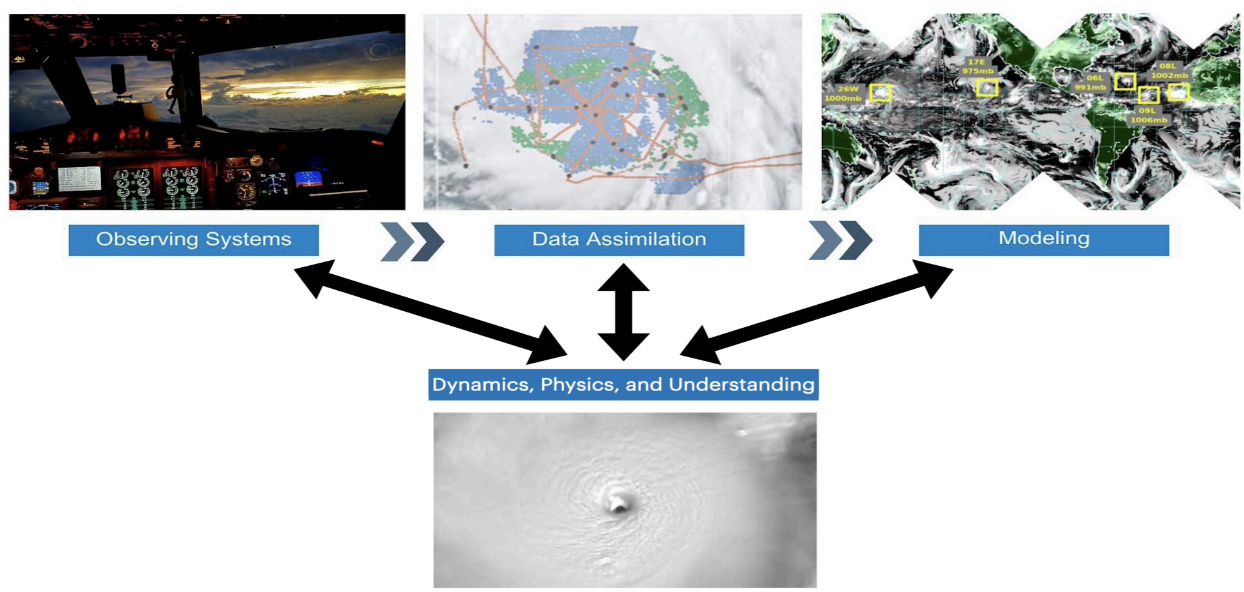
NOAA AOML's Hurricane Research Division

NOAA/OAR/AOML's Hurricane Research Division (HRD) supports NOAA's mission to improve forecasting of tropical cyclones to protect life and property. HRD improves forecasts and helps NOAA create a weather-ready nation by developing and deploying observing systems to study the structure and impact of tropical cyclones, quality controlling and assimilating the observation into computer models and developing and improving next-generation models for better prediction.

Our objective:

We are dedicated to characterizing, understanding, and predicting physical processes important to the prediction of tropical cyclone track, intensity, and structure change and their impacts (rainfall, surge, flooding, damaging waves, winds, and severe weather). AOML researchers optimize the use of observations to improve global and hurricane forecast guidance. AOML researchers strive to advance hurricane forecast guidance by creating and verifying next-generation numerical models, and advance data assimilation techniques in support of NOAA's Unified Forecast System.



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Atlantic Oceanographic and Meteorological Laboratory (AOML)
Hurricane Research Division (HRD)
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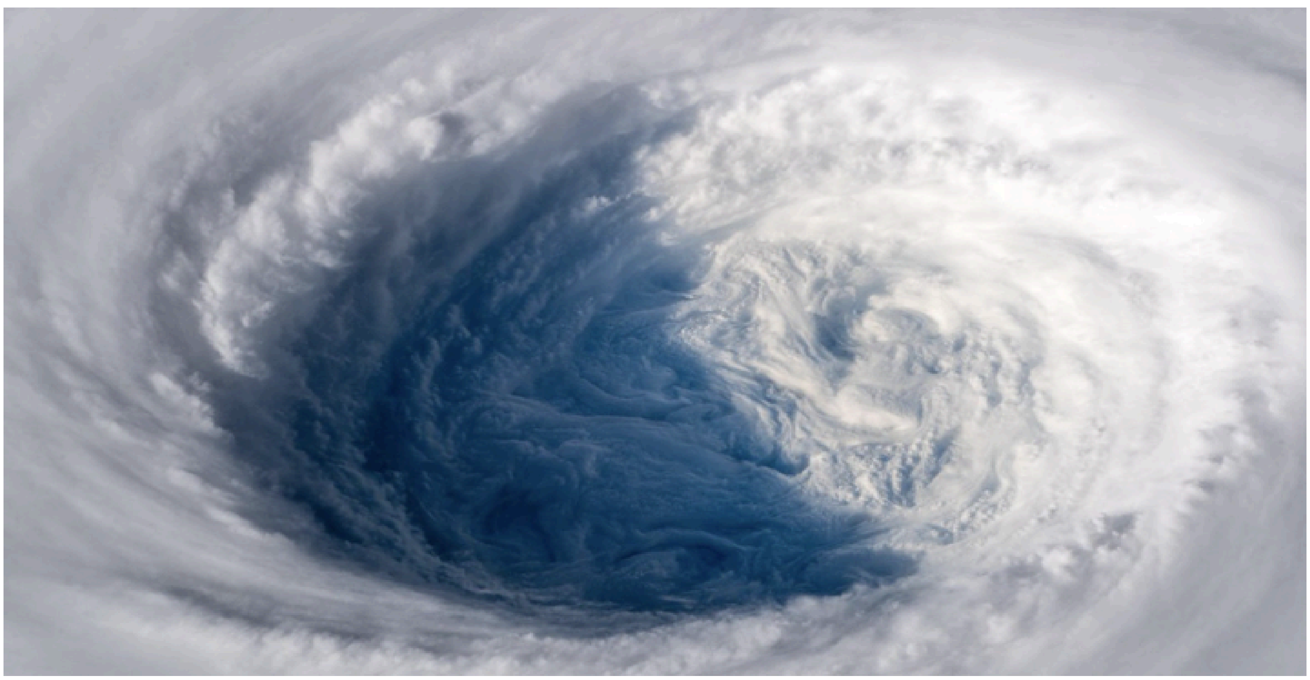

