Ocean OSSEs and OSEs for hurricane applications

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What are OSEs?

- **Observing System Experiments** (OSEs) aim at **quantifying the impact of existing observations**, using a **numerical model that assimilates observations**
- The impact of a certain type of observations is estimated by **comparing two experiments**:
  - One in which **all the available observations** are **assimilated**
  - Another one in which **all available observations** are assimilated, **except for the observations from the array under study**
  - The **difference in error reduction** between both experiments **quantifies the benefit of the observations**
- Alternatively, one can estimate the error reduction gained by assimilating only the observations under study, compared to the absence of data assimilation

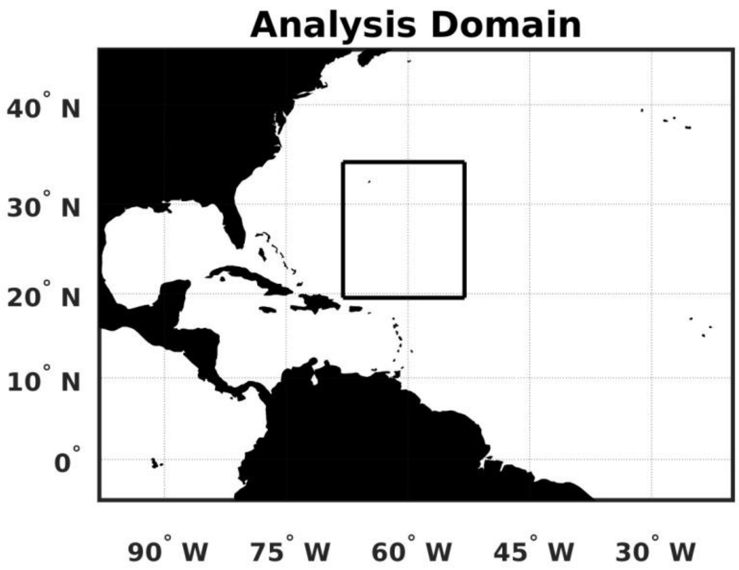
What are OSSES?

- **Observing System Simulation Experiments** (OSSEs) are the cousins of OSEs
- They **aim** at **examining** the performance of:
  - An observation platform or **system that does not exist** yet (e.g. satellites)
  - A **modified configuration** of an existing network (e.g. moorings, gliders etc.)
- In OSSEs, the **observations** are extracted **from a second, independent simulation** that **represents the Truth**. That simulation is called the **Nature Run**
- Simulated observations are extracted from the Nature Run to mimic the observations we want to study
- The **simulated observations** are then **assimilated** into the data-assimilative model, **as if they were real observations**
- The performance is estimated in a similar way as OSEs

Ocean OSSEs

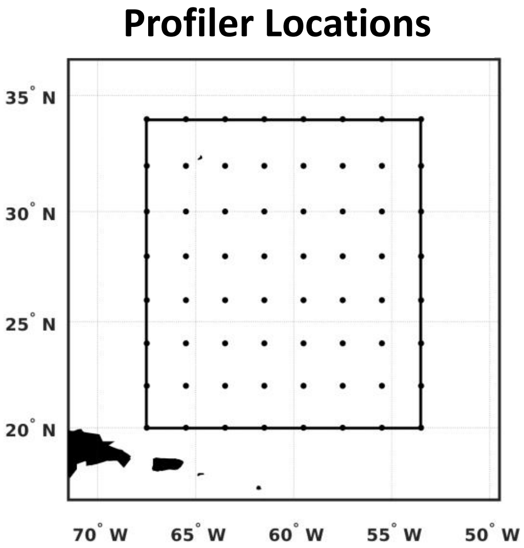
AOML ocean OSSE system

- **Nature Run** (NR):
  - Multi-year unconstrained simulation by an advanced ocean model, validated to represent the “truth”)
  - HYbrid Coordinate Ocean Model (HYCOM) run at 0.04º resolution
- **Ocean Forecast System:**
  - Forecast Model: HYCOM with substantially different configuration from the NR (“fraternal twin” system)
  - Ocean Data Assimilation procedure: Statistical interpolation system designed specifically for the HYCOM model



