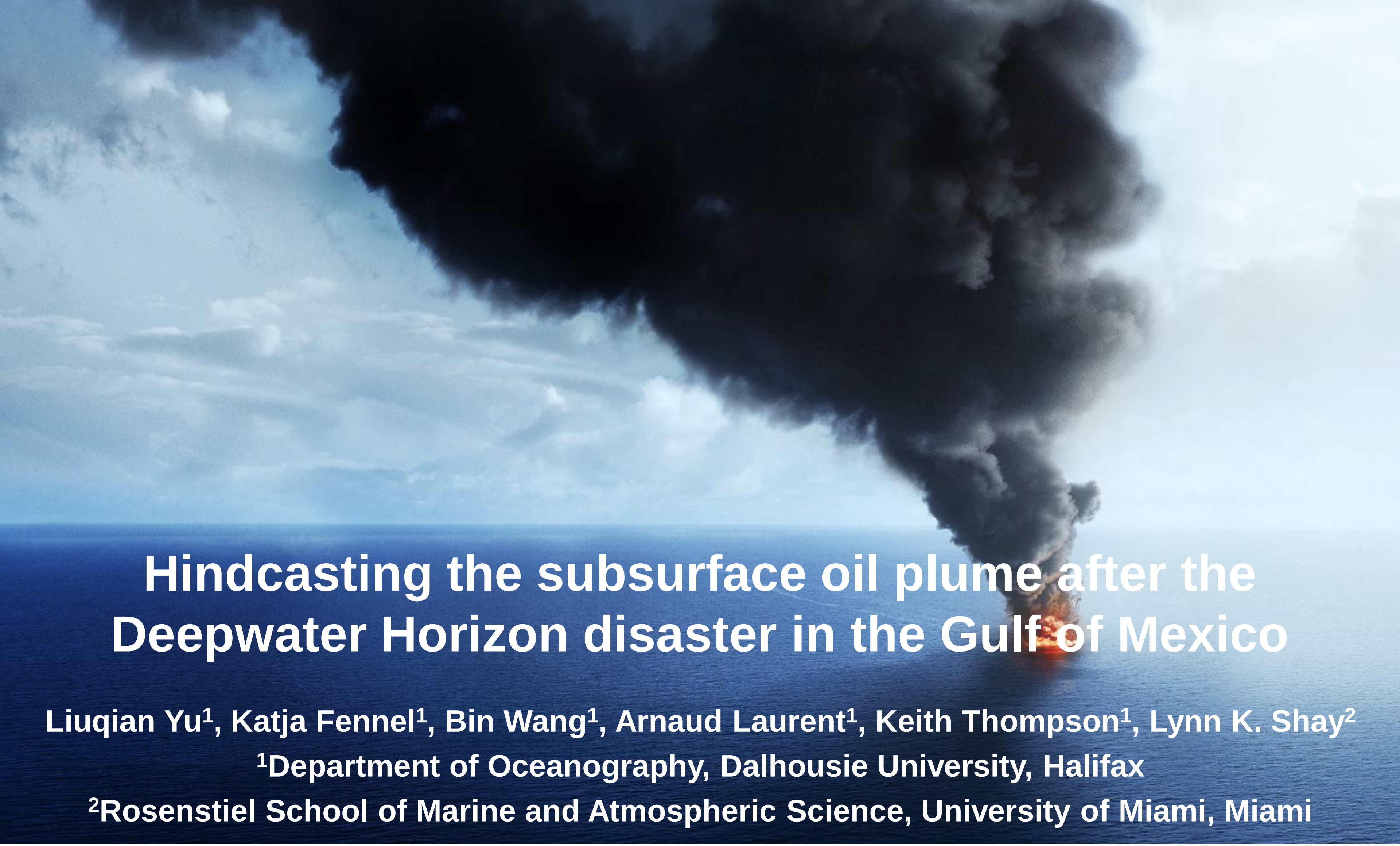

Hindcasting the subsurface oil plume after the Deepwater Horizon disaster in the Gulf of Mexico