Hurricane Research Division Structure

Leadership

Director: Ghassan "Gus" Alaka, Ph.D.
Deputy Director: Shirley Murillo

Observation Team

Sim Aberson, Ph.D. [Team Lead] (NOAA)
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Joseph J. Cione, Ph.D. (NOAA)
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Kathryn Sellwood (CIMAS)
Jun Zhang, Ph.D. (CIMAS)

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Data Assimilation Team

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Xin Yang, Ph.D. (CIMAS)

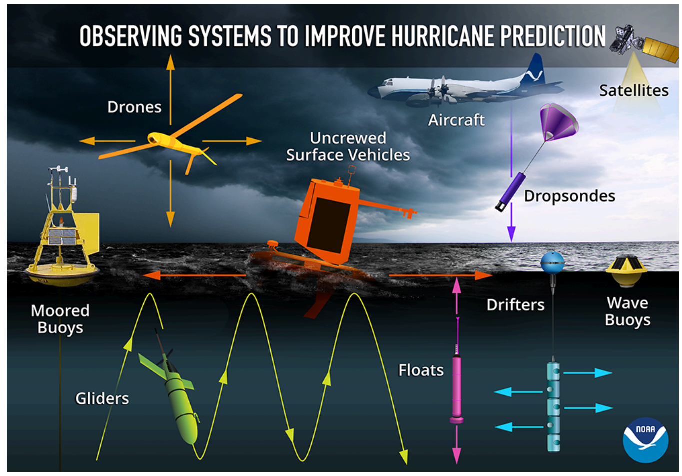
Observing Systems

Research Team Leading this Effort: Observations Team
Project Lead: Sim Aberson, Ph.D.

Researchers at AOML develop and deploy an array of instruments to measure conditions in and around tropical cyclones, work on quality control and transmission of the data to operational centers for **data assimilation** into models, validate new and remote observational platforms including satellites, and develop and verify optimal sampling strategies for forecast improvement. The data from these instruments are vital to enhance forecasters' understanding of tropical cyclone **dynamics and physics** behavior and their representation in numerical **models** and to improve hurricane prediction models, leading to better preparedness and response strategies.

The annual Hurricane Field Program has a variety of experiments to research the tropical cyclone lifecycle, from genesis to decay, as well as ocean observations and satellite validation, all in support of NOAA's Advancing the Prediction of Hurricanes Experiment (APHEX). APHEX broadens the goals of the 2005-2020 Intensity Forecasting EXperiment by incorporating current, 5-year Hurricane Forecast Improvement Program (HFIP) priorities around better forecasting and communicating for all hazards (wind, rain, surge, and tornadoes). In partnership with NOAA's Environmental Modeling Center; National Hurricane Center; Aircraft Operations Center; National Environmental Satellite, Data, and Information Service; and AOML's Physical Oceanography Division, the goal of APHEX is to improve understanding and prediction of hurricane track, intensity, three-dimensional structure, and hazards by collecting observations that will aid in the improvement of current operational hurricane models, such as the Hurricane Analysis and Forecast System (HAFS) model, and the development of the next-generation operational model and data assimilation systems.

Observational Instruments



NOAA's hurricane hunter aircraft are flying laboratories that make up the backbone of AOML's tropical cyclone observing capabilities. The WP-3D-Orion (P-3) flies directly into the tropical cyclones, whereas the Gulfstream IV-SP (G-IV) flies around them. A Gulfstream G550 will replace the G-IV after the 2025 hurricane season, and C-130J aircraft are expected to replace the P-3s by 2030. Much of the aircraft data are transmitted in real time for data assimilation into numerical models and operational analysis. The data are used by researchers to improve and verify model systems (including data assimilation) and to improve understanding of the dynamics and physics of tropical cyclones.

Flight-level Measurements [P-3s and G-IV]

Data from flight-level measurements are provided up to 40 times per second and include location, true air and ground speeds, radar and pressure altitudes, static and dynamic air pressures, air temperature, dew-point temperature, d-value, three-dimensional wind velocity, water vapor mixing ratio, and surface pressure extrapolated from the aircraft. These data serve as a baseline for other aircraft observations, and for studies of turbulence within the circulation..