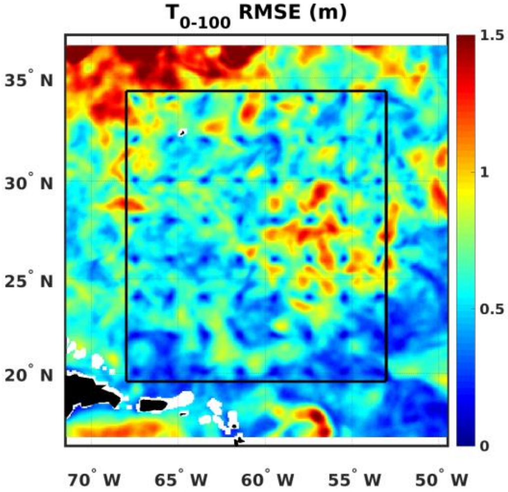
Example of an ocean OSSE: Impact of glider motion

OSSE evaluation of assimilating an array of profilers



• Simulate daily **1000 m temperature-salinity profiles** over a grid within the analysis box (right) at 2º resolution

• Profiles **simulated from the Nature Run** in May-October 2014, and then assimilated into the Forecast Model

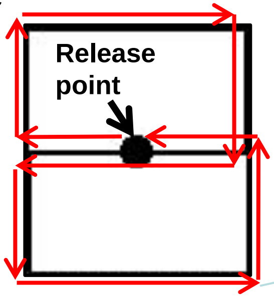


• For **stationary profilers**, accurate correction is **confined to regions** immediately **surrounding the profiler locations** (blue points)

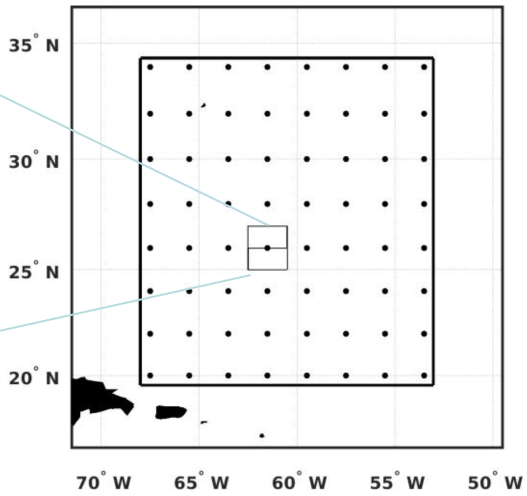
Root Mean Square Error (RMSE) in the average temperature between the surface and 100 m depth

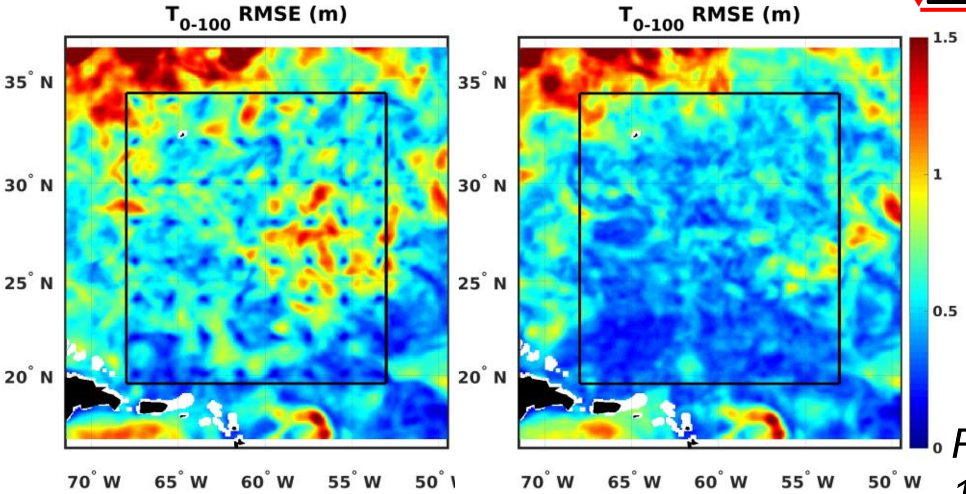
Example of an ocean OSSE: Impact of glider motion

- **Moving platforms** (gliders) released at the **same locations** as the stationary profilers
- Each glider moves in a figure-8 pattern at 0.25 m/s sampling 1000 m T-S profiles



Gliders deployed





Comparison of **errors** with respect to no observation assimilated:
- Gliders: **40%** error reduction
- Stationary profilers: only **14%**

