Priority Recommendations for Integrating Ocean Observations to Improve NOAA’s Hurricane Intensity Forecasts
**Introduction**

**Priority Recommendations**
- Coordinate efforts to close gaps in ocean and transition zone observations
- Evaluate the impacts of ocean and transition zone observations on hurricane intensity forecasts
- Improve assimilation of ocean and transition zone observations into numerical modeling systems
- Prioritize and recommend ocean and transition zone observations for future operational investment

**Enabling Frameworks and Infrastructure**
- Extreme Events Ocean Observations Task Team
- Coordinated Ocean Observations Working Group
- Aircraft Deployment Working Group
- Integrated Modeling Prediction Assimilation Coordination Team (IMPACT)
- Prioritization and Resourcing Working Group

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**Appendix B. Supporting Materials**

**Appendix C. Crosswalk of Line Office Priorities**

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Introduction

On September 8, 1900, the great Galveston Hurricane tore through the Texas island, with winds exceeding 130 miles per hour and a 15-foot storm surge. While Isaac Monroe Cline, the Galveston Weather Bureau climatologist, was aware the hurricane had passed over Cuba, wireless ship-to-shore communication was not available in 1900 to provide up-to-date information indicating the hurricane was strengthening and heading toward Texas. As the storm neared, Cline became increasingly suspicious of the weather and attempted to warn the citizenry of the approaching risk by raising the hurricane warning flags atop the Galveston Weather Bureau building the day before the hurricane struck. However, many people stayed on the beach and, to this day, the 1900 Galveston hurricane remains the Nation’s deadliest natural disaster, with more than 8,000 people killed and over 3,600 homes and buildings destroyed. This storm focused Cline’s research on understanding the physical forces of tropical cyclones and devising rules for forecasts and warning, together resulting in significant contributions to forecasters and the public.

The unprecedented 2020 Atlantic hurricane season highlights the massive improvements in hurricane forecasts over the past 120 years — and how important it is to improve them further. Whereas the error in 48-hour track forecasts has been reduced by more than half in the past two decades, intensity forecasts remain a challenge, particularly with storms that rapidly intensify. The unprecedented 2020 hurricane season also highlighted what scientists do, and do not, know about how hurricanes will change as the climate warms.

Scientists are increasingly aware of the important role the ocean plays in weather prediction. However, the frequency and density of ocean observations do not match the amount of data available for atmospheric parameters. The 2020 hurricane season underscores the importance of making the following our national priorities for sustained investments: (1) ocean observations; (2) co-location of air-sea observations; and (3) integration of these observations into numerical models. More accurate, and more reliable, forecasts will allow greater lead times for pre-storm mitigation efforts, enhanced protection of life and property, and an overall reduction in the economic impact of damaging storms, potentially saving hundreds of lives and billions of dollars.

“I decided that I could be of greater service to humanity by determining what are the physical forces in the cyclones that develop the storm tides and by devising rules for use in forecasting and warning the public in advance of their arrival”

-Isaac Cline
Priority Recommendations

The recommendations outlined in this report were informed by the 2020 Integrating Ocean Observations to Improve NOAA's Hurricane Intensity Forecasts Workshop. Addressing these recommendations will require coordinated implementation across NOAA mission areas, programs, and service areas and an integrated ocean observing system that can be used to better initialize and validate numerical models.

- **Coordinate efforts to close gaps in ocean and transition zone observations**
  Improving NOAA's hurricane intensity forecasts will require closing gaps in ocean and air-sea observations, as these data are key to better understanding the interaction processes that lead to the formation and intensification of storm systems. However, an integrated multi-platform, coordinated ocean observing system is not currently in place at NOAA. Ocean and air observing systems can be better leveraged and coordinated within NOAA and with external partners to close gaps in observations prior to and during the hurricane storm season (e.g., enhancing co-located ocean-atmosphere observations in the air-sea interface zone and the lower atmospheric boundary layer).

- **Evaluate the impacts of ocean and transition zone observations on hurricane intensity forecasts**
  Assessing the impacts of ocean and co-located air-sea data is necessary to understand the effectiveness of observation types during the course of a storm and to determine the optimal network design when planning a new observing strategy, reorganizing existing observing networks, or investing in future observing systems. Observing System Experiments (OSEs), Observing System Simulation Experiments (OSSEs), and data-denial studies must be done to assess the impacts of different observations and/or combined observations for improving NOAA's ocean observing strategies.

