Ocean Observations in Support of Studies and Forecasts of Tropical Cyclones

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Abstract

Understanding of the upper-ocean processes and conditions that contribute to genesis and intensification of tropical cyclones (TCs) has largely benefited from the climate-oriented ocean observing system. When the atmosphere is favorable, upper-ocean conditions have been shown to be a key factor governing air-sea enthalpy fluxes that can fuel these extreme weather events. Rapid intensification of TCs is often associated with TCs travelling over warm ocean and/or low-salinity barrier layers, which maintain warm sea surface temperatures (SSTs) near the convective center of the storm. Studies have shown that accurate TC intensity forecasts require the correct representation of these upper-ocean processes and conditions within the operational coupled ocean-atmosphere hurricane forecast models. This, in turn, requires the assimilation of sustained ocean observations from areas where these weather systems commonly travel and intensify. Increased societal/scientific interest, new technologies, pilot networks, targeted deployments of instruments, and state-of-the art coupled numerical forecast models have enabled advances in research and forecast skills and illustrate a potential framework for future development. Here, we present examples of new technologies and pilot networks that are effectively helping assess the ocean conditions that can contribute to TC intensification, and the overall recommendations from the scientific community for such component of the global ocean observing system.

Impact of Ocean Data in Tropical Cyclone Intensity Forecasts

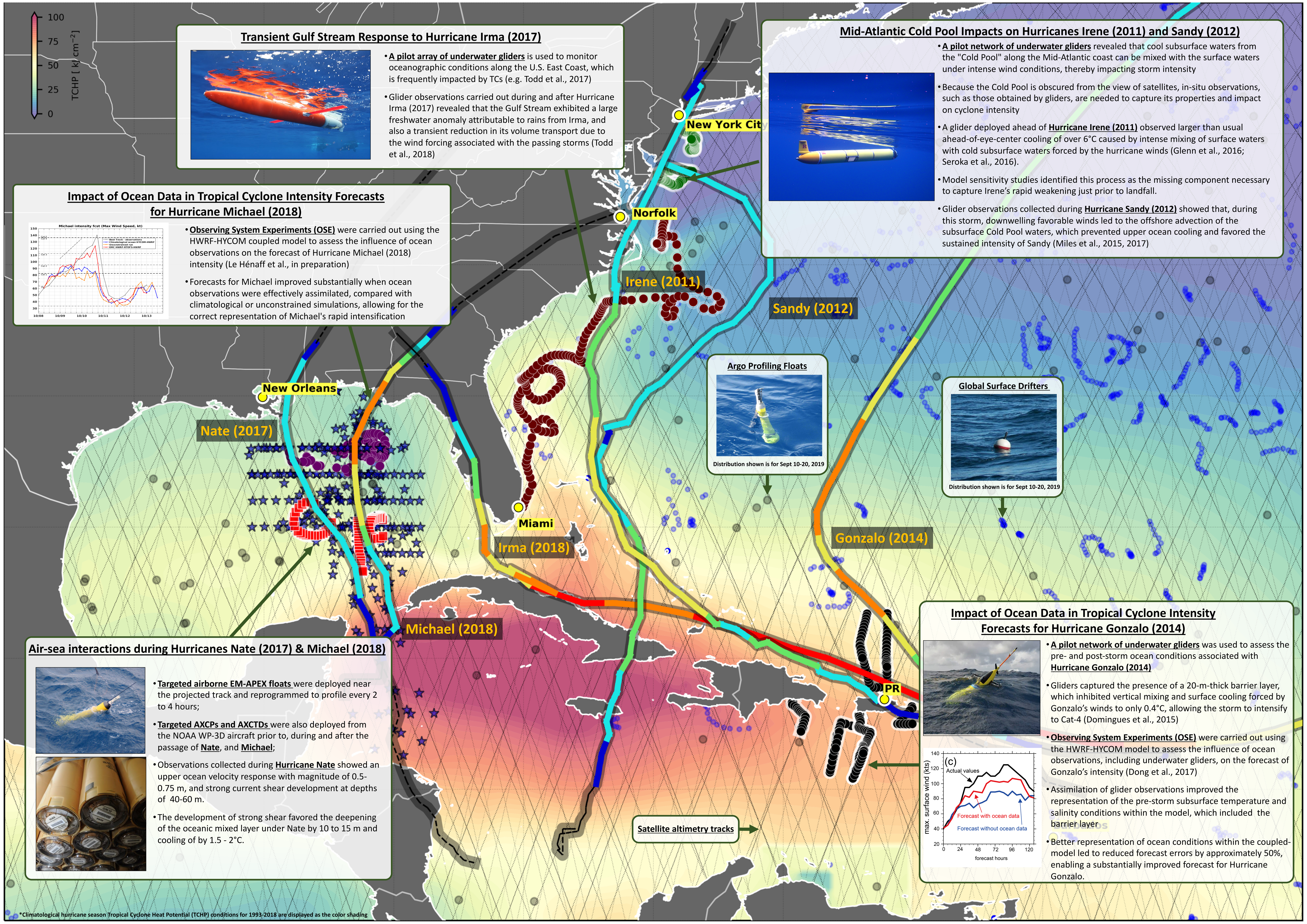
Assimilation of ocean observations is a leading-order factor in reducing initialization errors within coupled TC forecasts (Halliwell et al. 2011). Examples of overall data assimilation impacts by platform within coupled-models described here:

- **Satellite altimetry:** improved representation of oceanic mesoscale field;
- **Satellite SST:** temperature bias corrections within the mixed layer;
- **Argo profiling floats:** large-scale scale subsurface temperature and salinity bias corrections;
- **Underwater gliders:** improved 3D representation of sub-mesoscale and mesoscale temperature and salinity subsurface conditions and gradients, and including low-salinity barrier layers;
- **Surface drifters:** improved barometric pressure representation and satellite SST calibration.

Sustained data stream in real time and longer than 3 days is required for initial data assimilation, and longer than 30 days for effective model corrections to take place.

Recommendations

- Maintain the elements of the observing system that have proven valuable for Tropical Cyclone ocean research and operational intensity forecast.
- Utilize numerical Observing System Experiments (OSEs) to quantify the impact of the current ocean observing platforms in Tropical Cyclone forecasts.
- Evaluate optimal ocean observational strategies in support of Tropical Cyclone studies and forecasts using numerical Observing System Simulation Experiments (OSSEs).
- Implement sustained and targeted ocean observations (gliders, profiling floats, drifters, etc.) dedicated to improving Tropical Cyclone intensity forecasts; and foster co-incident, co-located air-deployed profile observations (AXBTs, AXCTDs, floats, thermistor chains, etc.) of ocean temperature, salinity, and currents.
- Foster additional sustained measurements of sea level pressure (e.g., from drifters and moorings), and of waves, sea spray, and mixed-layer turbulence (e.g., from gliders) to help develop, evaluate, and validate boundary layer parameterizations.
- Use upper ocean metrics (e.g., Tropical Cyclone heat potential, ocean mean temperature, barrier layer thickness, etc.) derived from profile and satellite ocean observations in the operational evaluation and validation of numerical forecast models.
- Continue with efforts focused on improving coupled ocean-atmospheric numerical weather models, especially those relating to enhancing ocean data assimilation techniques and mixed layer parametrizations.
- Create an ocean database easily accessible to the scientific community to facilitate research in support of assessments of the role of the ocean in Tropical Cyclones studies.
- Enhance data management efforts to transmit and QA/QC data in real-time for assimilation in operational forecast models.



*Climatological hurricane season Tropical Cyclone Heat Potential (TCHP) conditions for 1993-2018 are displayed as the color shading

Transient Gulf Stream Response to Hurricane Irma (2017)

- **A pilot array of underwater gliders** is used to monitor oceanographic conditions along the U.S. East Coast, which is frequently impacted by TCs (e.g. Todd et al., 2017)
- Glider observations carried out during and after Hurricane Irma (2017) revealed that the Gulf Stream exhibited a large freshwater anomaly attributable to rains from Irma, and also a transient reduction in its volume transport due to the wind forcing associated with the passing storms (Todd et al., 2018)

Impact of Ocean Data in Tropical Cyclone Intensity Forecasts for Hurricane Michael (2018)

- **Observing System Experiments (OSE)** were carried out using the HWRF-HYCOM coupled model to assess the influence of ocean observations on the forecast of Hurricane Michael (2018) intensity (Le Hénaff et al., in preparation)
- Forecasts for Michael improved substantially when ocean observations were effectively assimilated, compared with climatological or unconstrained simulations, allowing for the correct representation of Michael's rapid intensification

Mid-Atlantic Cold Pool Impacts on Hurricanes Irene (2011) and Sandy (2012)

- **A pilot network of underwater gliders** revealed that cool subsurface waters from the "Cold Pool" along the Mid-Atlantic coast can be mixed with the surface waters under intense wind conditions, thereby impacting storm intensity
- Because the Cold Pool is obscured from the view of satellites, in-situ observations, such as those obtained by gliders, are needed to capture its properties and impact on cyclone intensity
- A glider deployed ahead of **Hurricane Irene (2011)** observed larger than usual ahead-of-eye-center cooling of over 6°C caused by intense mixing of surface waters with cold subsurface waters forced by the hurricane winds (Glenn et al., 2016; Seroka et al., 2016).
- Model sensitivity studies identified this process as the missing component necessary to capture Irene's rapid weakening just prior to landfall.
- Glider observations collected during **Hurricane Sandy (2012)** showed that, during this storm, downwelling favorable winds led to the offshore advection of the subsurface Cold Pool waters, which prevented upper ocean cooling and favored the sustained intensity of Sandy (Miles et al., 2015, 2017)