Root Mean Square Error in the average 0-100 m temperature for both study cases

Key findings

- Arrays of ocean profilers deployed at **fixed locations** at a nominal separation distance of 2º have an impact that is **limited around measurement locations**
- This limited radius of accurate correction is substantially **extended** by assimilating profiles from **moving gliders**
- Arrays of **underwater gliders** deployed at a nominal separation distance of 2º provide **significantly improved reduction of errors** compared to static platforms
- Results are presented in:
    - Halliwell, G.R., Goni, G.J., Mehari, M.F., Kourafalou, V.H., Baringer, M. and Atlas, R. (2020). OSSE assessment of underwater glider arrays to improve ocean model initialization for tropical cyclone prediction. *J. Atmos. Ocean. Technol.*, 37(3), 467-487
- Other observing systems and other aspects of the ocean observing strategy studied by our group

Ocean-hurricane OSEs

AOML coupled ocean-hurricane OSE system

- Coupled model HYCOM-HWRF adapted from operational NOAA EMC system
- HWRF H218 version (3 domains of resolution 13.5/4.5/1.5 km)
- HYCOM component of the coupled model:
  - Same Forecast Model used for ocean OSSEs
  - 1/12^{o} horizontal resolution
  - **Assimilates ocean observations** prior to coupling with HWRF
  - Used to **examine various initial ocean conditions** for the coupled experiments, depending on the ocean observations assimilated in the ocean model, while keeping the same atmospheric component
- Simulations: “cycles” of 5-day forecast using the coupled model

Example of a coupled OSE: Impact of of ocean observations on hurricane forecasts during Hurricane Michael (2018)

- We performed **various ocean simulations** with the HYCOM model:
  - A simulation forced to represent **climatological ocean conditions** ("Clim")
  - A simulation in which **all available ocean observations** (altimetry, SST, in situ float data) are **assimilated** to make the simulation as close to reality as possible ("All Obs")
  - A **free-running simulation**, without constrain from data assimilation of observations ("No DA")

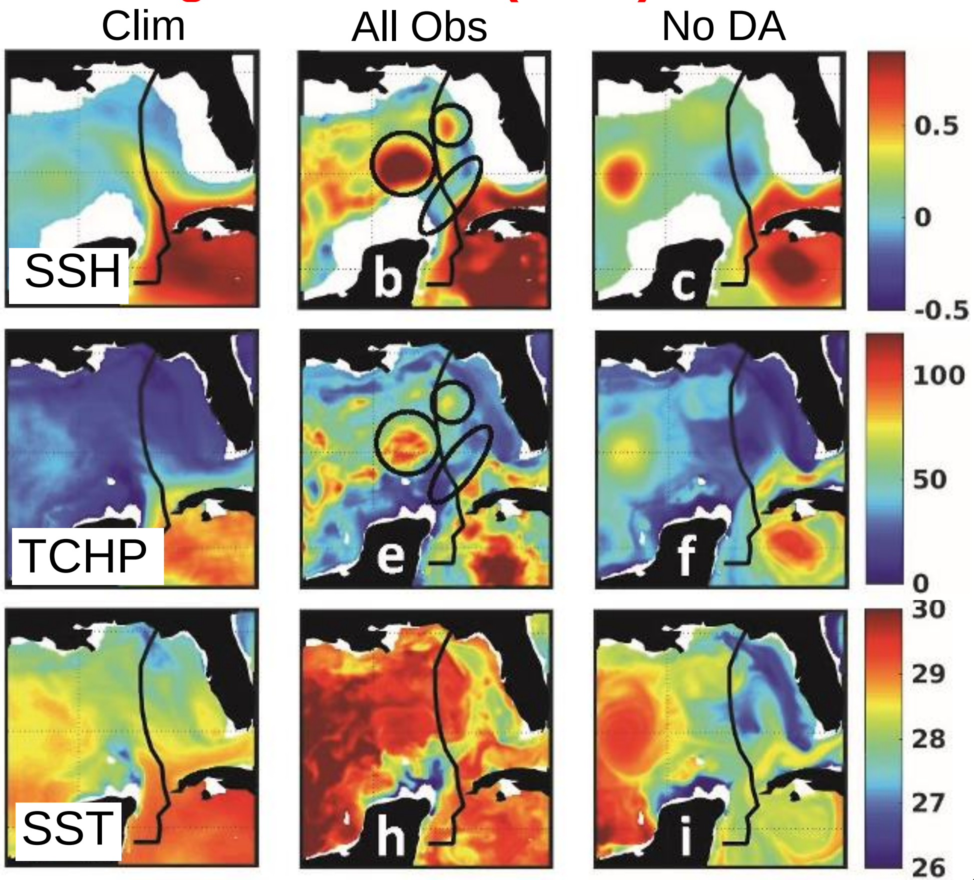
- The simulations started on January 1st, 2018 (i.e., before hurricane season)

Impact of of ocean observations during H. Michael (2018)

