and model development for mid-latitude and arctic stable boundary layers, convective boundary layers, orographic effects, wind energy generation, and severe storms. The research to date has proven the viability of sUAS to generate datasets that compare well with measurements obtained using proven methods (Leuenberger et al. 2020; Bell et al. 2020; Barbieri et al. 2019) and demonstrated that targeted drone observations in TCs could provide extremely valuable data sets for improving TC forecasting (Cione et al. 2016, Cione et al. 2020, Bryan et al. 2017, Bousquet et al. 2021).

In order to continue improving TC intensity forecasts, an increased use of sUAS targeted in situ measurements has been proposed. NOAA, in collaboration with Area-I, recently launched the new Altius 600 sUAS (Fig.11a) into the eye of Hurricane Ian to mark the center of the storm, and sample the atmospheric boundary layer environment of the storm a few hours before it made landfall on the west coast of Florida on September 28th, 2022 (Fig. 11b). Future plans for NOAA and Area-I are to conduct additional flights into TCs with an upgraded payload including Black Swift Technologies' multi-hole turbulence probe together with a radar altimeter capable of improved vertical height assignment.

Figure 11: *(a) The Area-I's Altius 600 sUAS being deployed from one of the two NOAA P-3 aircrafts. (b) Location of the drone into the eye of Hurricane Ian superimposed on radar reflectivity on 28 September 2022. Credit: NOAA.*

In a parallel effort, Black Swift Technologies (BST) is currently conducting the development and flight validation of the S0, a commercial sUAS platform designed for air deployment, which will build on the successes of the Aerosonde and Coyote platforms. The key innovation is to reduce the complexity and weight compared with existing platforms, offering an order of magnitude decrease in cost, without sacrificing performance, endurance, and measurement quality. This new development will allow for larger quantities of vehicles to be deployed per season, opening up opportunities for advanced applications such as cooperative control to further improve data gathering capabilities of the system.

3.2.2 Saildrones

Uncrewed surface vehicles such as the Saildrone Explorer developed by *Saildrone Inc.* and *NOAA* represent another great opportunity to sample near-surface atmospheric and upper-ocean properties. These autonomous and remotely piloted surface vehicles are, in particular, capable of making multiple concurrent measurements (wind speed, wave height, temperature, pressure, salinity) outside and within TCs to better understand and forecast ocean processes occurring during rapid TC intensification.

In July 2021, NOAA and Saildrone Inc. deployed five Saildrones equipped with ruggedized "hurricane wings" specifically designed for operating in extreme weather conditions (Fig. 12). One of these Saildrones (SD-1045) encountered Category 4 Hurricane Sam approximately 450 nautical miles NE of Puerto Rico on September 30, 2021. It remained in the storm for several hours, experiencing winds gusting over 57 ms^{-1} and waves up to 27.6 m, while sending near-real-time data (Fig. 13) and video throughout the storm (Foltz et al. 2022; Ricciardulli et al. 2022). During this test field experiment, other Saildrones were also able to make measurements in the vicinity of Tropical Storms Fred, Grace, Henri and Peter.

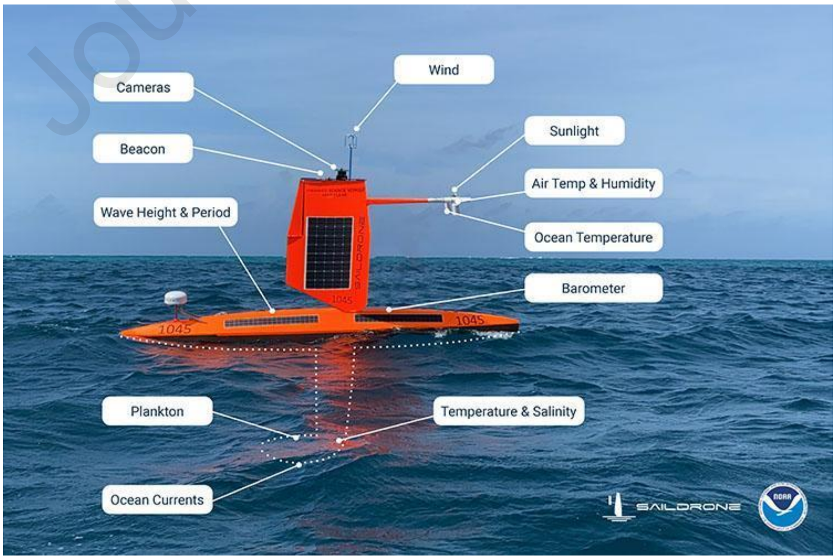


***Figure 12**: Picture of the extreme weather Saildrone uncrewed surface vehicle and its suite of different sensors. Credit: NOAA and Saildrone Inc., ©2021.*

A second test field campaign was conducted during the 2022 North Atlantic TC season, with seven new Saildrones launched from the US Virgin Islands, Florida and Texas. Four of the Saildrones were able to take measurements within Hurricane Fiona during its development from tropical storm to Category 4 hurricane (15-22 September), while another one made measurements northwest of the center of Hurricane Ian during its landfall at the west coast of Florida on 28 September. These unique datasets, which have yet to be processed, will undoubtedly improve our understanding of how air-sea interaction affects TC intensity and significantly help advance TC prediction models.

