Observing System Evaluation showcase: Impact of ocean observations on hurricane forecasts – The cases of Hurricanes Maria (2017) and Michael (2018)

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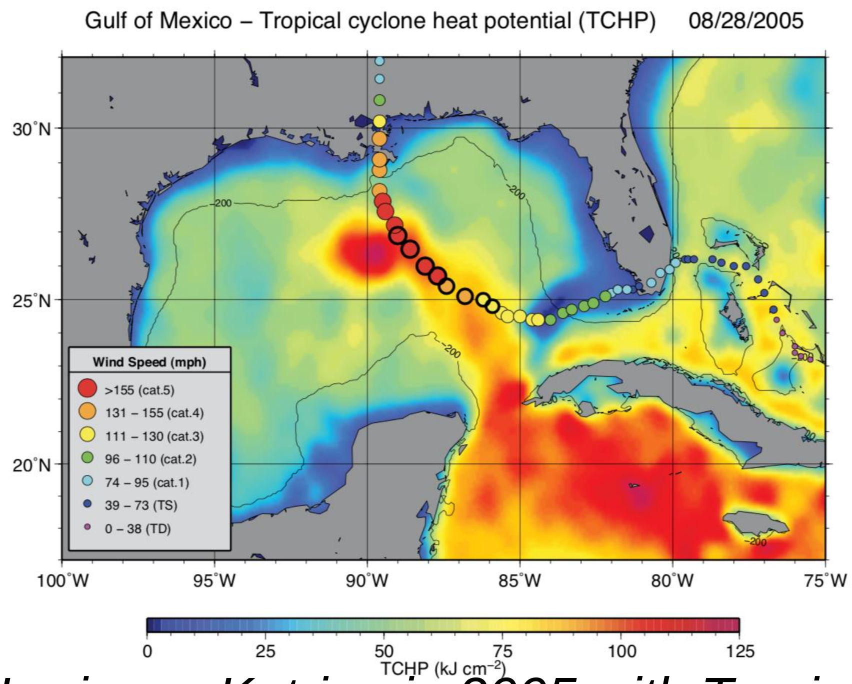
Motivation



Hurricane Katrina in 2005 with Tropical Cyclone Heat Potential (TCHP) derived from altimetry. Goni et al. (2009).

- **Ocean features** can **impact hurricane intensity**: Opal (1995), Katrina (2005), …
- **SST** and **ocean vertical structure** (Tropical Cyclone Heat Potential) are key to influence hurricanes
- Hurricane models should take into account the **correct representation of the ocean:**

1. Ocean models to **assimilate observations** to be closer to the real ocean
2. **Coupled ocean-hurricane forecast models** then used to represent the ocean-atmosphere interactions during a hurricane

Examples: Hurricane Maria (2017) and Hurricane Michael (2018)

Ocean Observing System Experiments (OSEs):

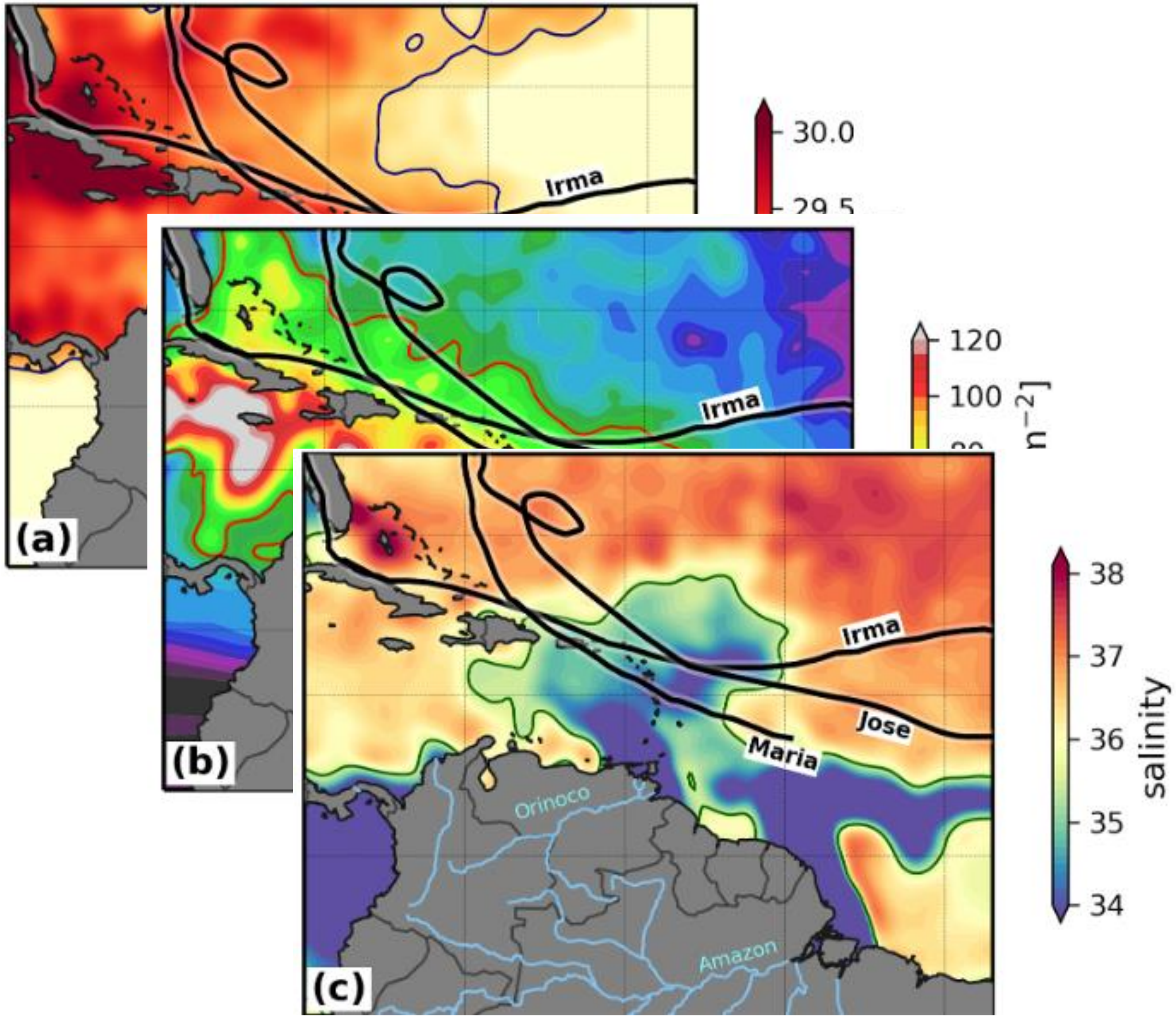
- **HYCOM** at 0.08º resolution
- **North Atlantic** domain
- Ocean **Data Assimilation** procedure: Statistical interpolation system designed specifically for the HYCOM model (early version of T-SIS)
- Assimilates various combinations of ocean observations