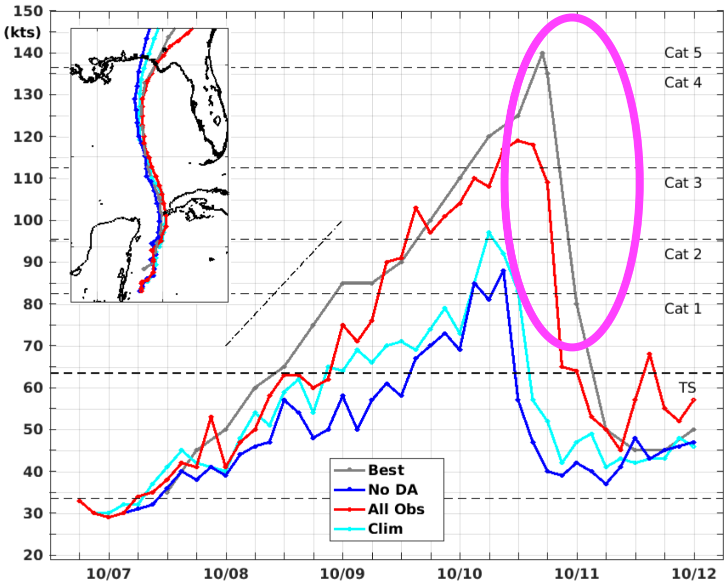
- The data assimilative ***All Obs*** simulation represents the **ocean features of interest**: anticyclonic eddies with high Tropical Cyclone Heat Potential (TCHP), warm surface waters

- The climatological simulation ***Clim*** has a **diffused Loop Current** without eddies, and very low TCHP inside the Gulf

- The free running ***No DA*** simulation has a retracted Loop Current but **no warm-core eddies**, and overall lower TCHP and SST than observed



Example of a 5-day coupled simulation of Michael (2018)

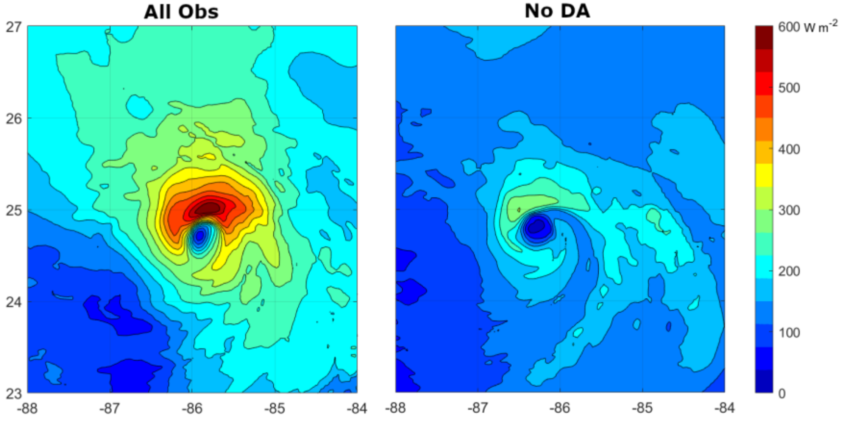


Observed wind intensities (Best, grey), with simulated ones for the All Obs (red), No DA (blue), Climatology (cyan) cases starting on 6 Oct., 18Z.

- Hurricane **tracks close to observed**
- ***All Obs***: **rapid intensification** to **Cat. 4**
- Unconstrained (***No DA***) and climatology (***Clim***) cases **do not intensify as much** (Cat. 1-2)