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Motivation

- Deepwater Horizon oil spill in April 2010

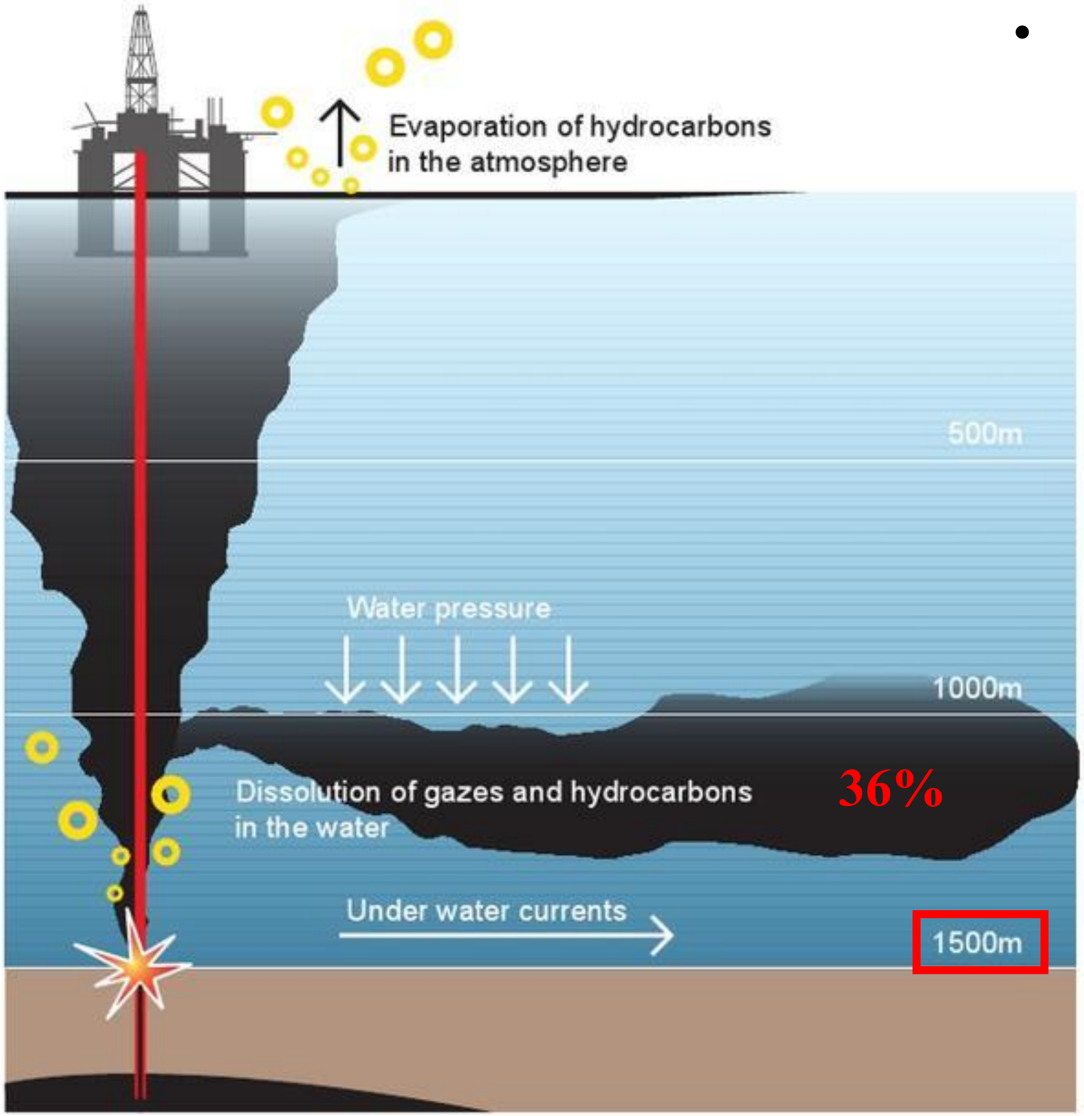


Image from: https://actu.epfl.ch/news/deep-below-the-deepwater-horizon-oil-spill/