- **Improve assimilation of ocean and transition zone observations into numerical modeling systems**
  Assimilation of more ocean and co-located air-sea data into numerical models is needed to improve hurricane intensity forecasts. Collaboration between NOAA and non-NOAA partners is needed to improve data assimilation (DA) software and development practices to build state-of-the-art assimilation systems; observational targeting practices through analysis of available ensemble model sensitivity patterns; NOAA's current and next generation hurricane modeling systems; understanding of hurricane processes using high-resolution numerical modeling systems; and physical parameterizations in modeling systems.

- **Prioritize and recommend ocean and transition zone observations for future operational investment**
  Improving future observing strategies requires understanding the following questions: What observations are needed? When are these observations needed? Why are these observations needed? Which observing systems are best to gather these data? The evaluation of the impacts of ocean and co-located air-sea observations on hurricane intensity forecasts must be assessed with economic valuation studies to answer these questions, allow NOAA to measure and track the societal contributions of its outputs, and inform future investment decisions that generate a high societal contribution (see also: NOAA's Economic Valuation Guide 2021).
Enabling Frameworks and Infrastructure

The recommendations outlined in this report are designed to bolster coordination across NOAA mission areas, programs, and service areas. Implementing the recommendations requires a coordinated approach from planning to implementation, as well as strengthening and expanding partnerships with academic, private, and international groups, and Federal, State, regional, local, and Tribal governments. The following groups, composed of subject matter experts from across NOAA and external partners, have been set up to coordinate the planning and implementation of the priority recommendations.

Extreme Events Ocean Observations Task Team

The Extreme Events Ocean Observations Task Team (EEOOTT) provides the unifying organizational infrastructure for NOAA and external partners to coordinate efforts for implementing the priority recommendations. The task team meets bi-monthly and consists of NOAA and non-NOAA subject matter experts responsible for observations, forecasts, research modeling, funding, and logistical support. Due to the breadth of subject matter the priority recommendations encompass, the EEOOTT has also convened working groups of subject matter experts focused on advancing the priority recommendations. Working groups report regularly to, and will coordinate with, the EEOOTT to provide recommendations for future priorities and investments at NOAA to improve hurricane intensity forecasts.

**Coordinated Ocean Observations Working Group**

<table>
<thead>
<tr>
<th>Priority Recommendation</th>
<th>Coordinated Ocean Observations Working Group Response</th>
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<tbody>
<tr>
<td>Coordinate efforts to close gaps in ocean observations.</td>
<td>This team will focus on coordinating ocean observations efforts, possibly co-located with atmospheric observations, to improve hurricane intensity forecasting by using an evidence-based approach to determine the optimal spatial and temporal ocean observations required. To close gaps in ocean observations, this group will take advantage of advancements in ocean observing technologies and focus on resolving upper ocean features, such as spatial and temporal variability of meso-scale and synoptic features including eddies, boundary currents, and seasonal water masses.</td>
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**Aircraft Deployment Working Group**

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<th>Priority Recommendation</th>
<th>Aircraft Deployment Working Group Response</th>
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<tbody>
<tr>
<td>Coordinate efforts to close gaps in ocean observations.</td>
<td>This team will work with the Coordinated Ocean Observations Team to coordinate aircraft-deployed atmospheric and oceanic observations with surface-based ocean observation efforts. This group will: (1) better understand the process and timelines of different aircraft groups; (2) better understand the how, when, and why priorities are set among competing interests; (3) describe the existing and upcoming technical packages and understand loading, securing, and launching needs and constraints; (4) map out staging</td>
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locations and understand the criteria and constraints for using those staging locations; (5) define the communications chain and points of contact for this chain; (6) build and enhance rapport between aircraft deployment groups.