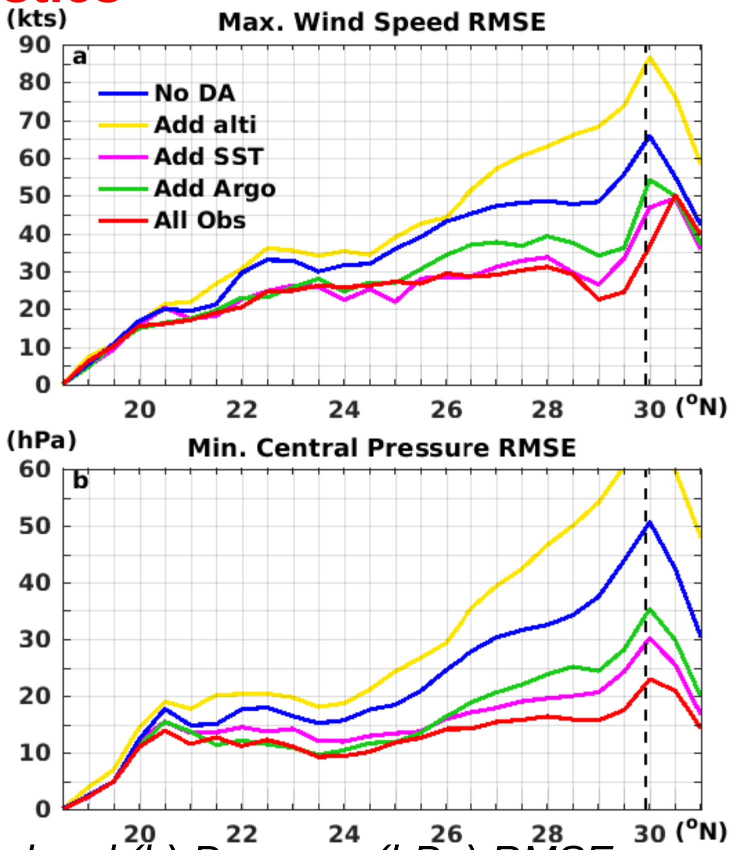
- **Ocean DA** leads to **higher energy fluxes** from the ocean toward the hurricane

Surface enthalpy flux averaged over the 60-66 hour period (left: All Obs, right: No DA)



Hurricane Michael (2018): ensemble statistics

- Wind intensity and central pressure errors over 4 forecast cycles (every 6 hrs on 6 Oct. 2018, early stage of the storm):
- ***No DA***: **large error** (33.6 kts on average, 55.7 kts at landfall)
- ***All Obs.***: **lowest error** (22.8 kts on average, 24.5 kts at landfall): leads to an error reduction of 32% on average, 56% at landfall
- ***Add SST*** (magenta, 23.9 kts on average) and ***Add Argo*** (green, 26.6 kts on average) show **significant contributions** of the respective platforms to error reduction (Argo floats, SST)



(a) Wind and (b) Pressure (hPa) RMSE as a function of latitude following the hurricane

Key findings

- The coupled ocean-hurricane model is **able to reproduce the rapid intensification** of Hurricane Michael in 2018
- Assimilating **ocean observations** leads to **large error reduction** in **wind intensity forecast** of Michael: strong impacts of the ocean on the storm
- The **correct representation of the ocean** leads to reduced error in hurricane intensity forecasts, which is best achieved by assimilating a **combination of observations** (altimetry: mesoscale features, profilers: vertical structure, SST: mixed layer temperature and heat)
- Results are presented in:
    - Le Hénaff, M., R. Domingues, G. Halliwell, J.A. Zhang, H.S. Kim, M. Aristizabal, T. Miles, S. Glenn, and G. Goni (2021). The role of the Gulf of Mexico ocean conditions in the intensification of Hurricane Michael (2018). *Journal of Geophysical Research: Oceans*, 126, p.e2020JC016969.
- Other hurricanes investigated: Hurricane Gonzalo (2014), Hurricane Maria (2017)

Current and future developments

Current and future developments

- Current: Ocean diagnostics using the **NOAA operational system** RTOFS-DA, based on HYCOM and on the 3D-Var Navy Coupled Ocean Data Assimilation (NCODA) system: allows us to make diagnostics using the same tools as the operational center
- Current: **Three-way coupling** ocean-waves-atmosphere (HYCOM-WW3-HWRF), which Hyun-Sook Kim just presented
- Current and future: NOAA Unified Forecast System (**UFS**)
  - Unified modeling tools for whole (most) of NOAA
  - Atmosphere: FV3, Hurricane Analysis and Forecast System (**HAFS**) for hurricanes
  - Ocean: Modular Ocean Model v.6 (**MOM6**)
  - In parallel, Joint Effort for Data assimilation Integration (**JEDI**): DA tools for both the atmosphere and the ocean

Current and future developments

- Current: NOAA AOML in Miami involved in code development and configuration testing, for both the atmosphere and the ocean components of UFS, in **collaboration with** NOAA Environmental Modeling Center (**EMC**)
- Current: **MOM6** on the **North Atlantic** ($1/12^o$ + 50 vertical layers) + **JEDI** (3DVar or LETKF)
- Current: **Weakly coupled DA** – EnVar for an atmospheric model (HWRF or HAFS), LETKF for an ocean model (MOM6), future: LETKF for a wave model (WW3)
- Future: **Strongly coupled DA**
- Future: OSEs, OSSEs, Forecast Sensitivity to Observations (FSO) using MOM6, HAFS and JEDI