Coupled OSEs:

- System adapted from operational NOAA EMC HWRF-HYCOM
- **HWRF** H218 version (3 domains of resolution 13.5/4.5/1.5 km)
- Same HYCOM component
- Used to examine **various initial ocean conditions from the Ocean OSES** for the coupled model, while keeping the **same atmospheric component**
- Simulations: "**cycles**" of **5-day forecast** using the coupled model

Hurricane Maria (2017)

• Made landfall on Puerto-Rico on Sept. 20, 2017, causing ~3,000 deaths and ~$90 billion in damages



Ocean Conditions in August 2017:

• **Warm SSTs** with values ranging from 28-30ºC (values above above 26ºC are required to sustain genesis and intensification)

• **TCHP** values **were consistently above 50 kJ.cm^{-2}**, which is threshold required for intensification.

• Widespread **low-salinity plume** (<35) associated with the Amazon and Orinoco riverine plumes, which are generally associated with barrier layers that favor intensification

Hurricane Maria (2017)

Impact of Ocean Data Assimilation on HYCOM outputs (2 experiments)

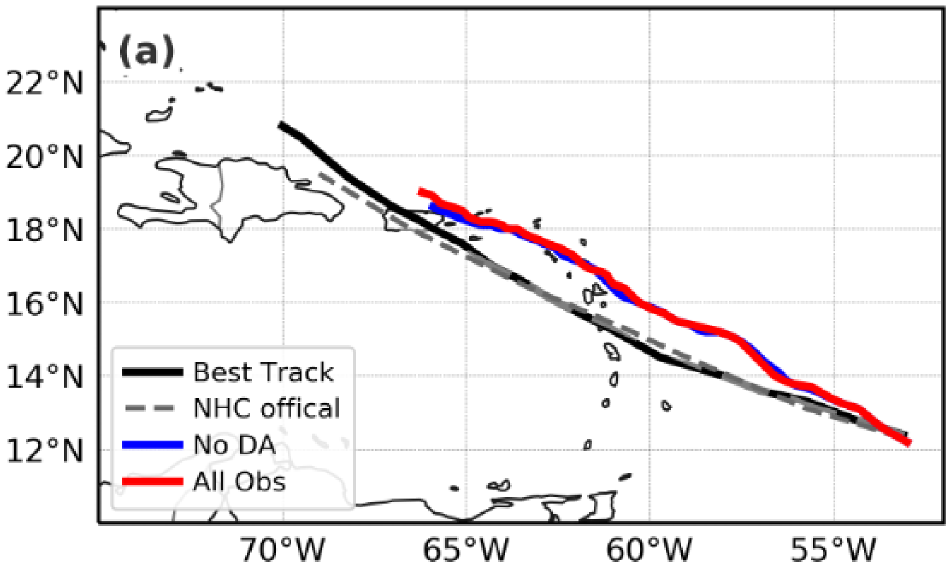
- Temperature errors wrt satellite and underwater glider observations (17 Sept. 00Z):

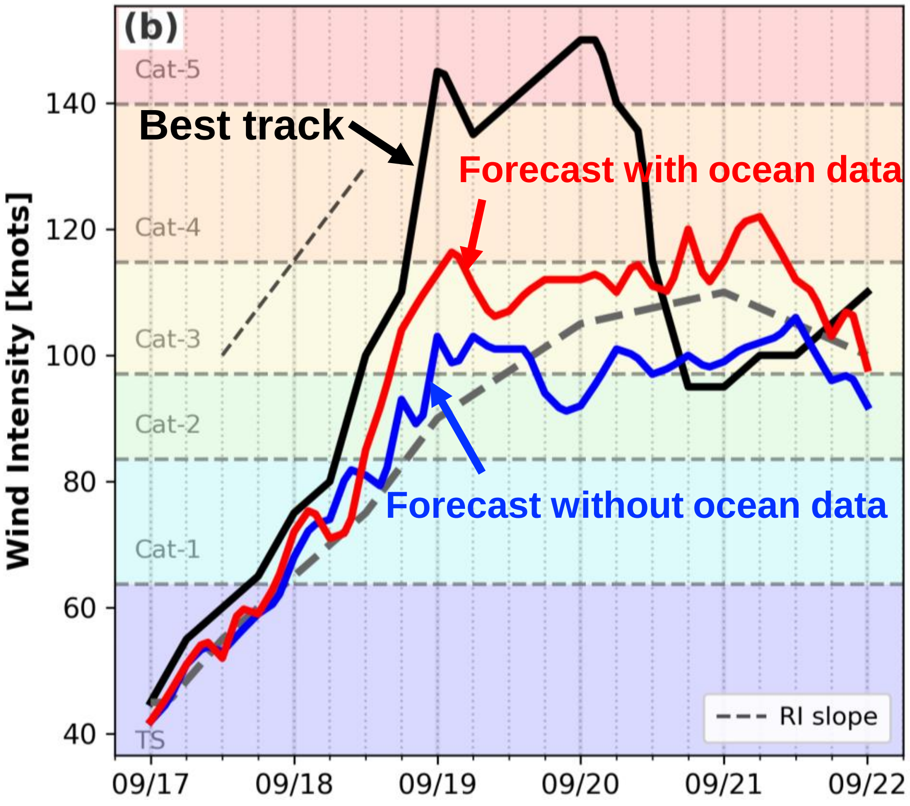
- Without ocean data assimilation: ocean model too cold in the upper-ocean

Hurricane Maria (2017)