### Integrated Modeling Prediction Assimilation Coordination Team (IMPACT)

<table>
<thead>
<tr>
<th>Priority Recommendation</th>
<th>IMPACT Response</th>
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<tbody>
<tr>
<td>Evaluate the impacts of ocean observations on hurricane intensity forecasts.</td>
<td>IMPACT will: (1) summarize conclusions from previous model runs and comparisons; (2) outline and conduct the necessary analyses (e.g., OSEs) to evaluate the impacts of ocean observations on hurricane intensity forecasts.</td>
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<tr>
<td>Improve data assimilation of ocean observations into hurricane modeling systems.</td>
<td>IMPACT will evaluate the ocean component of the existing (operational and experimental) coupled atmosphere-ocean hurricane forecasting models. This group will also evaluate the impact of ocean data assimilation on hurricane intensity forecast. Due to maturity or availability of DA systems, data impact studies will be expected to start only when RTOFS-DA and/or ROMS 4DVar are available to EEOOTT members. Because regional MOM6 is in the development stage, the use of Marine JEDI DA in coupled hurricane modeling systems is expected at a later date. The work of this group will benefit from data impact studies performed with available Data Assimilation systems such as COAMPS-TC, HWR-ROMS, and HWRF-HYCOM. A major outcome will be to recommend sampling strategies to improve hurricane intensity forecast.</td>
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### Prioritization and Resourcing Working Group

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<tr>
<th>Priority Recommendation</th>
<th>Prioritization and Resourcing Working Group response</th>
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<tr>
<td>Prioritize and recommend ocean observations for future operational investment.</td>
<td>This group will work ongoingly to leverage and procure resources to fill gaps in the hurricane intensity forecasting space (observing platforms, data assimilation needs, impact studies, visualization tools, etc.). The group will also work to conduct economic valuation studies of observing systems and combine these results with those from the Coordinated Ocean Observations, Aircraft Deployment, and IMPACT Working Groups to provide NOAA leadership with justifiable, evidence-based recommendations that prioritizes sustained and targeted ocean observations based on cost and relative impact.</td>
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# Appendix A. Acronyms

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<tr>
<th>ACRONYM</th>
<th>DEFINITION</th>
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<tbody>
<tr>
<td>AOML</td>
<td>Atlantic Oceanographic and Meteorological Laboratory</td>
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<td>DA</td>
<td>Data Assimilation</td>
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<tr>
<td>EEOOTT</td>
<td>Extreme Events-Ocean Observations Task Team</td>
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<tr>
<td>GOMO</td>
<td>Global Ocean Monitoring and Observing</td>
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<td>HFIP</td>
<td>Hurricane Forecast Improvement Program</td>
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<td>IMPACT</td>
<td>Integrated Modeling Prediction Assimilation Coordination Team</td>
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<tr>
<td>IOOS</td>
<td>Integrated Ocean Observing System</td>
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<td>JEDI</td>
<td>Joint Effort for Data Assimilation Integration</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NWS</td>
<td>National Weather Service</td>
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<td>OSE</td>
<td>Observing System Experiments</td>
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<td>OSSE</td>
<td>Observing System Simulation Experiments</td>
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<tr>
<td>RTOFS</td>
<td>Real Time Ocean Forecast System</td>
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<tr>
<td>TC</td>
<td>Tropical Cyclone</td>
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Appendix B. Supporting Materials

B1. NOAA Hurricane Forecast Improvement Program (HFIP) Strategic Plan
B3. NOAA Administrative Order 212-15: Management of Environmental Data and Information
B4. The FAIR Guiding Principles for Scientific Data Management and Stewardship
B5. 2020 NOAA Data Strategy
B6. NOAA's Economic Valuation Guide 2021
B7. Precipitation Prediction Grand Challenge Strategy
B8. IOOS-OAR Workshop’s Two Pager: Hurricanes
B9. IOOS-OAR Workshop’s Two Pager: Cloud Computing
B10. IOOS-OAR Workshop’s Two Pager: Technology Development and Transition
B11. Weather, Water, Climate Five-Year Strategy
B12. NOAA Climate and Fisheries Initiative
B13. EPIC Strategic Plan
B154 Workshop Crosswalk with NOAA Line Offices and Programs
## Appendix C. Crosswalk of Line Office Priorities

<table>
<thead>
<tr>
<th>Priority Recommendations for Integrating Ocean Observations to Improve NOAA’s Hurricane Intensity Forecasts</th>
<th>Coordinate efforts to close gaps in ocean observations</th>
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<td><strong>NESDIS</strong></td>
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## Appendix D. Crosswalk of Intra-Agency Efforts