Tail Doppler Radar (TDR) [P-3s and G-IV]

The P-3 and G-IV TDR have two solid-state transceivers that simultaneously transmit through two antennas canted approximately 20 degrees fore or aft of the aircraft fuselage. They measure the radar reflectivity (precipitation intensity) and the wind toward and away from the radars. The raw data are transmitted from the aircraft for assimilation into numerical models. Data from the two antennas are combined into three-dimensional analyses of the wind that are transmitted for operational analysis of intensity and structure. The data form the basis for studies of physical and dynamical processes since they show full, three-dimensional kinematic structures and how they change in time.

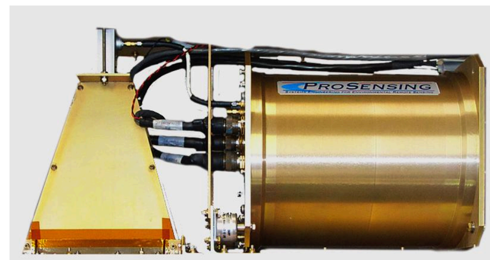
Multi-Mode Radar (MMR) [P-3s]

The MMR is a horizontally-scanning pulse Doppler radar system with a range up to 200 n mi, that has multiple operational modes available to the radar operator. Most relevant to hurricane operations is the Hurricane Weather mode with turbulence identification. The radar reflectivity provides snapshots of the tropical cyclone structure.

Ocean Platforms & Expendables [P-3s]

Airborne Expendable BathyThermographs measure ocean temperature from the surface to depths of 400 m (shallow water probes) and 800 m (deep water probes). Airborne Expendable Current Profilers measure ocean temperature and velocity as they descend in the ocean. Airborne Expendable Conductivity, Temperature, and Depth probes: measure ocean temperature and salinity versus depth as they descend. MicroSWIFT expendable wave buoys measure significant wave height, peak wave period, dominant wave direction, the scalar wave energy spectrum, and directional moments of the spectrum. Much of these data are available for assimilation into numerical models. All these data are important for studies of the boundary layer, air-sea interaction, and the ocean response to tropical cyclones.

Stepped-Frequency Microwave Radiometer (SFMR) [P-3s]



SFMR retrieves surface wind speed and column rain rate estimates by measuring the surface brightness temperature directly below the aircraft at six frequencies. The apparent brightness temperature of the ocean surface is sensitive to the sea surface temperature (SST) and surface foam coverage due to wave breaking; as the surface wind speed increases, so does the coverage of sea foam and, subsequently, the brightness temperature increases with surface wind speed for a given SST.

Global Positioning System Dropsondes [P-3s and G-IV]

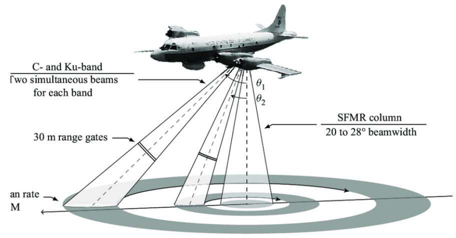
Figure 4: Release of a dropsonde from a NOAA Twin Otter aircraft. (Image

The GPS dropwindsonde (dropsonde) measures atmospheric temperature, pressure, humidity, and wind velocity up to four times per second as it falls from the aircraft to the surface and transmit the data back to the aircraft during their descent for quality control and transmission to operational centers, and have enabled some of the key forecast and research innovations during the last few decades.

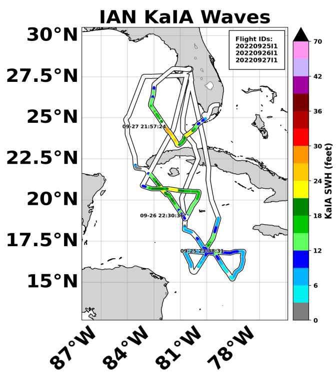
Cloud Microphysics [P-3]

These probes image cloud and precipitation particles to create particle-size distributions. The Droplet Measurement Technologies, Inc. Cloud Combination Probe (CCP) includes 2 instruments, the Cloud Droplet Probe and the Cloud Imaging Probe, to measure particles at a wide range of sizes, providing two-dimensional images and precipitation size distributions. The Precipitation Imaging Probe and the Cloud and Aerosol Spectrometer measure hydrometeor sizes not seen by the CCP. All these data are used to study the precipitation composition and structure within the tropical cyclone and to improve the representation of cloud microphysics in numerical models.

Imaging Wind and Rain Airborne Profiler (IWRAP) [P-3]



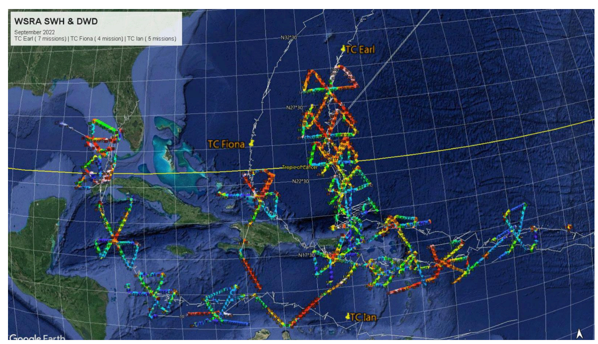
IWRAP, also known as the Advanced Wind and Rain Airborne Profile, consists of two dual-polarized, dual-incidence angle radar profilers that measure volume reflectivity and Doppler velocity of precipitation, as well as ocean surface backscatter. These measurements are vital to understanding the low-level wind and precipitation structures that impact the earth's surface.