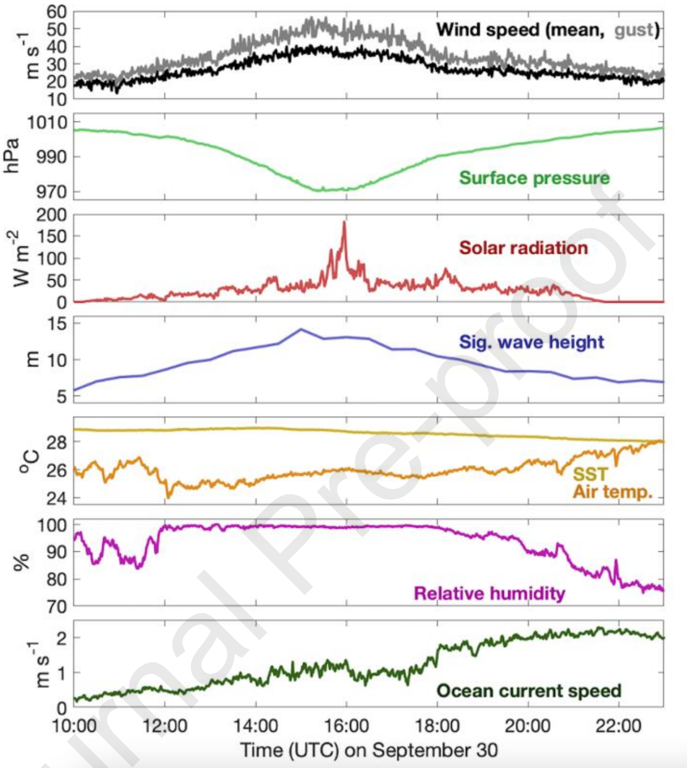


Figure 13*: 1-minute averaged data of wind speed (m s^{-1}), surface air pressure (hPa), solar radiation (W m^{-2}), significant wave height, sea surface and air temperatures, relative humidity, and ocean current speed at a depth of 6 meters, as measured by SD-1045 in Hurricane Sam.* *Reproduced from Foltz et al. (2022).*

3.2.3 Aeroclippers

The Aeroclipper is a balloon device vertically stabilized by a guide rope floating on the ocean surface. It follows the surface wind (quasi-Lagrangian trajectory) and provides surface low-level wind and thermodynamic parameters for up to several weeks in remote regions of tropical oceans. During the VASCO (Validation of the Aeroclipper System under Convective Occurrence) field experiment in the southwestern Indian Ocean (2007), two Aeroclippers penetrated into TC Dora during its developing stage and remained trapped within the eye of the storm for several days (Duvel et al. 2009). Although no atmospheric data were transmitted, this unprecedented event opened new perspectives on the possibility of collecting continuous real-time observations inside TCs from balloon-borne devices.

A new version of the Aeroclipper, specifically designed for TC observations, was eventually developed in 2019 and tested for the first time from the island of Guam in 2022. This new device, which uses a new and much smaller balloon (16 m^3 instead of 100 m^3 in 2007) as well as new acquisition and transmission electronics, can now be deployed by a couple of non-specialists with minimal logistic effort (Fig. 14). The instrumented payload collects pressure, temperature, humidity, wind, and sea surface temperature data with a time step of 6 s and transmits the mean and standard deviation of these parameters over 1 minute in real time via the Iridium satellite system. In order to maximize the chances to intercept a TC, a deployment strategy was also developed:

i) The best deployment sites for a given TC basin are selected by computing a series of virtual Aeroclipper trajectories using climatological data (ERA-5 and IBTrAC). This method can also be used to optimize a combination of deployment sites to better sample a given basin for operational purposes.

ii) During a field campaign, a statistic on trajectories computed every 6 hours using ECMWF and GFS ensemble prediction systems gives the chance to intercept a targeted TC within a five-day window.