Impact of Ocean Data Assimilation on Hurricane Maria forecasts

• Forecast Cycle starting September 17 00Z





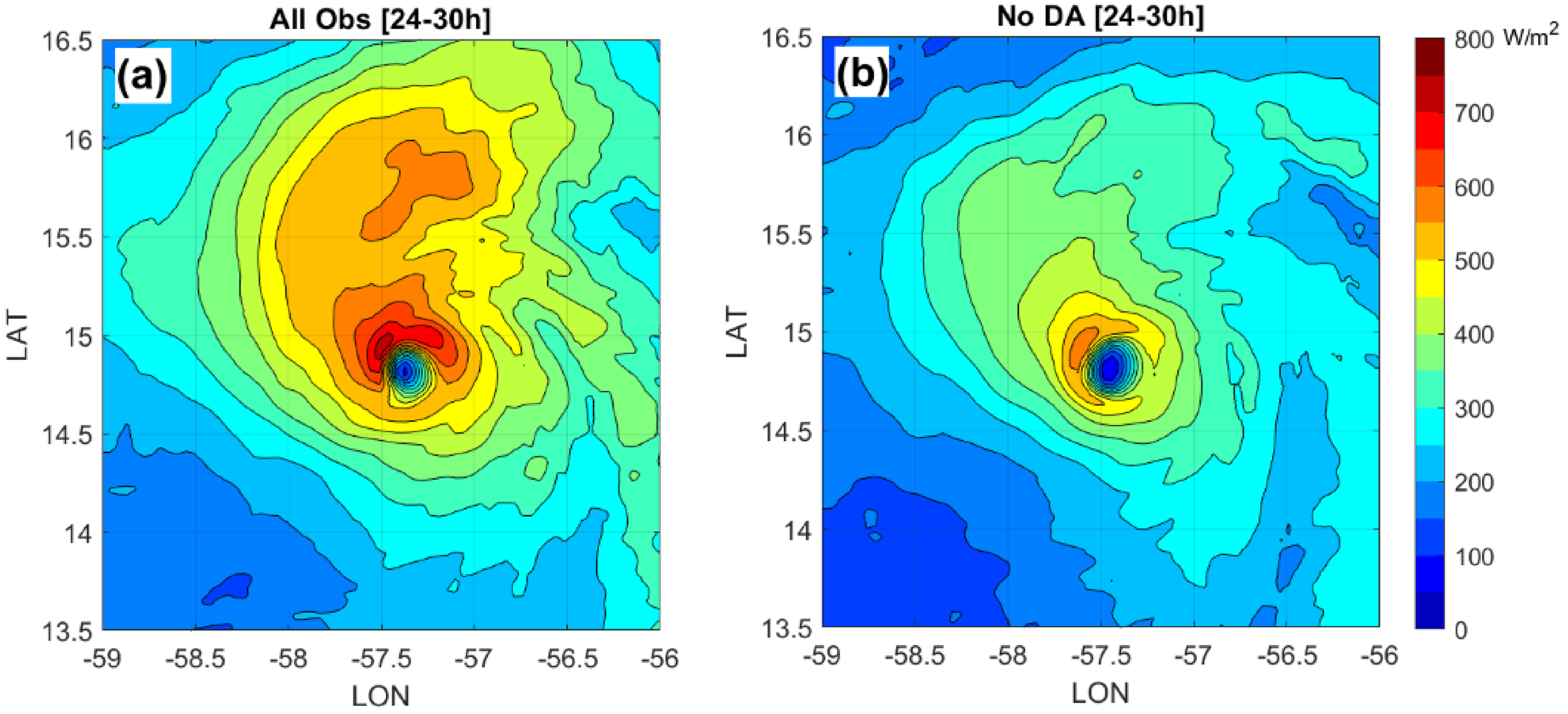
• The **All Obs** case is able to better reproduce the **rapid intensification** than **No DA**

• The assimilation of ocean observations led to a **25% improvement** in the **intensity forecast** of Maria

Hurricane Maria (2017)

Impact of Ocean Data Assimilation on Hurricane Maria forecasts

- Forecast Cycle starting September 17 00Z: Ocean-hurricane **enthalpy fluxes**

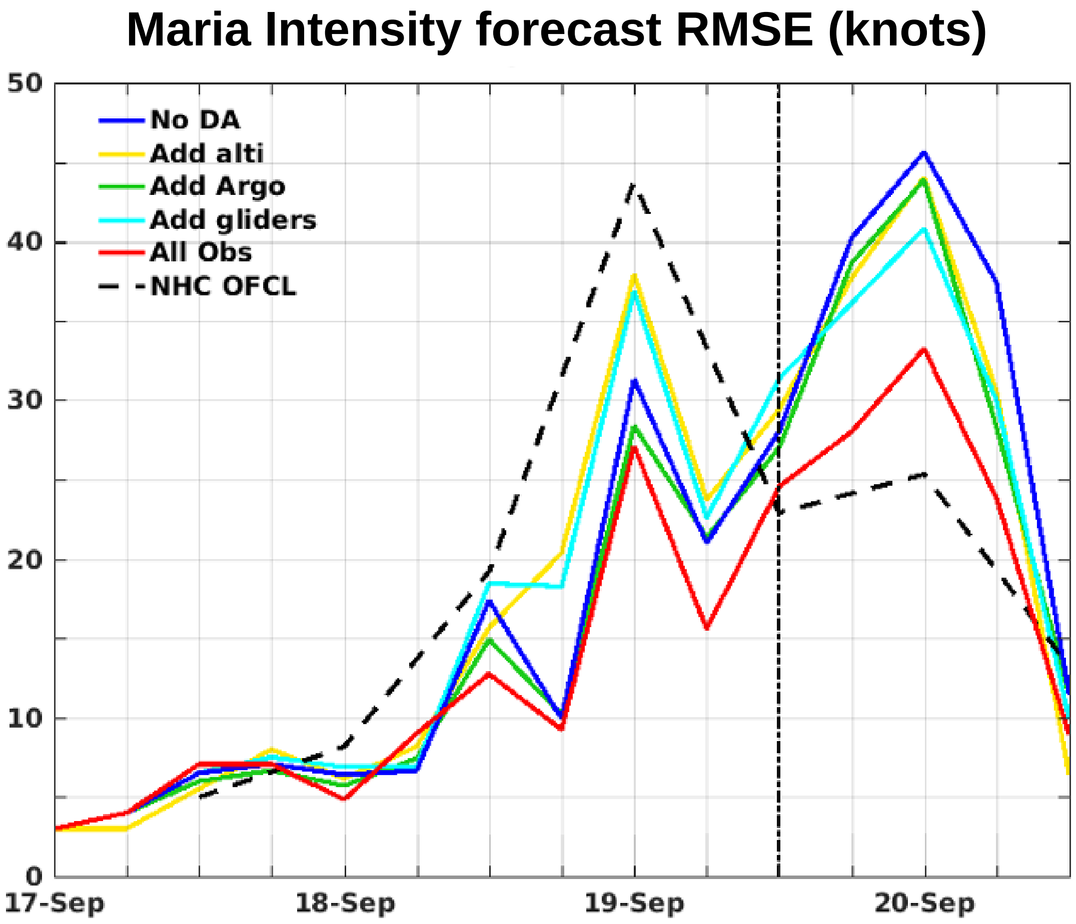


- The assimilation of ocean observations led to a **significant increase** in **enthalpy fluxes** toward the storm, allowing it to intensify