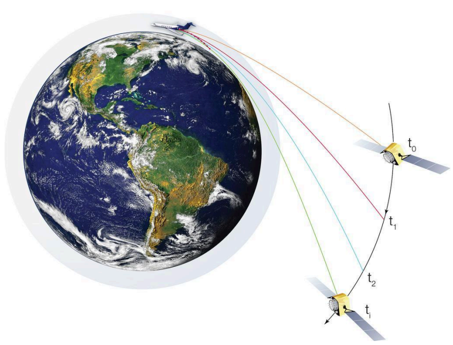
Ka-band Interferometric Altimeter (KaIA) [P-3]

KaIA is a next-generation centimetric radar altimeter that provides real-time observations of significant wave height of the ocean surface directly below the aircraft. KaIA can retrieve mean-squared surface slope, relative ocean height, and wind speed estimates at low wind speeds where other instruments are not as accurate.

Wide Swath Radar Altimeter (WSRA) [P-3]



The ProSensing Inc. WSRA measures sea surface topography and rain rate. It offers real-time information on significant wave height, ocean directional wave spectra, the mean-square slope of the ocean surface, and rain rate. These data are critical to understanding ocean processes and storm surges.



Airborne Radio Occultation (ARO) System [P-3 & G-IV]

The ARO system uses Global Navigation Satellite System signals, including GPS, to retrieve refractivity profile observations continuously during flight, typically providing 30-45 profiles over a 7-8 hour flight. ARO provides slanted profiles of temperature and moisture with 400 m vertical resolution roughly 400 km to the side of the flight track.

Platforms independent of Hurricane Hunter Aircraft

Gliders, autonomous underwater vehicles (AUVs) deployed during hurricane season to gather data to allow ocean conditions to be more accurately represented in forecast models.

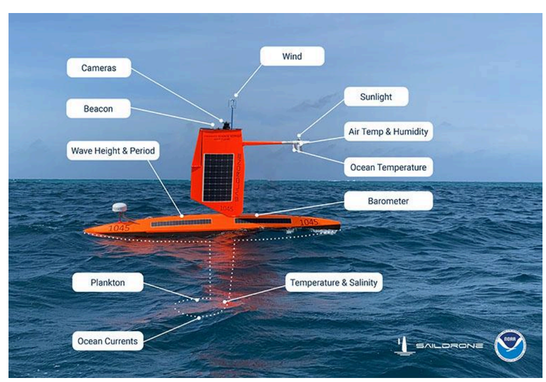
Argo floats that drift with ocean currents and move up and down from the surface to 2 km below. These floats are distributed all over the global ocean and are in place year-round to measure temperature and salinity in the upper ocean.

Emerging Technologies

In addition to these vital instruments that have been used for decades, AOML researchers develop new tools designed to capture data in previously inaccessible regions of the tropical cyclone. Researchers work to develop, test, and implement promising new technologies and concepts of operations.

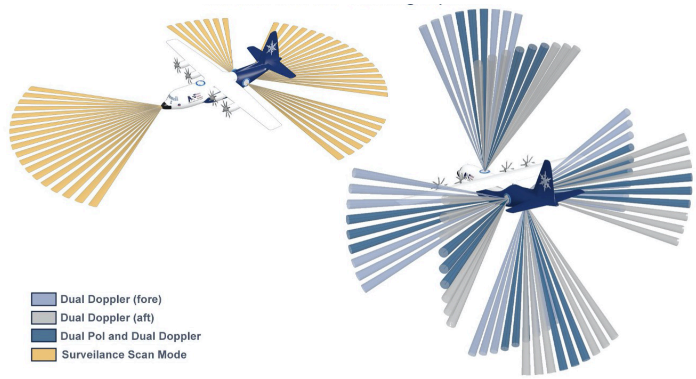
Uncrewed Aircraft Systems, commonly known as drones, provide data for scientists to study the boundary layer where the atmosphere directly interacts with the ocean's surface. AOML researchers work with multiple organizations and businesses to develop platforms to measure this critical region that has previously been difficult to measure.

Saildrones represent the intersection of atmospheric and oceanic observation instruments; their unique shape allows them to take measurements above and below the water. The data provide scientists with crucial information about the boundary layer where the ocean and atmosphere transfer the energy that fuels the tropical cyclones.



StreamSondes are ultra-lightweight, biodegradable instruments developed by Skyfora that are released from the aircraft to gather atmospheric data similar to the GPS dropwindsondes. Upgrades will allow up to 50 to be in the air at one time, as compared to 8 for the current dropsonde systems.

With the hurricane hunter P-3 scheduled to be replaced with C-130J aircraft by 2030, a new vertically-scanning Doppler radar system will be required. AOML researchers work with other NOAA agencies and affiliates to ensure that research requirements are met in the radar design. Additionally, to facilitate the timely acceptance of the new radar for operational and research use, AOML researchers develop new, automated radar processing software that employs modern techniques like machine-learning methods to maximize the benefit of the new radar for hurricane operations and the research community in collaboration with other aircraft stakeholders.