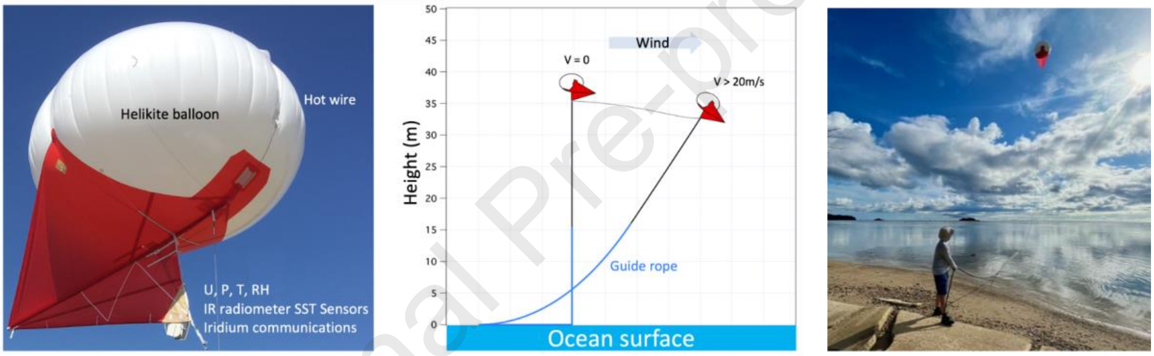


Figure 14: *Pictures and schematic of the Aeroclipper System. (left and middle): design and measurement principle, (right) Aeroclipper released from Guam in September 2022. Credit: Jean-Philippe Duvel.*

The three Aeroclipper prototypes released during the Guam test campaigns in May and September 2022 showed very good reliability for a period of more than 20 days and for heavy rain and wind conditions above 40 kt (~20.6 m s^{-1}). The analysis of these first data has made it possible to improve the new Aeroclipper device and to optimize the deployment decision support tools. A new campaign to evaluate the potential contribution of Aeroclippers to TC observations is planned for September-October 2023.

3.2.4 Smart Weather Balloons

Transformative long-duration balloon technologies have the potential to greatly expand the global observing system by collecting repeated vertical profiles of atmospheric observations throughout the world. Long-duration balloons are especially well suited to collect observations in remote regions including oceanic areas where TCs form and evolve. While the techniques that enable long-duration and vertically navigable balloon flight are not novel, the Global Sounding Balloon system developed by WindBorne

Systems is the first known large-scale demonstration and productization of long-duration, vertically controllable balloons.

Global Sounding Balloons can fly for days to weeks and have been optimized to collect data through repeated vertical profiling of the atmosphere, from 200 m up to 20 km above the surface. With near-real-time bi-directional satellite communications and fully flexible altitude control, the balloons can be actively navigated to target regions by selecting varying winds at different altitudes, allowing for targeted observations despite the balloons lacking active propulsion. The resulting data most closely resembles radiosonde or dropsonde profiles, but with the launch and hardware costs amortized over dozens of soundings and without the need for a separate delivery vehicle to reach any point on Earth. As of today, over 500 Global Sounding Balloons have been flown during 5 different field campaigns conducted in the Pacific Ocean (2), the Arctic (2), and the tropical Atlantic (1), respectively. During summer into fall of 2022, 85 Global Sounding Balloons were flown in the tropical Atlantic, with coverage over nearly the entire basin from only 3 launch locations (Fig. 15).

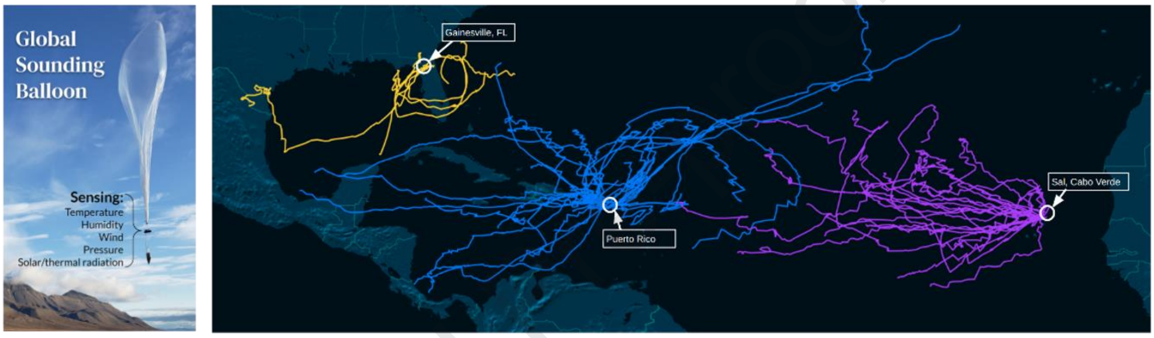


***Figure 15:** Fall 2022 Global Sounding Balloon Atlantic Flight Map — Trajectories of 85 Global Sounding Balloons launched from 3 sites over Sept-Oct 2022, showing the wide geographical reach possible with altitude-controlled long-endurance balloons.*