Hurricane Maria (2017)

Impact of individual components of the ocean observing system on Maria forecasts

• Statistical analysis: Root Mean Square Error (RMSE) over 6 forecast cycles every 12 hours between 17 Sept. 00Z and 19 Sept. 12Z



Average RMSE for the **3-day forecast of Maria**:

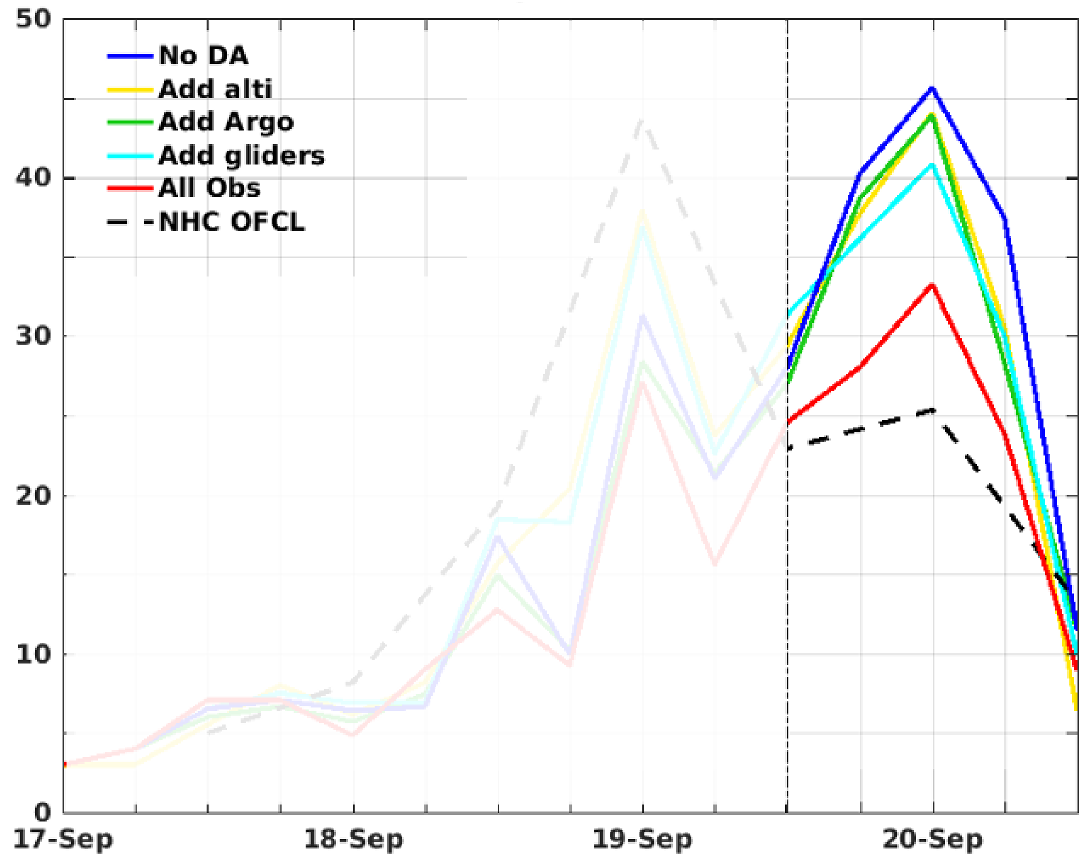
- **No DA**: 23 knots
- **All Obs**: 18.5 knots (20% better than No DA)
- **Add Alt**: 22.4 knots (4% better)
- **Add Argo**: 21.8 knots (10% better)
- **Add gliders**: 22.5 knots (3% better)

Hurricane Maria (2017)

Impact of individual components of the ocean observing system on Maria forecasts

• Statistical analysis: Root Mean Square Error (RMSE) over 6 forecast cycles every 12 hours between 17 Sept. 00Z and 19 Sept. 12Z

Maria Intensity forecast RMSE (knots)



Average RMSE for the **24 hours before landfall**:

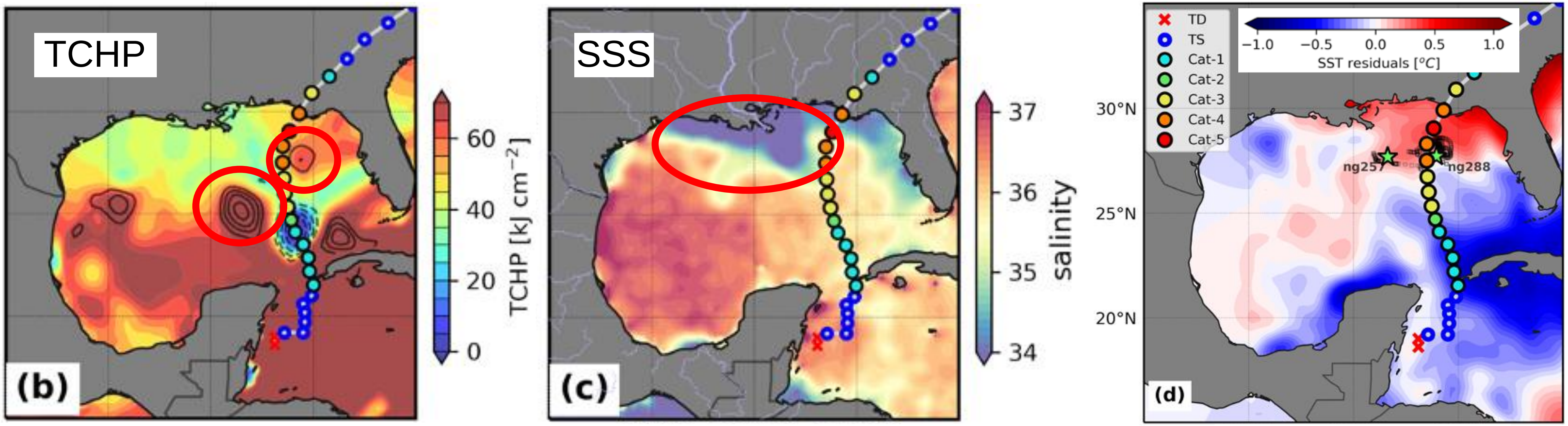
- **No DA**: 33.7 knots
- **All Obs**: 23.5 knots (**30% improvement** over No DA)