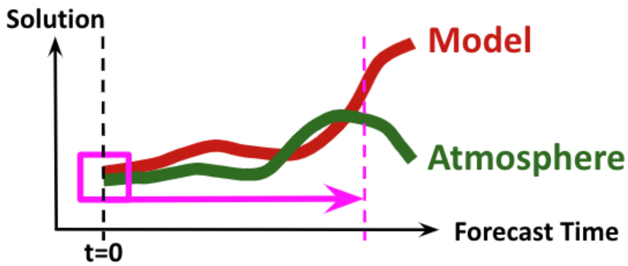


Who We Collaborate With: *NOAA:* National Weather Service, Environmental Modeling Center, National Hurricane Center, Central Pacific Hurricane Center, Aircraft Operations Center, National Environmental Satellite, Data, and Information Service Center for Satellite Applications and Research, Global Ocean Monitoring and Observing, Physical Sciences Laboratory, National Severe Storms Laboratory

Other federal: Office of Naval Research, National Aeronautics and Space Administration

Academic: University of Wisconsin Cooperative Institute for Meteorological Satellite Studies, University of San Diego Scripps Institution of Oceanography, University of Miami, Florida State University, Colorado State University, National Center for Atmospheric Research

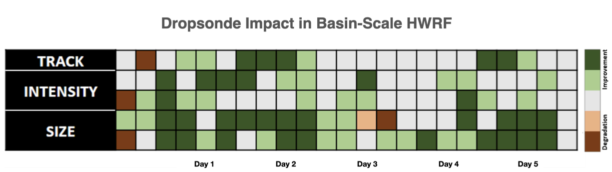
Data Assimilation



Research Team Leading this Effort: Data Assimilation Team
Project Lead: Jason Sippel

The atmosphere/ocean system is chaotic, resulting in forecasts rapidly diverging due to very small initial differences. One solution to examining tropical cyclones and improving model forecasts is to use data assimilation (DA) techniques to combine previous forecasts with new observations, minimizing the difference between the model and the atmosphere at the analysis time. AOML focuses on **observing systems** to analyze tropical systems and their near environments to study their structure and **dynamical and physical** processes, and to improve numerical **models and prediction**. Specifically, AOML researchers focus on HAFS and the Modular Ocean Model 6 ocean component and their DA to understand how to better use the observations to improve NOAA's operational forecasts. AOML researchers are part of the NOAA/Environmental Modeling Center's team that works on the Joint Effort for Data Assimilation Integration (JEDI) system with the goal of integrating all NOAA models into this new data assimilation platform.

Observing System Experiments to systematically evaluate and optimize observations for sampling of tropical weather systems. In particular, these experiments inform strategies for using mobile platforms such as reconnaissance aircraft, and test data from emerging technologies in both the global model and regional hurricane models.



Advanced verification techniques allow for verification of model forecasts beyond the traditional metrics of track and intensity. Variables verified include track, two measures of TC intensity (maximum sustained surface wind speed and minimum sea-level central pressure) as well as the surface wind structure (maximum radii of 34-, 50-, and 64-kt sustained surface wind speed in four quadrants. A new consistency metric evaluates the robustness of forecast improvements. It combines useful information from mean absolute errors, the frequency of superior performance (how often one model forecast is better than another), and median absolute errors (the value at which the same number of forecasts have larger and smaller errors). Thus, this new metric effectively compresses information about the error distribution into a simple, yet thorough, way to gauge consistency in a sample.

To optimize the use of observations within the DA system, new diagnostic tools to evaluate the system's performance for each observation type, advanced quality control techniques to robustly identify outlier observations that may be problematic, and improved observation error assignments to effectively use observations are continuously developed and implemented in experimental versions of HAFS-DA. The ultimate goal is to work with the NOAA/Environmental Modeling Center to transition all of these developments into the future operational implementation of the JEDI platform.

Who We Collaborate With: *NOAA:* Environmental Modeling Center; National Hurricane Center, National Environmental Satellite, Data, and Information Service Satellite Oceanography and Climatology Division, Office of Science and Technology Integration Modeling Program Division

Other federal: Joint Center for Satellite Data Assimilation

Academic: University of Miami, University of Maryland - College Park, University of Oklahoma, Florida State University, Embry-Riddle Aeronautical University, University Corporation for Atmospheric Research, Colorado State University Cooperative Institute for Research in the Atmosphere

Corporate: StratoSolutions, WindBorne Systems

Modeling & Prediction

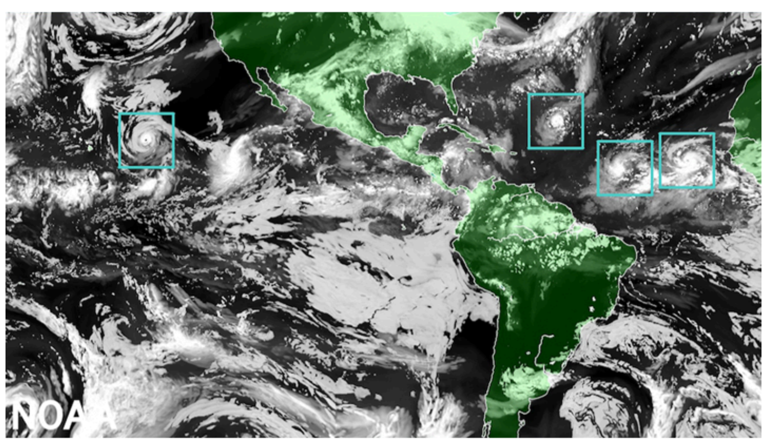
Research Team Leading this Effort: Modeling Team
Project Leads: Sundararaman (Gopal) Gopalakrishnan, Ph.D.