- Released crude oil: 4.9 million barrels
  - **36%** (neutrally buoyant fractions) remained at depth (> 1000m)

➔ requires accurate estimation of circulation at depth

- **Significant O_2 drawdown** due to the microbial degradation of the hydrocarbons
  - O_2 profiles were collected to track the movement of the hydrocarbon plume and estimate its mass and decay

➔ requires optimal sampling schemes for best estimate

Objectives

1. Does assimilation improve the simulated subsurface circulation?

- Fraternal twin experiments

2. Does assimilation improve the simulated HydroC plume?

- Assimilate real observations

  - impact of assimilation on physical fields

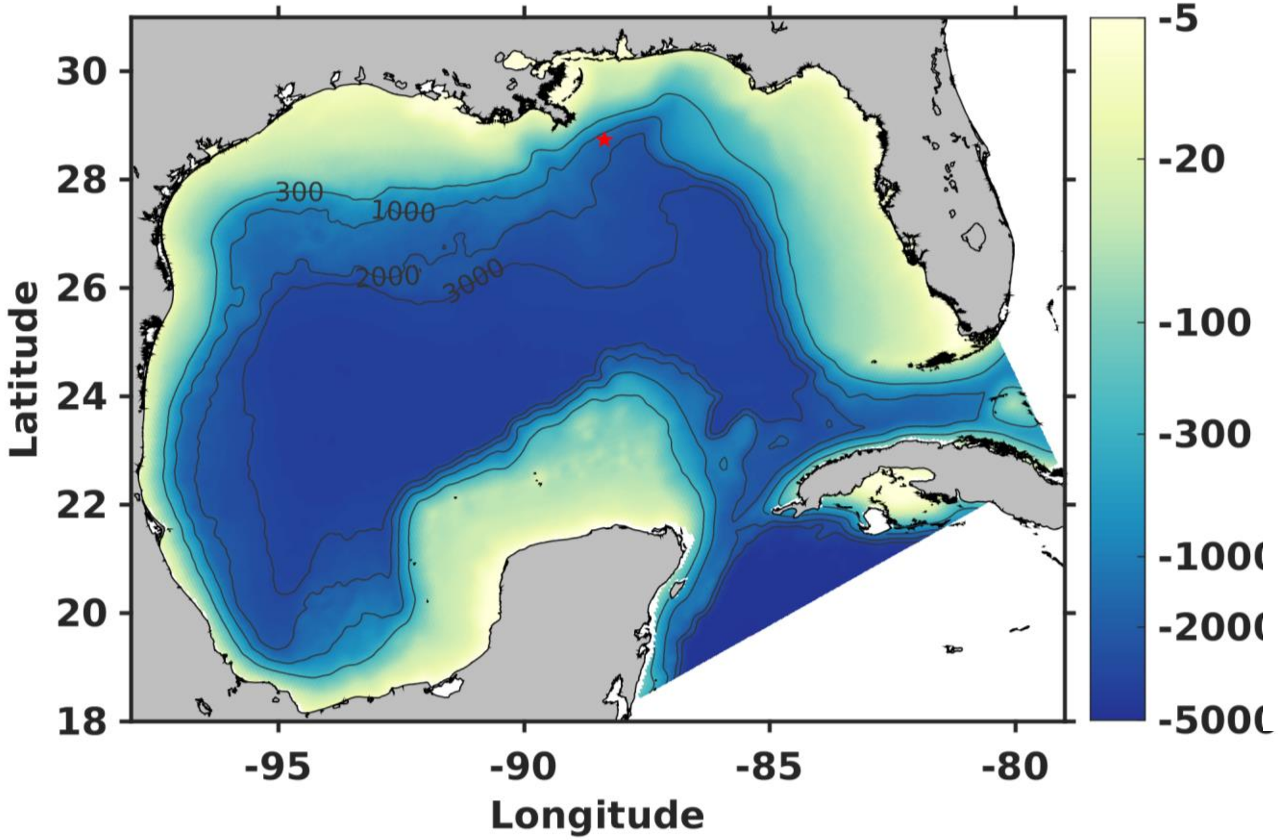
  - validation against the observed O_2 drawdown