Over the 2022 North Atlantic TC season, there were already many cases of data collection within tropical waves that had potential for TC development, in the environments around and ahead of TCs, and even within Hurricane Ian (Fig. 16). Although more attempts at navigating into TCs are needed to better understand the possibilities and limitations when flying in TCs of varying intensity, this first demonstration of navigating a Global Sounding Balloon into a TC confirms the high potential of this new device for both research and operational applications.

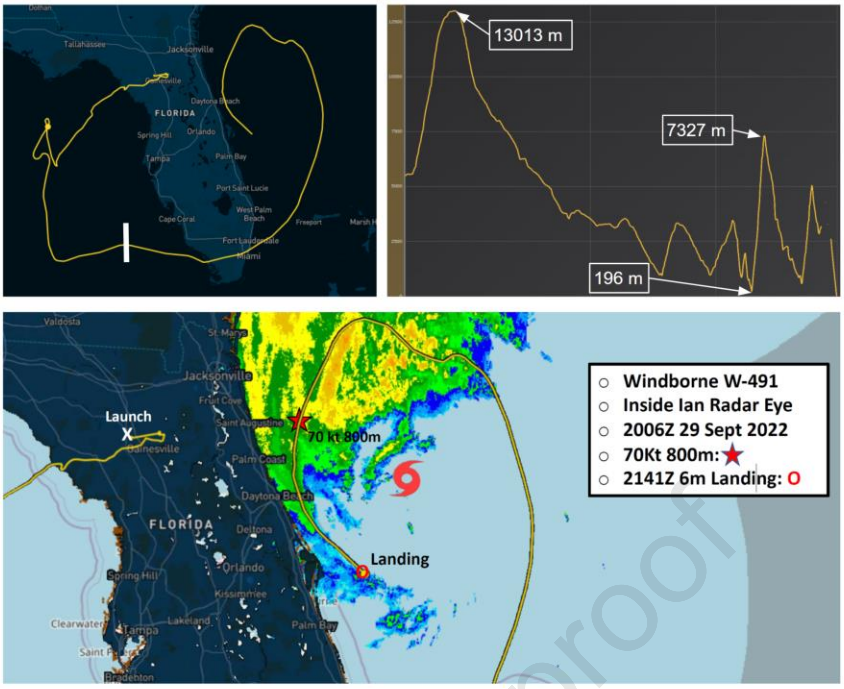


Figure 16: *Path (upper left) of a Global Sounding Balloon that circled Hurricane Ian between 27 September and 29 September 2022. The path is overlaid on a radar image (bottom panel) valid at 21 UTC 29 September just after Ian passed into the Atlantic Ocean and began re-intensification. Over the final 21 hours of flight, the Global Sounding Balloon circled (bottom panel) within the cyclone descending from over 13000 m to as low as 196 m before ascending and descending several times prior to landing (upper right). Wind speeds over 70 kts (36 m/s) were observed at 800 m above ground level at 2006 UTC 29 September.*

4. **Summary and Conclusions**

Significant advancements have been made over the past four years in the collection of aircraft and in situ observations of TCs. Operational data collection in the North Atlantic and East Pacific continues to evolve as research provides new information on the most beneficial methods, times, and regions to sample TCs for the largest impact on improvements to forecasts from NHC and CPHC as well as from numerical weather prediction models. Aircraft and in situ sampling of TCs in the Western Pacific basin also continues to advance with the testing of several uncrewed aerial vehicles and uncrewed aircraft systems through collaborative programs in that region.

New experimental instrumentation (sUAS, expendables, gliders) and emerging technologies (saildrones, balloon-borne devices, biologging) that have the potential to further improve ocean-atmosphere coupled intensity forecasts have also shown promising results and will significantly advance our understanding and sampling of TCs. To realize their full potential these technologies will continue to be more closely integrated with established regional and global ocean and atmosphere observing platforms.

Acknowledgments

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Figure Captions

Figure 1: Percent of NHC-tasked missions out of total NHC-tasked missions categorized by intensity of the system. Missions include both Air Force Reserve and NOAA aircraft and from both Atlantic and East/Central Pacific basins.

Figure 2: A summary of DC-8 flight tracks from NASA’s 2021 CPEX-AW (a) and 2022 CPEX-CV (b) field programs.

Figure 3: Schematic view of the double warm cores observed for Typhoon Lan (2017). Reproduced from Yamada et al. (2021).