Contribution to All Obs error reduction:

- **Add Alt**: 29.7 knots (33% of the improvement in All Obs case)
- **Add Argo**: 30.6 knots (27%)
- **Add gliders**: 29.2 knots (**40%**)

Hurricane Michael (2018)

- Hit the Florida Panhandle, near Mexico Beach, on October 10, 2018
- Michael was the first Cat. 5 Hurricane to hit the continental US since Andrew in 1992



Prior to landfall, Hurricane Michael interacted with:

- Recently detached **LC Eddy** (warm waters, high TCHP)
- Small **anticyclonic eddy** in the Northeastern Gulf
- **Mississippi River plume** (low SSS), which is prone to form barrier layer
- **Warmer Northwestern GoM** than usual (SST anomalies of 0.5-1^{o}C)

Hurricane Michael (2018)

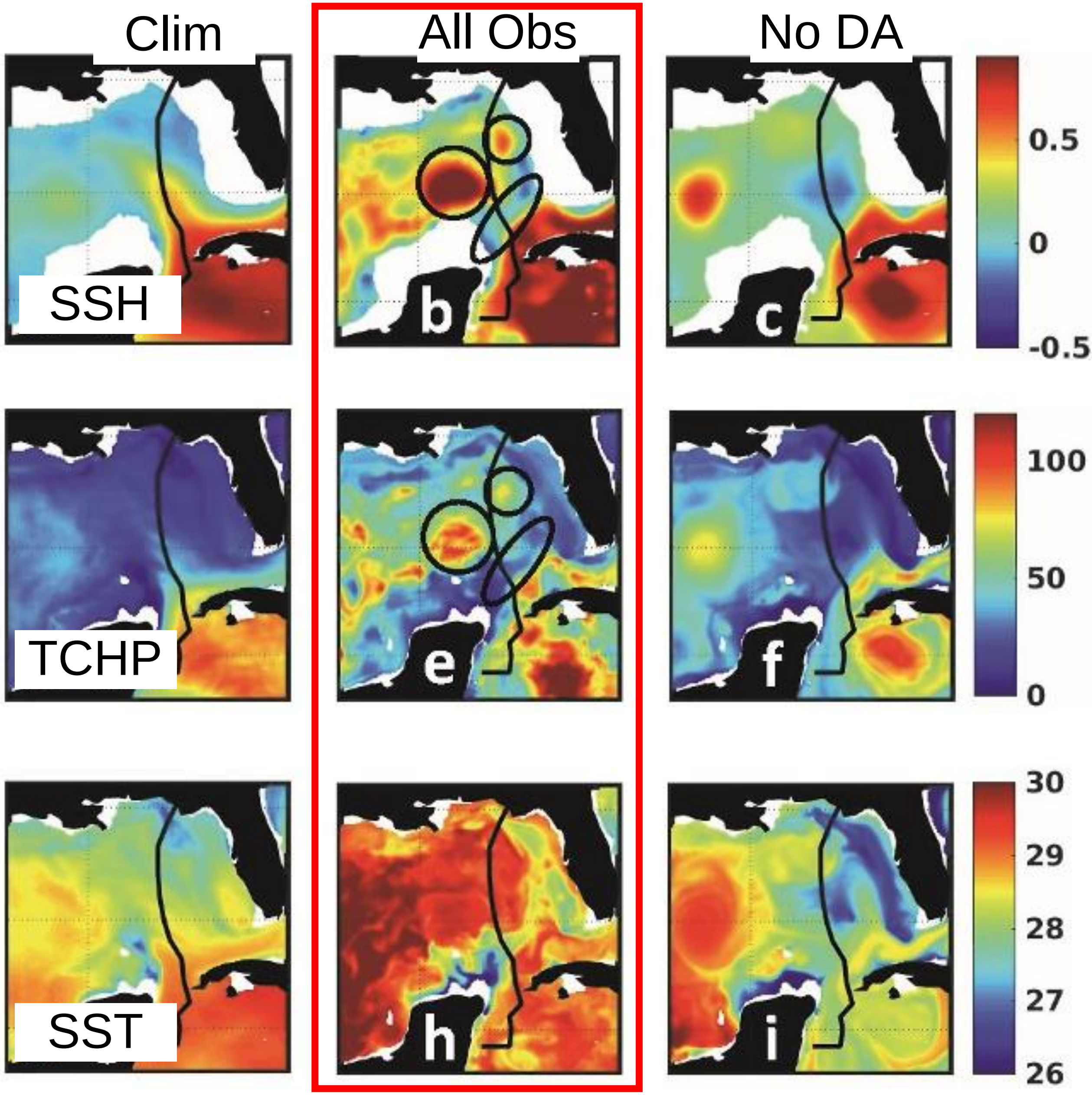
Impact of ocean conditions on hurricane forecasts:

- We performed various **ocean OSEs**, which were then used to provide initial conditions for the coupled HWRF-HYCOM hurricane-ocean forecast model:
  - A simulation relaxed to Navy GDEM-4 **climatology** (“Clim”)
  - A simulation in which **all available ocean observations** (altimetry, SST, in situ float data) are assimilated (“All Obs”)
  - A **free-running** simulation (“No DA”)
- The ocean experiments started on January 1st, 2018

Hurricane Michael (2018)

Impact of ocean observations on ocean state estimate:

• The data assimilative **All Obs** experiment represents the **essential ocean features** of interest: anticyclonic eddies with high TCHP, warm surface waters



Hurricane Michael (2018)