Argo Profiling Floats

Distribution shown is for Sept 10-20, 2019

Global Surface Drifters

Distribution shown is for Sept 10-20, 2019

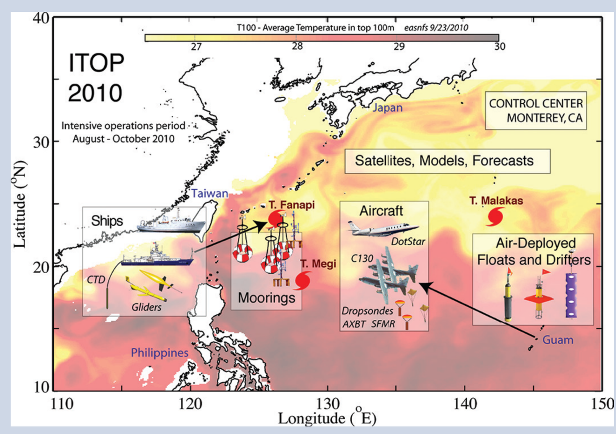
Air-sea interactions during Hurricanes Nate (2017) & Michael (2018)

- **Targeted airborne EM-APEX floats** were deployed near the projected track and reprogrammed to profile every 2 to 4 hours;
- **Targeted AXCPs and AXCTDs** were also deployed from the NOAA WP-3D aircraft prior to, during and after the passage of **Nate**, and **Michael**;
- Observations collected during **Hurricane Nate** showed an upper ocean velocity response with magnitude of 0.5-0.75 m, and strong current shear development at depths of 40-60 m.
- The development of strong shear favored the deepening of the oceanic mixed layer under Nate by 10 to 15 m and cooling of by 1.5 - 2°C.

Impact of Ocean Data in Tropical Cyclone Intensity Forecasts for Hurricane Gonzalo (2014)

- **A pilot network of underwater gliders** was used to assess the pre- and post-storm ocean conditions associated with **Hurricane Gonzalo (2014)**
- Gliders captured the presence of a 20-m-thick barrier layer, which inhibited vertical mixing and surface cooling forced by Gonzalo's winds to only 0.4°C, allowing the storm to intensify to Cat-4 (Domingues et al., 2015)
- **Observing System Experiments (OSE)** were carried out using the HWRF-HYCOM model to assess the influence of ocean observations, including underwater gliders, on the forecast of Gonzalo's intensity (Dong et al., 2017)
- Assimilation of glider observations improved the representation of the pre-storm subsurface temperature and salinity conditions within the model, which included the barrier layer
- Better representation of ocean conditions within the coupled-model led to reduced forecast errors by approximately 50%, enabling a substantially improved forecast for Hurricane Gonzalo.

The 2010 Impact of Typhoon on Pacific (ITOP) field campaign



- The ITOP international field campaign in the western North Pacific Ocean is an important example for future field observation strategy and planning;
- The field campaign used targeted aircraft AXBT observations to collect the pre-storm temperature profiles ahead of three TCs from 2010 with distinct intensity: Megi, Fanapi, and Malakas;
- Among the three, Megi intensified over warm ocean temperatures, characterized by TCHP values larger than 140 kJ cm^{-2}, while Fanapi and Malakas travelled over waters with TCHP values lower than 100 kJ cm^{-2}.
- Paired ocean-atmosphere observations during TC intensification events were also collected to evaluate air-sea sensible and latent heat fluxes by deploying co-incident/co-located atmospheric dropsoundes and ocean AXBTs during TC-penetration flights. These observations confirmed that enthalpy fluxes were substantially larger during Supertyphoon Megi as it reached Cat-2 and then continued to intensify into a Cat-5 Supertyphoon.
- Analysis of the available ocean observations revealed that these large differences in upper ocean heat content played a key role in the intensification of Megi, Fanapi, and Malakas (Lin et al., 2013a; D'Asaro et al., 2014).

Reference: Domingues et al., (2019). Ocean Observations in Support of Studies and Forecasts of Tropical and Extratropical Cyclones. Frontiers in Marine Science, 6, 446. doi:10.3389/fmars.2019.00446

Agencies and institutions supporting these efforts*:
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[14]Environmental Modeling Center, National Oceanic and Atmospheric Administration,
[15]U.S. Integrated Ocean Observing System, National Oceanic and Atmospheric Administration

***The observations and results presented in this work were made possible from contributions by various people beyond the listed authors in this poster, including the NOAA's Aircraft Operations Center**

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