AOML's Hurricane Modeling Team develops and evaluates experimental and operational hurricane forecast models and products for transitions from research to applications and operations. The group's scientists are from the diverse fields of meteorology, oceanography, numerical models, and computer science. The team leads the research and development of NOAA's hurricane model systems, specifically next-generation HAFS. New developments and innovations to model systems are based on data from **observing systems** and their **assimilation** into the models, and are tested and evaluated in near real-time during each hurricane season and successful ones are transitioned to operations. The model systems are integral to understanding the complicated **dynamics and physics** of tropical systems.

Objectives:
The primary objective to develop and advance NOAA hurricane research and forecast model systems. The program's efforts aim to:

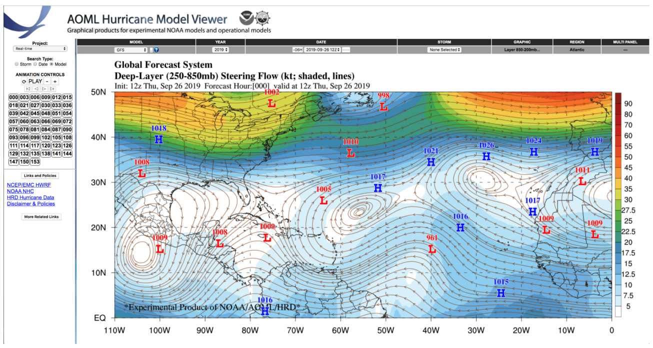
- Develop research and forecast models
- Advance the understanding of hurricane processes using high-resolution numerical model systems
- Utilize observations from the Hurricane Field Program to improve physical parameterizations
- Transition model research and developments into operations

Hurricane Analysis and Forecast System (HAFS) development



HAFS is NOAA's next-generation numerical model and data assimilation system, developed within the framework of the Unified Forecast System. HAFS reliably and accurately forecasts tropical cyclone track, intensity, and structure, including rapid intensity changes, genesis, and size. Key advancements from the team include the development and implementation of multiple moving nests, and the evaluation of model physics. These mark a significant step forward in NOAA's hurricane forecast capabilities.

Hurricane Model Viewer



The AOML Hurricane Model Viewer is a web portal displaying products to enhance research and evaluation of experimental/operational models. It serves to inform numerical weather prediction model developers and forecasters, to enhance situational awareness in NOAA's Hurricane Field Program, and as a testbed to improve operational forecast products. Users have the ability to compare large-scale fields, vortex-scale fields, and statistical metrics across different model output and storms. Products that compare model output to observations are available (e.g., simulated radar reflectivity versus NOAA P-3 Tail Doppler Radar). The Viewer has been a critical tool to evaluate Hurricane Forecast Improvement Project Real-time Experiments, contributing to the improvement of the Global Forecast System and HAFS.

Statistical Models

Rapid intensification occurs in over 80% of major hurricanes and all category-four and -five hurricanes in the Atlantic Basin. The largest operational intensity forecast errors occur due to the difficulty in forecasting processes relating to rapid intensification. Improving forecasts of these cases is a major priority to the operational community. A suite of statistical models has been developed to aid forecasters in predicting rapid intensification in both the Atlantic and Pacific basins. These models use the National Center for Environmental Prediction's global model output, additional satellite data, and information on past hurricanes to estimate the probability that a tropical cyclone will undergo rapid intensification at a given lead time through five days. This is in contrast to the full-physics models such as the global model and HAFS.

One model developed jointly by researchers from AOML, NHC, and NOAA/NESDIS is the SHIPS rapid intensification index. It uses linear discriminant analysis to estimate the probability of rapid intensification. Upgrades include development of models for different lead times through 3 days. Though the suite of models improves forecasts, some errors remain large, and further innovations include a new probabilistic RI consensus forecast model based on the current suite.

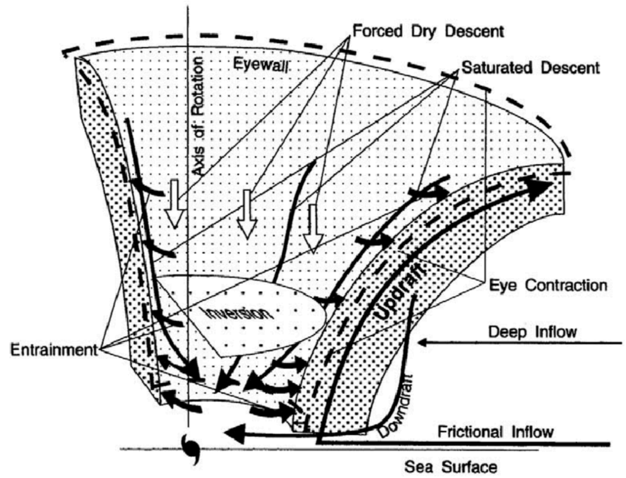
Who We Collaborate With: *NOAA:* AOML/Physical Oceanography Division, Environmental Modeling Center, National Hurricane Center, Office of Science and Technology Integration Modeling Program Division, Geophysical Fluid Dynamics Laboratory.