Figure 4: (left panel): Typhoon "Nangka" (No. 2016) multi-platform collaborative observation drone detection route and typhoon path. (right panel): The target observation sensitive areas of Typhoons "Conson" and "Chanthu", which are shown in the black box near the center of the typhoon.

Figure 5: (left): IWRAP wind profile below the P-3 measured during an inbound pass into Hurricane Ida on August 29, 2021. Corresponding flight level and SFMR surface wind speeds are shown above and below the IWRAP profile, respectively. (right): Example IWRAP vertical wind speed profile.

Figure 6: KaIA significant wave height data collected during a flight into Hurricane Ida on August 28, 2021 plotted along the flight track (top) and as a time series (middle) as well as the corresponding IFREMER forecast significant wave height and SFMR wind speed and rain rate (bottom).

Figure 7: (left): Underwater glider deployed in the Caribbean Sea in 2018. (right): Location of ocean observational assets in the tropical Atlantic during the passage of Hurricanes Fred and Grace in 2018, with gliders (purple circles), Argo floats (black), XBTs (green), and saildrones (red).

Figure 8: Temperature and salinity measurements (left panel) and current profile measurements (right panel) from an APEX-EM float deployed in Hurricane Nate (2017) over a warm core eddy. Red, light blue, and dark blue profiles signify pre-, in-, and post-storm measurements, respectively. GCW, STW, and SAAIW stand for Gulf Common Water, Subtropical Water, and Sub Antarctic Intermediate Water in the left panel. Velocity profiles (color coded by temperature) were obtained at each black dot (for clarity in the presentation, every other profile is shown). Reproduced from Shay et al. (2019).

Figure 9: Metrics comparing the NCODA analysis to observations from the ALAMO float 9077 deployed ahead of Hurricane Guillermo (Eastern Pacific) in 2015: (a) the sea surface temperature (°C), (b) depth of the 26°C isotherm (m), (c) TC heat potential (kJ cm^{-2}), and (d) average temperature of the upper 100 m (°C). Small triangles with gray dotted lines and TC names along the time axis indicate the time of closest point of approach between the float and each storm. Reproduced from Jayne et al. (2022).

Figure 10: Sea turtles trapped in the vicinity of TCs Kenneth and Herold in the Southwest Indian Ocean. Satellite images of (a) TC Kenneth on 15 April 2019 and (b) TC Herold on 15 March 2020. Animal symbols show the location of the sea turtle “Brice” during the cyclogenesis of TC Kenneth (left panel) and of the sea turtles “India” and “Tom” during the

intensification phase of TC Herold (right panel). (c) Evolution of the sea surface temperature (°C) near the center of TC Herold, as measured by the sea turtle “India” between 14-20 March 2020 within the area [51.93-52.62°E; 13.9/14.67°S]. Reproduced from Bousquet et al. (2021).

Figure 11: (a) The Area-I’s Altius 600 UAS being deployed from one of the two NOAA P-3. (b) Location of the drone into the eye of Hurricane Ian superimposed on radar reflectivity on 28 September 2022. Credit: NOAA.

Figure 12: Picture of the extreme weather saildrone uncrewed surface vehicle and its suite of different sensors. Credit: NOAA and Saildrone Inc., ©2021.

Figure 13: 1-minute averaged data of wind speed (m s^{-1}), surface air pressure (hPa), solar radiation (W m^{-2}), significant wave height, sea surface and air temperatures, relative humidity, and ocean current speed at a depth of 6 meters, as measured by SD-1045 in Hurricane Sam. Reproduced from Foltz et al. (2022).

Figure 14: Pictures and schematic of the Aeroclipper System. (left): design and measurement principle, (right) Aeroclipper released from Guam in September 2022. Credit: Jean-Philippe Duvel.

Figure 15: Fall 2022 Global Sounding Balloon Atlantic Flight Map — Trajectories of 85 Global Sounding Balloons launched from 3 sites over Sept-Oct 2022, showing the wide geographical reach possible with altitude-controlled long-endurance balloons.

Figure 16: Path (upper left) of a Global Sounding Balloon that circled Hurricane Ian between 27 September and 29 September 2022. The path is overlaid on a radar image (bottom panel) valid at 21 UTC 29 September just after Ian passed into the Atlantic Ocean and began re-intensification. Over the final 21 hours of flight the Global Sounding Balloon circled (bottom panel) within the cyclone descending from over 13000 m to as low as 196 m before ascending and descending several times prior to landing (upper right). Wind speeds over 70 kts (36 m/s) were observed at 800 m above ground level at 2006 UTC 29 September.