3. Are available O_2 profile observations sufficient to map the HydroC plume?

- Sensitivity to HydroC decay rates

4. Improve O_2 profiles sampling strategy to track & estimate HydroC plume

EnKF-based data assimilative physical-hydrocarbon model



- Regional Ocean Modelling System (**ROMS**)
- Horizontal resolution: **5 km**
- 36 vertical layers
- ECMWF forcing
- Initial and boundary conditions from HYCOM
- HSIMT advection scheme
- **April - October 2010**

Two tracers to represent deep-water oil plume:

- ***HydroC1*** (suspended fraction)
- ***HydroC2*** (soluble fraction)

$$\frac{\partial C}{\partial t} = -\boldsymbol{u} \cdot \nabla C + \nabla \cdot (K \nabla C) + \boxed{S - r\,C}$$

oil spill source
HydroC decay

I. Impact of DA on subsurface circulation: *fraternal twin*

- **Reference ("truth") run**
  - **HYCOM global simulation**
  - Sample synthetic observations (SSH, SST, T&S profiles)

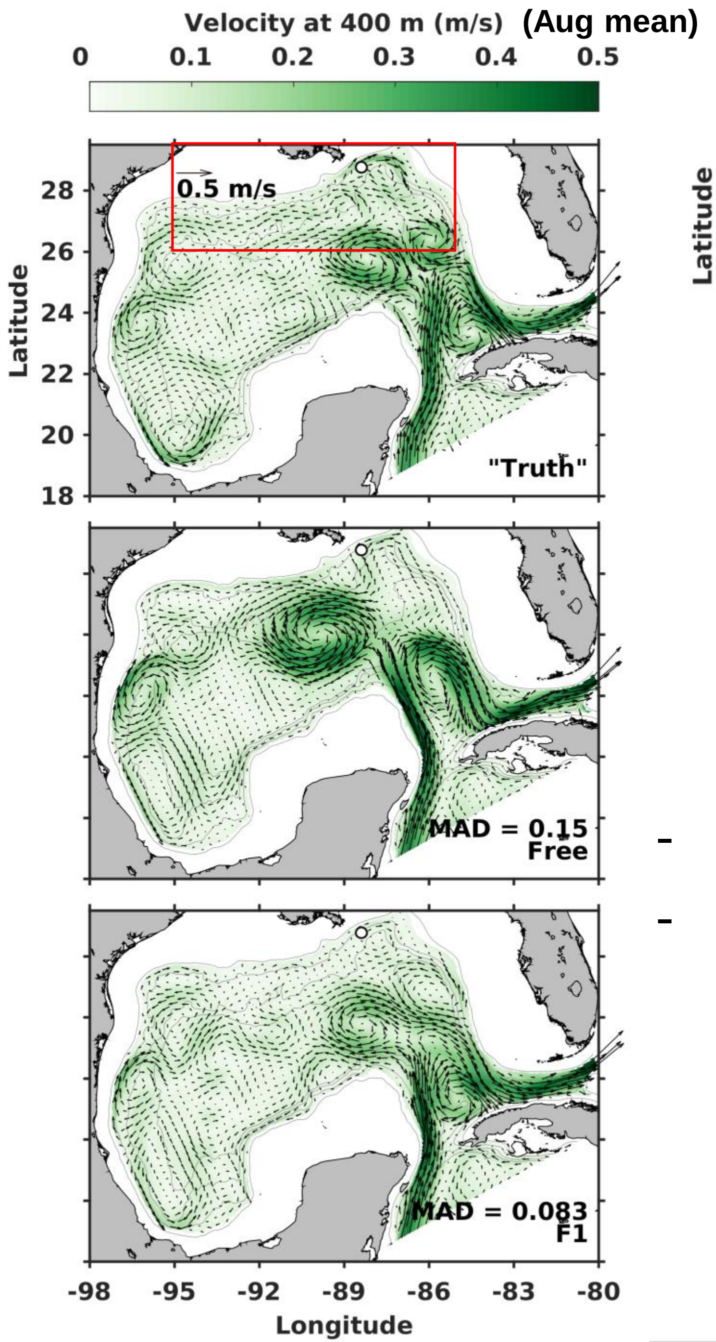
- **Free run**
  - A ROMS simulation run from **April to October 2010**