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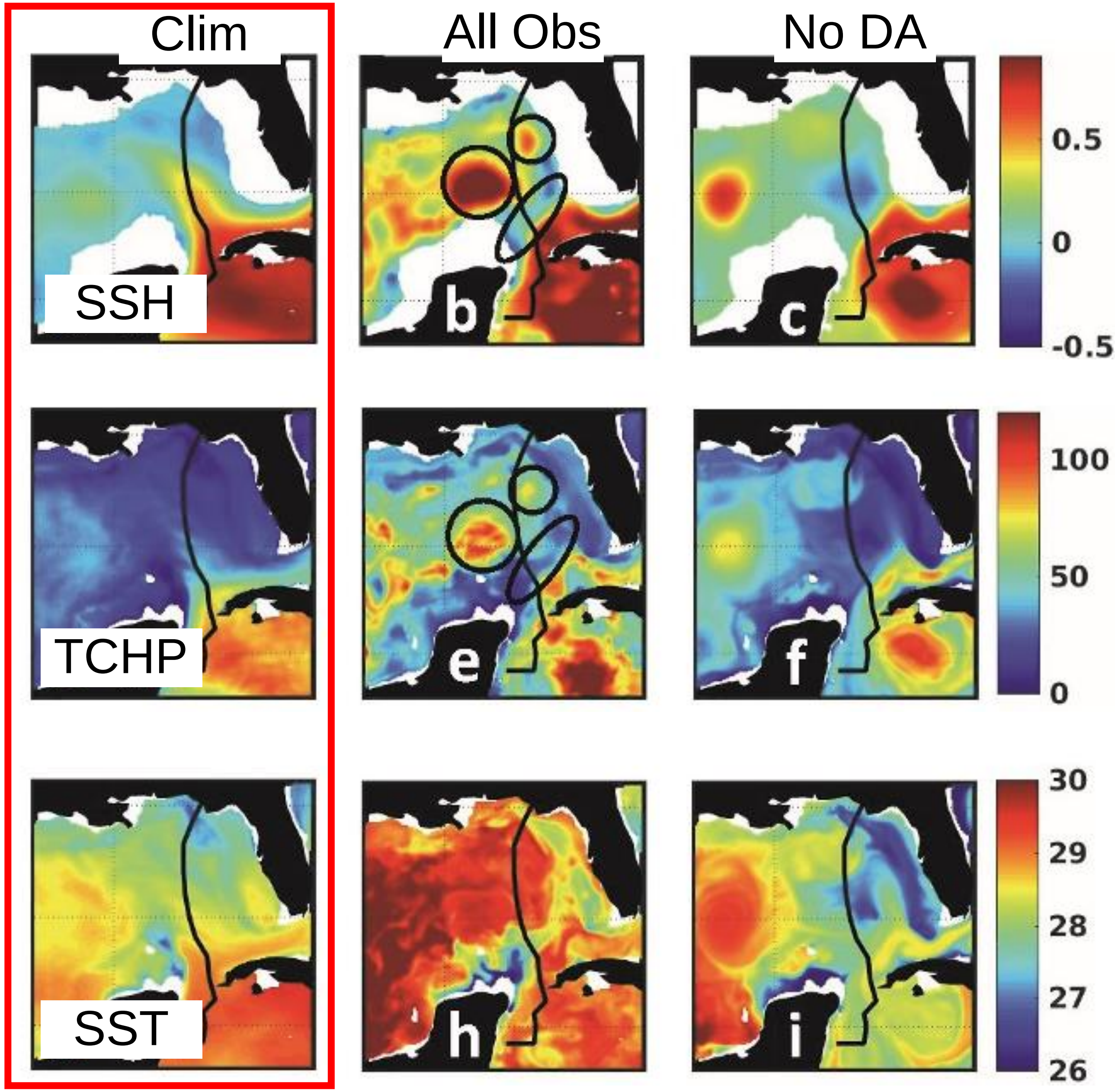
- The data assimilative **All Obs** experiment represents the **essential ocean features** of interest: anticyclonic eddies with high TCHP, warm surface waters
- The climatological experiment **Clim** has **diffused Loop Current** without eddies, and **very low TCHP** inside the Gulf



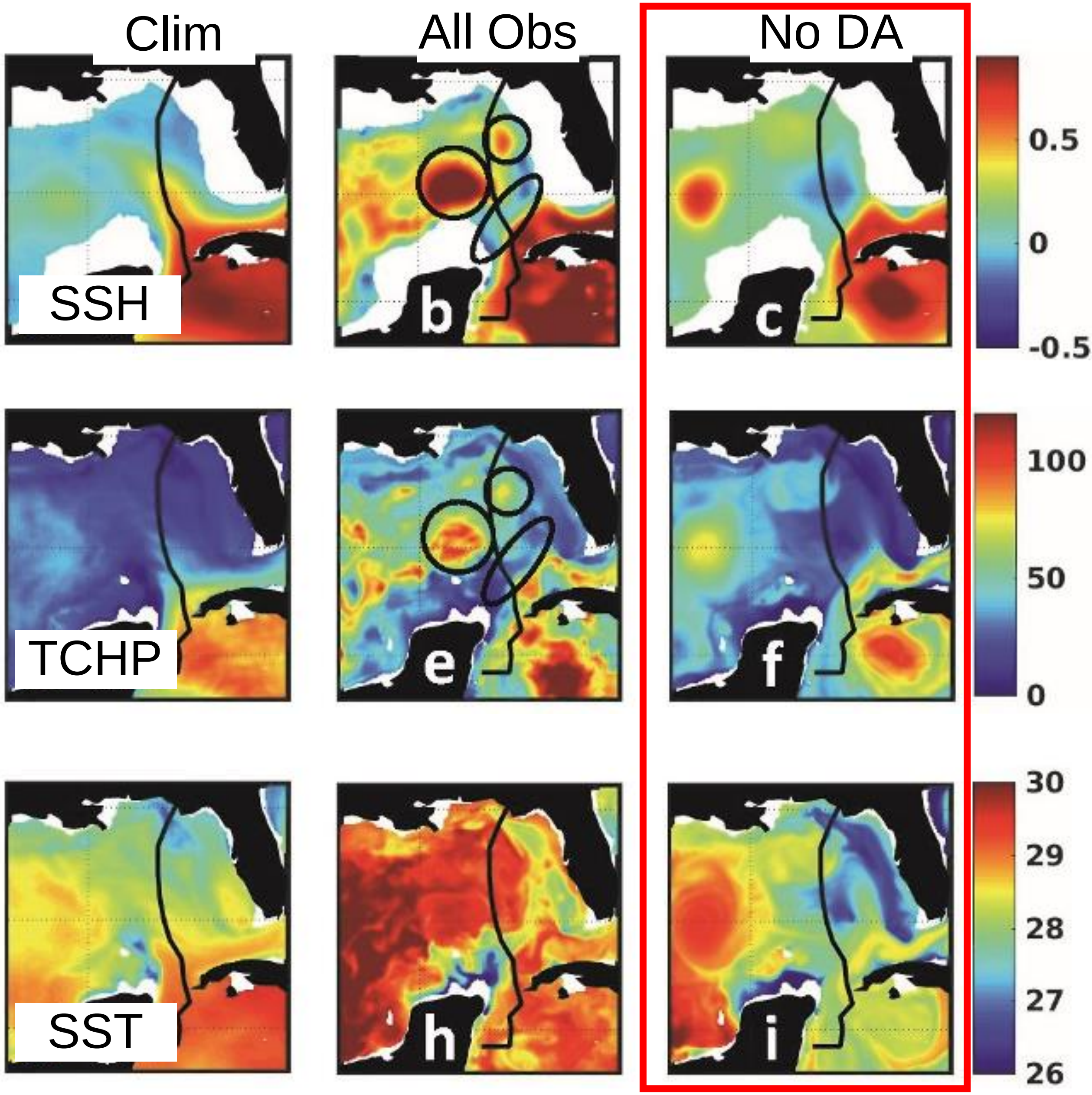
Hurricane Michael (2018)