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<td><strong>Precipitation Prediction Grand Challenge</strong></td>
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<td>Objective 1. Enhance and sustain user engagement</td>
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<td>Objective 2. Improve precipitation prediction products and applications</td>
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<td>Objective 3. Improve prediction systems for precipitation</td>
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<td>Objective 4. Sustain, enhance, and explicit observations</td>
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<td>Objective 5. Improve process-level understanding and modeling</td>
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<td>Objective 6. Advance understanding of precipitation predictability</td>
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<td>Action // Enhance the utility of existing climate information</td>
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<td>Action // Advance NOAA’s regional modeling system</td>
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<td>Action // Establish regional teams and a national community of practice</td>
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<td>Action // Fuel innovation and applications through targeted research</td>
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<td><strong>WWC Strategy (2022-2026)</strong></td>
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<td><strong>EPIC Strategic Plan</strong></td>
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<td>3.1 Accurate and reliable operational models</td>
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<td>3.2 Community contributions to operational modeling systems</td>
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<td>3.3 Community engagement</td>
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</table>
Appendix E. Who’s Who of Hurricane Intensity Forecasting

Mohamed Adel (mohamed@mohamedadel.com) is a Consultant at the Ocean Sciences and Techniques Academy.

Captain Dr. Abdulmoneim Al Janahi (memac@batelco.com.bh) is the Director of the Marine Emergency Mutual Aid Center (MEMAC).

Maria Aristizabal (maria.aristizabal@noaa.gov) is a Support Scientist at NOAA/EMC. I will carry out research, development, and transition to operations of ocean numerical models that are coupled to regional hurricane forecast systems.

Krisa Arzayus (krisa.arzayus@noaa.gov) is the Deputy Director of the U.S. IOOS Program Office.

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Christine Bassett (christine.bassett@noaa.gov) is a Knauss Marine Policy Fellow at NOAA’s NWS OBS.

Peter Black (peter.black@noaa.gov) is a senior scientist consultant with I.M. Systems Group working with NOAA’s NCEP/EMC on dropsonde use for error reduction in operational hurricane and winter storm forecast models employed by NOAA’s NHC and WPC. He collaborates with NOAA’s AOML and is a Hurricane Ocean Impacts ‘Tiger Team’ member. He has 40 years of experience flying into tropical cyclones and 55 years analyzing airborne atmospheric and oceanographic observations collected to define structure and improve forecasting of these storms.

Cameron Book (cameron.book@noaa.gov) is a Contractor at NOAA’s EMC.

Sebastien Boulay (sebastien.boulay@sofarocean.com) is the Director of Business Development at Sofar Ocean Technologies.

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Joseph Cione (joe.cione@noaa.gov) is a Meteorologist at NOAA's AOML HRD.

Tripp Collins (Clarence.o.collins@usace.army.mil) is a Research Oceanographer with the USACE Coastal and Hydraulics Laboratory at the Field Research Facility in Duck, NC. Observation and analysis of ocean waves and momentum fluxes.

Sam Coakley (sic244@marine.rutgers.edu) is a Graduate Student at Rutgers University in the RU COOL lab working on problems of upper ocean mixing in hurricanes and ocean mixed layer dynamics. I am also interested in using 'science storms' to validate coupled models.

John Cortinas (john.cortinas@noaa.gov) is the Director of NOAA's AOML.

Josh Cossuth (joshua.cossuth@navy.mil) is a Program Manager with the Marine Meteorology Program at the Office of Naval Research.

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Tom Cuff (thomas.cuff@noaa.gov) is the Director of NOAA OBS.

Eric D'Asaro (dasaro@apl.washington.edu) is a Senior Principal Oceanographer at the University of Washington.
Howard Diamond (howard.diamond@noaa.gov) is the Director of the Atmospheric Sciences and Modeling Division at NOAA's ARL.

Steven DiMarco (sdimarco@tamu.edu) is a Professor (Depts. of Oceanography and Ocean Engineering) and the Ocean Observing Team Lead for the Geochemical and Environmental Research Group at Texas A&M University; a Fellow of the Marine Technology Society; and principal investigator of the Texas Automated Buoy System (http://tabs.gerg.tamu.edu). His research focuses on interdisciplinary studies of the coastal and deep processes of marginal seas.

Ricardo Domingues (Ricardo.Domingues@noaa.gov) is an Oceanographer at NOAA’s AOML.

James Doyle (james.doyle@nrlmry.navy.mil) is a Senior Scientist at the U.S. Naval Research Laboratory (NRL) Marine Meteorology Division in Monterey, CA and leads the model development team for the Navy’s COAMPS- COAMPS-TC. He leads multiple research programs on tropical meteorology and predictability, and has led numerous field campaigns. Dr. Doyle is a fellow of the AMS and has published over 175 peer-reviewed publications.

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