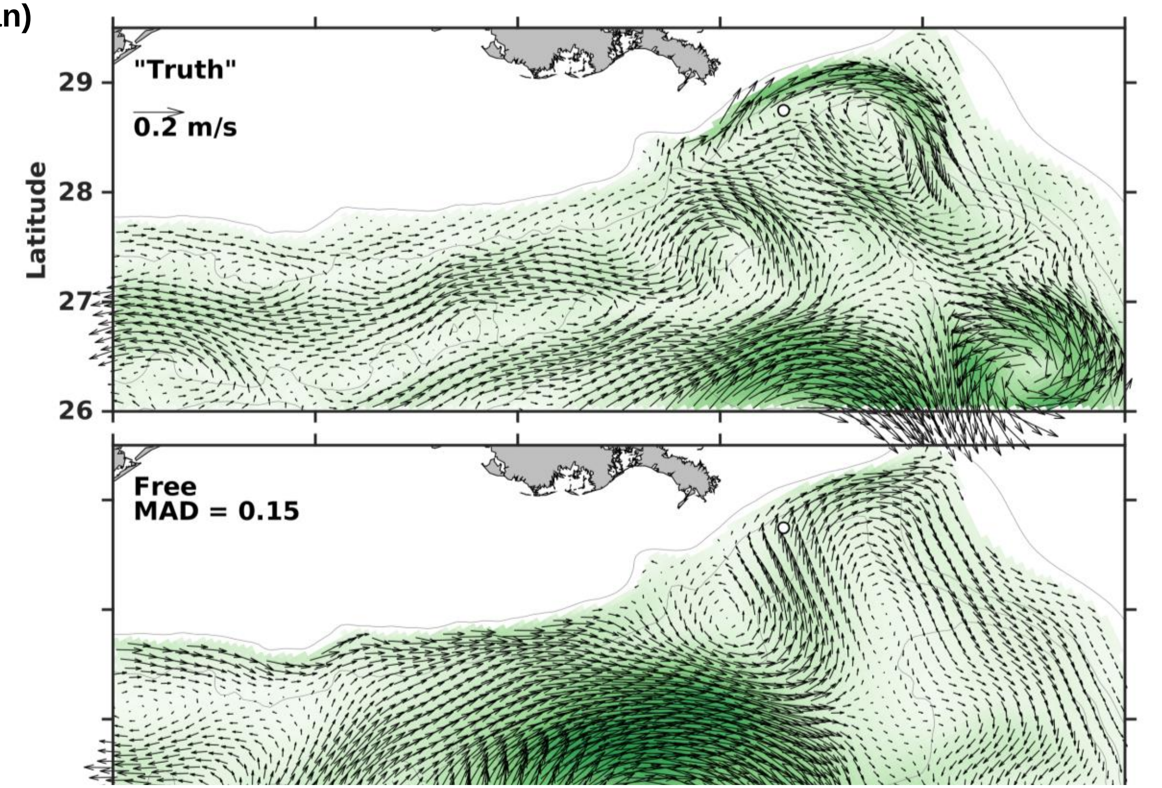
- **Data-assimilative ROMS run**
  - Start from an ensemble (*n*=20) of **initial conditions**, and forced with **perturbed boundary conditions** and **wind**
  - Assimilate observations to update 3D T&S fields