Impact of ocean observations on ocean state estimate:

• The data assimilative **All Obs** experiment represents the **essential ocean features** of interest: anticyclonic eddies with high TCHP, warm surface waters

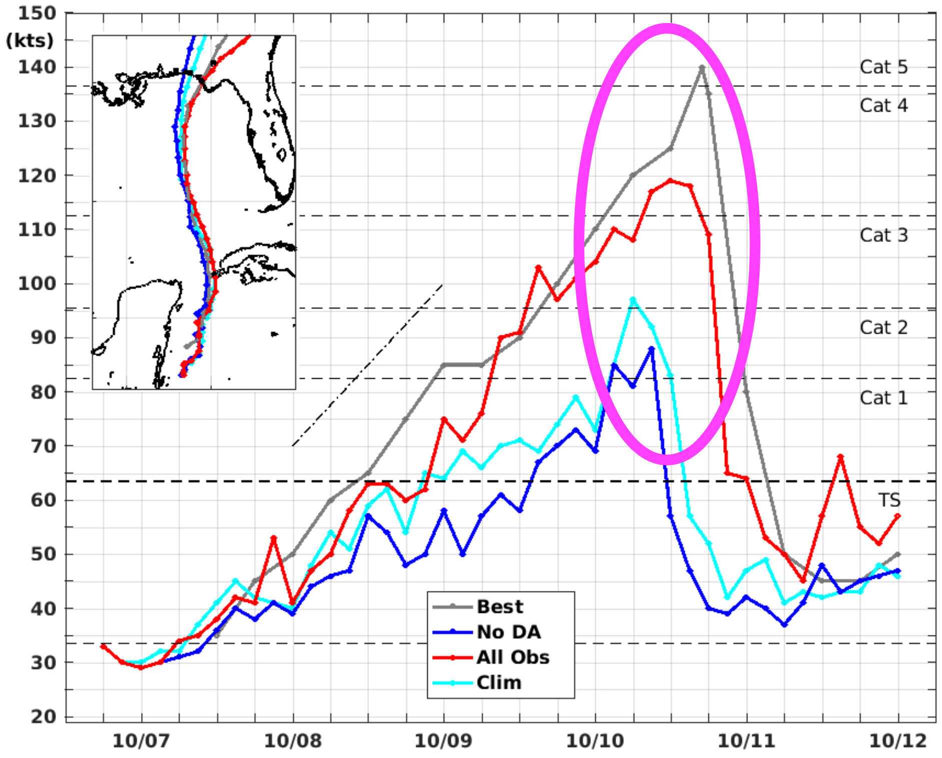
• The climatological experiment **Clim** has **diffused Loop Current** without eddies, and **very low TCHP** inside the Gulf

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



Hurricane Michael (2018)

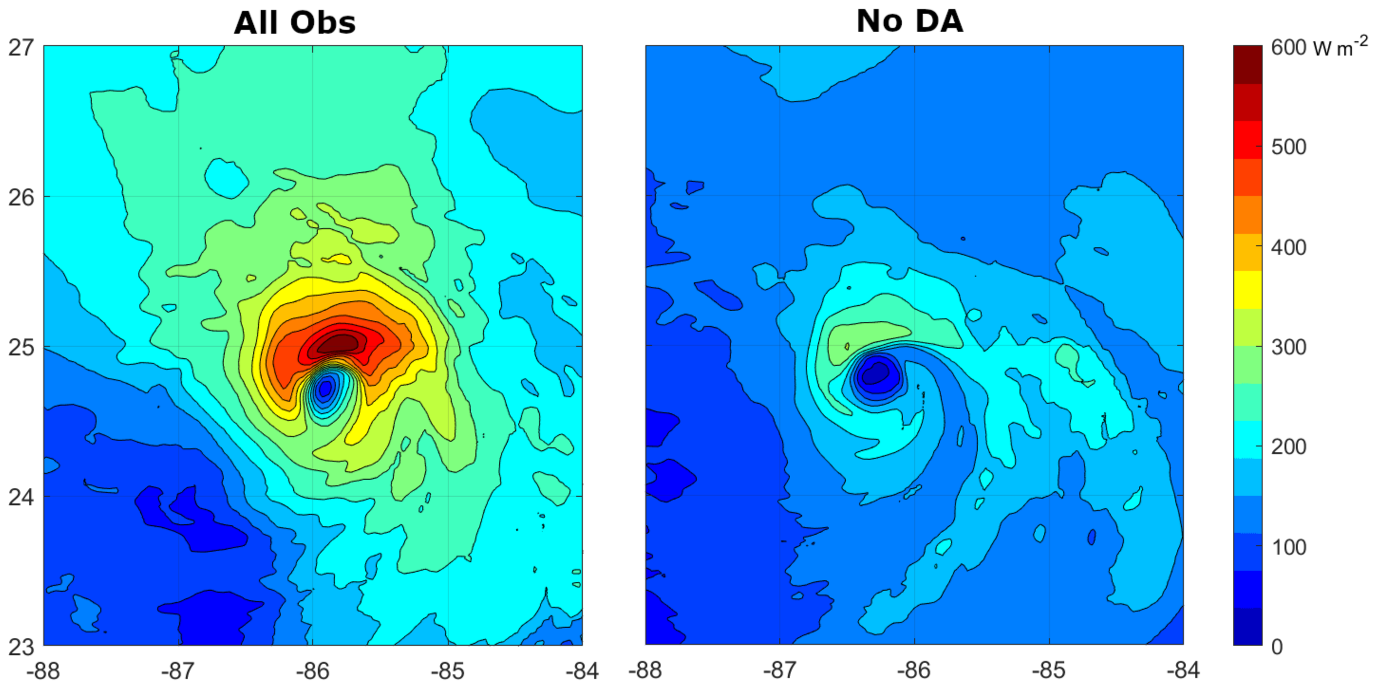
Impact of ocean observations on hurricane forecasts: example of a 5-day cycle