Other federal: National Aeronautic and Space Administration Jet Propulsion Laboratory
Academic: University of Texas-Austin, University of Miami, Colorado State University Cooperative Institute for Research in the Atmosphere, University of Alabama in Huntsville, University at Albany - State University of New York

International: India Ministry of Earth Sciences, National Institute of Technology, Rourkela, India

Dynamics and Physics

Research Team Leading this Effort: Division wide

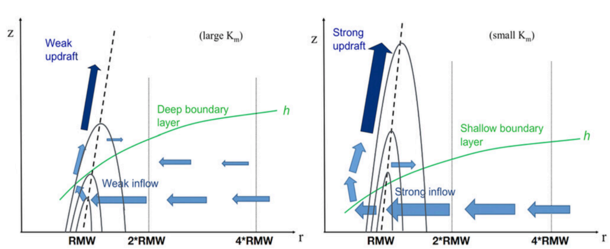


The destructive potential of a hurricane is governed by its interaction with the environment and internal physical processes. Researchers at AOML use a variety of tools, such as **observations** and **numerical model** and **assimilation** systems, to better understand how phenomena from the larger environmental scale down to the cloud and turbulent scales interact (multi-scale interactions) to produce such changes. AOML researchers work closely with scientists from other disciplines to improve the tools available and to apply a new understanding in a way that benefits prediction and improves forecasts.

To comprehensively examine and model tropical cyclones, AOML researchers investigate components of the external environment such as distributions of moisture and wind and sea surface temperature , the interaction with the tropical cyclone itself, and physical processes that operate within the tropical cyclone core leading to significant short-term changes in size and intensity.

Objective:
To improve understanding of tropical cyclone structure and intensity change through the application of fundamental physical principles.

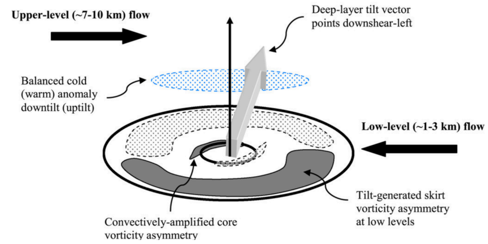
Tropical cyclogenesis:
Although the ingredients for tropical cyclone formation have been well-documented for decades, it is still difficult to predict which disturbances will develop and which ones will not. A big factor in this uncertainty is the amount of moisture in the air mass ahead of, and interacting with, the disturbance. Also important is the precipitation (rainfall) structure and organization and the developing circulation response, in the context of environmental characteristics, during the formation process.



Boundary layer/Air-sea interaction
The boundary layer between the ocean and the atmosphere is where the tropical cyclone is in direct contact with the ocean moisture and heat sources which power them. Understanding and improving models of boundary layer processes is crucial to creating better forecasts, especially of intensity and surface wind structure.

Vortex tilt and alignment

The tropical cyclone intensification rate is strongly related to the vertical alignment of its circulation. However, the physical processes responsible for changes in the circulation's alignment are only beginning to be understood.

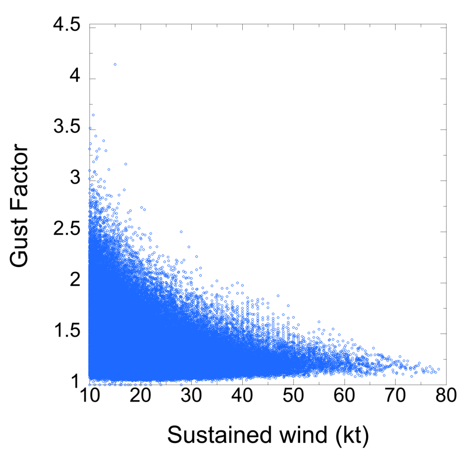


Rapid intensification

Although strong shear is detrimental to tropical cyclone intensification, and weak shear may spur intensification, the impact of moderate shear is not well understood. Tropical cyclones in moderate shear are often asymmetric, and substantial intensification can occur on short time scales (1-2 hours or less). By focusing on where the strong winds and rain exist, scientists can understand how intensification begins and improve forecasts of this potentially devastating event.

Surface wind structure

Estimation of tropical cyclone wind hazards often requires assumptions about surface wind characteristics relative to available flight-level observations. Approximations of surface wind with flight-level data have been routinely supported by symmetric assumptions, but observational and model comparisons suggest departures from this framework. Research is being done to refine assumptions asymmetrically, estimate the uncertainty in quadrant wind radii, investigate asymmetries in the boundary layer as they relate to wind and wave hazards, and expose potential biases in numerical weather and climate models. At landfall, tropical cyclones often produce a variety of high-impact weather, including tornadoes and damaging winds (particularly gusts) for which there exists limited objective forecast guidance. Research on these topics focuses on improving both understanding and capability to predict the dangerous phenomena occurring with landfalling systems.

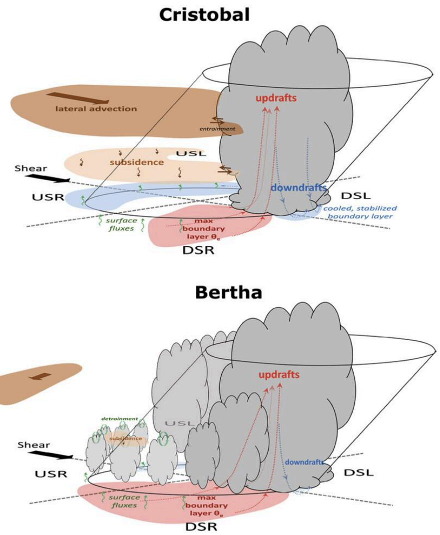


Surface wind gusts

Although wind gusts are responsible for much of the wind damage from landfalling tropical cyclones, there is currently very little objective guidance on wind gust magnitude. Constant gust factor values are typically applied to the sustained wind speed to predict wind gust magnitudes though there is considerable spread. The relationship between gust factors and sustained wind speed, surface roughness, distance and azimuthal location from the center, time relative to landfall, and storm latitude are being studied to continuously improve models and forecasts.