MAD reduction	SSH	T	S	u	v
F1	51%	29%	11%	25%	25%

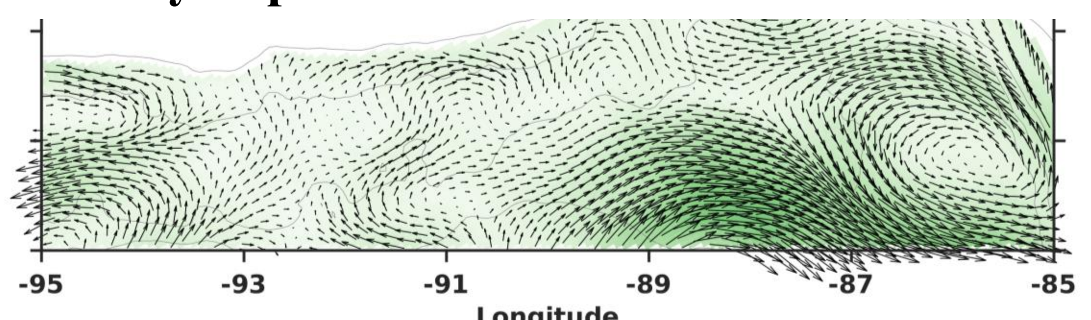
- Mean Absolute Deviation (MAD) is averaged over entire simulation period and whole water column over the open Gulf (bathymetry > 300m deep)

I. Impact of DA on subsurface circulation: *fraternal twin*

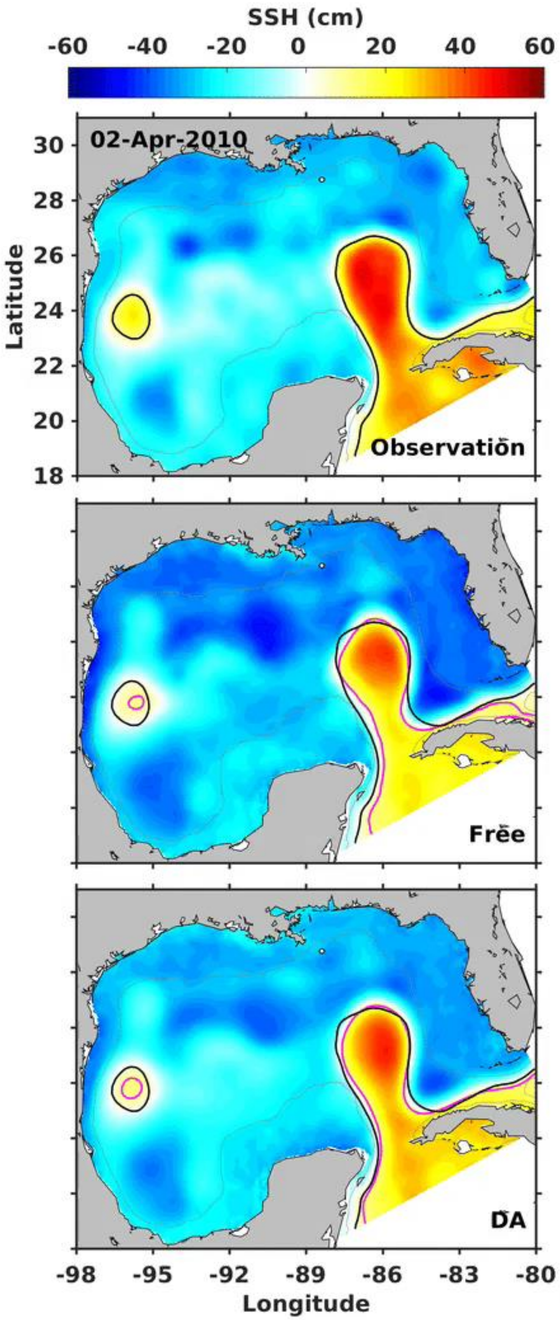




- **Significantly improves the mesoscale circulation**
- **Smaller scale circulation** near the oil spill site is **modestly improved**