*Observed wind intensities (Best, grey), with simulated ones for the **All Obs**, **No DA**, **Clim** 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)

Impact of specific ocean observations on the forecasts of Michael:

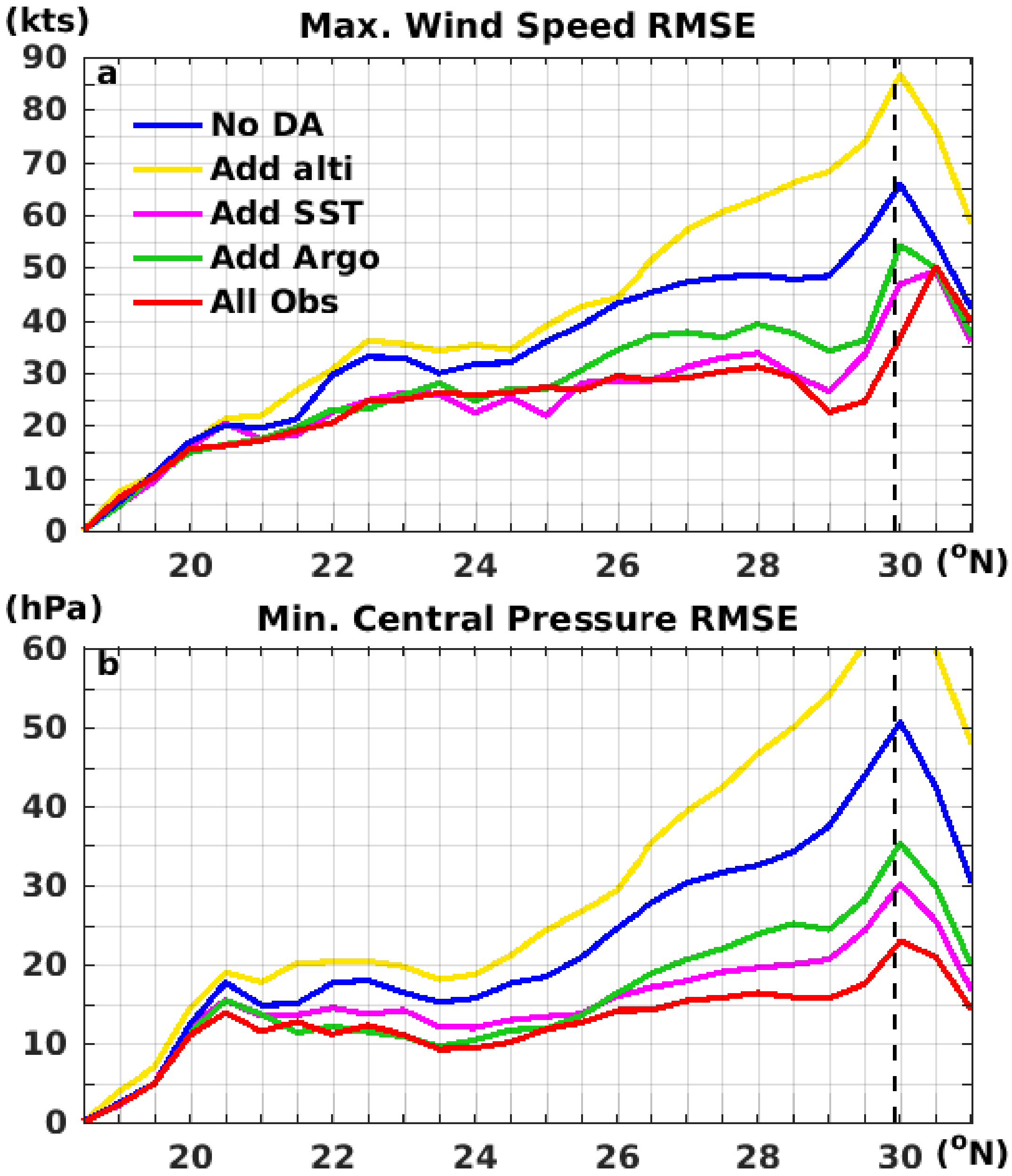
- We performed additional **ocean OSEs**:
  - An experiment in which **only Argo** float observations are assimilated (“*Add Argo*”)
  - An experiment in which **only SST** observations are assimilated (“*Add SST*”)
  - An experiment in which **only altimetry** observations are assimilated (“*Add alti*”)
- These cases are to be compared with the *All Obs* and *No DA* experiments
- We performed a statistical analysis over **4 forecast cycles** (every 6 hrs starting on 6 Oct. 2018 00Z, early stage of the storm) for each set of observations assimilated

Hurricane Michael (2018)

Impact of specific ocean observations on the forecasts of Michael

Wind intensity and central pressure errors over the 4 forecast cycles:

- ***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*** (23.9 kts on average) and ***Add Argo*** (26.6 kts on average) show **significant contributions** to error reduction: Argo floats south of 25ºN, SST north of 25ºN
- Altimetry alone (*Add alti*) degrades the forecast



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

Key findings

• The coupled model HWRF-HYCOM is **able to reproduce the rapid intensification** of **both hurricanes** Maria (2017) and Michael (2018)

• **<u>Maria</u>**: Ocean observations enabled an overall 20% improvement in the 72-hour intensity forecasts; **gliders** were **efficient in the 24 hrs preceding landfall** (due to the limited spatial extent of their error reduction): suggests a **dense network of profilers** is **necessary** to constrain ocean models

• **<u>Michael</u>**: Assimilating ocean observations led to an average 32% error reduction in wind intensity forecast, and 56% at landfall. This large error reduction stresses the **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)

Key findings

Results can be found:

- Domingues, R., M. Le Hénaff, G. Halliwell, J.A. Zhang, F. Bringas, P. Chardon, H.-S. Kim, J. Morell, and G. Goni (2021). The impact of ocean conditions on the intensification and forecasts of three major Atlantic hurricanes of 2017. *Monthly Weather Review*, 149(5), pp.1265-1286

- 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

- Dong, J., Domingues, R., Goni, G., Halliwell, G., Kim, H.-S., Lee, S.-K., et al. (2017). Impact of assimilating underwater glider data on Hurricane Gonzalo (2014) forecasts. *Weather and Forecasting*, 32(3), 1143–1159. https://doi.org/10.1175/WAF-D-16-0182.1