Extratropical transition

Tropical cyclones may either decay (spin down) or transform into powerful extratropical cyclones when they encounter cold water below or high wind shear in the atmosphere. The mechanisms by which tropical cyclones become extratropical is not well forecast by numerical models leading to large errors, especially in impacts downstream of the actual transitioning cyclone.

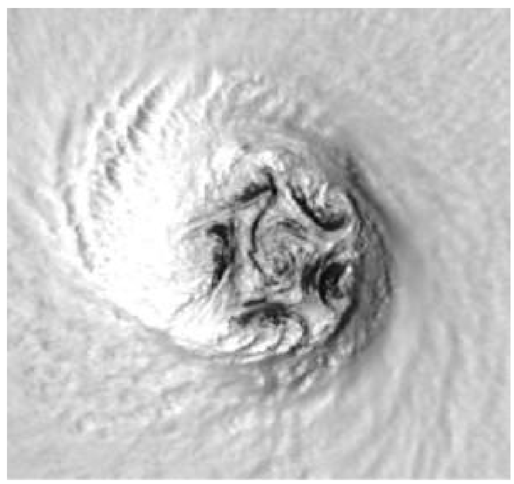


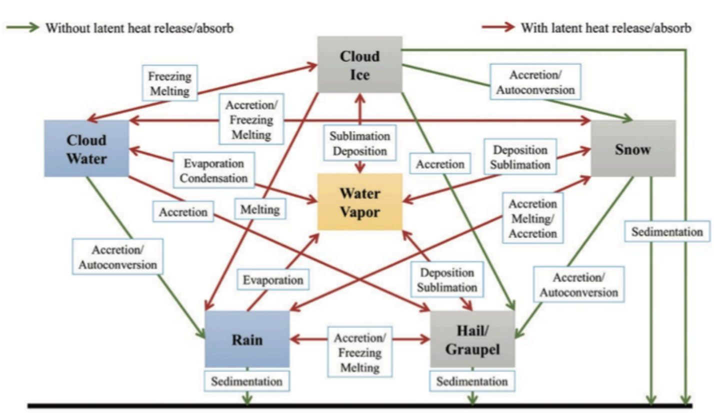
Dry-air entrainment/ventilation

Ventilation occurs when dry and/or cool environmental air intrudes into a sheared or tilted tropical cyclone. Ventilation pathways include lateral intrusion and downward intrusion of dry and/or cool air. Both pathways may inhibit intensification but the link between ventilation and intensity change requires further study.

Eye-eyewall mixing

Small features in the eyewalls of very intense tropical cyclones are hypothesized to increase the amount of energy available for hurricane intensification or cause damaging surface wind at landfall or intense turbulence features impacting flight operations. The structures of these features, especially the temperature and humidity structures, have never been documented, and their importance remains unknown.



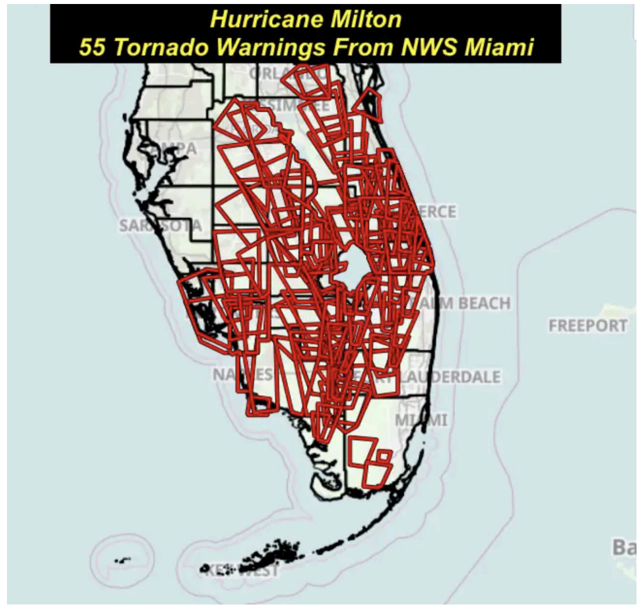


Cloud Microphysics

The distribution of cloud and rain droplets and ice and snow particles are vital in understanding the energy release in tropical cyclones. How they vary is important for the understanding of intensification and for improvement of model microphysical parameterizations.

Fundamental vortex research

Until recently, no objective definition of a vortex was available. New techniques to define vortices provide the opportunity to find new ways to understand the large hurricane circulation and meso- and miso-scale vortices that are embedded within.



Supercells and tornadoes in hurricanes

Supercells in landfalling tropical cyclones TCs often produce tornadoes, but their existence is not explained by conditions around the storm, suggesting the importance of internal processes. Past case studies point to temperature and moisture contrasts between ocean and land or convergence along the coast as a possible mechanism for enhancing supercell mesocyclones and storm intensity. New work has shown that conditions near the surface over land may impact tornado development.

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