II. Impact of DA: *assimilating real observations*



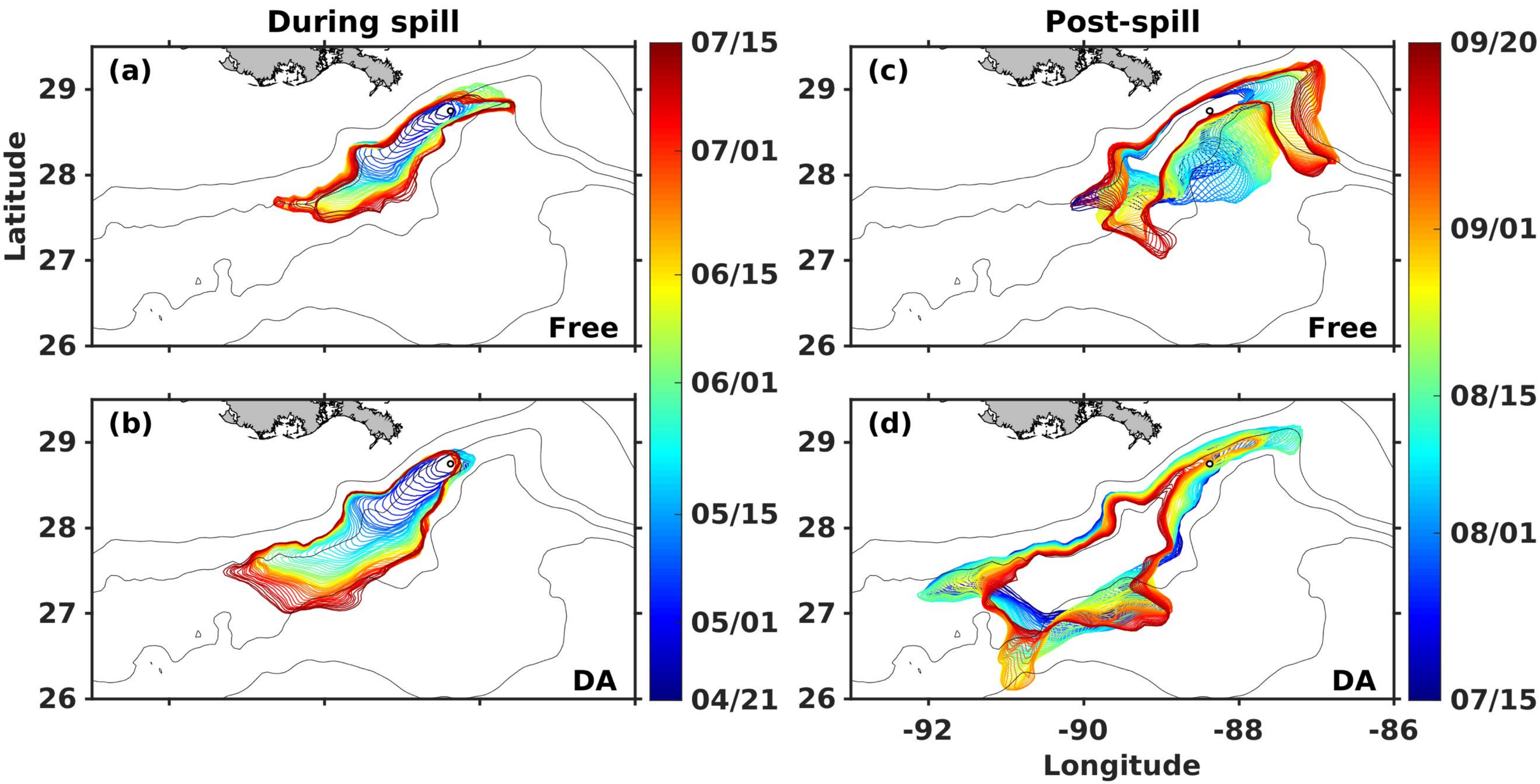
10 cm SSH isoline

- position of the Loop Current fronts and eddies

→ Assimilation run reproduces the observed evolution of Loop Current fronts and eddies well

II. Impact of real DA on hydrocarbon plume distribution

- Time-evolving 0.01 g m^{-2} hydroC contours

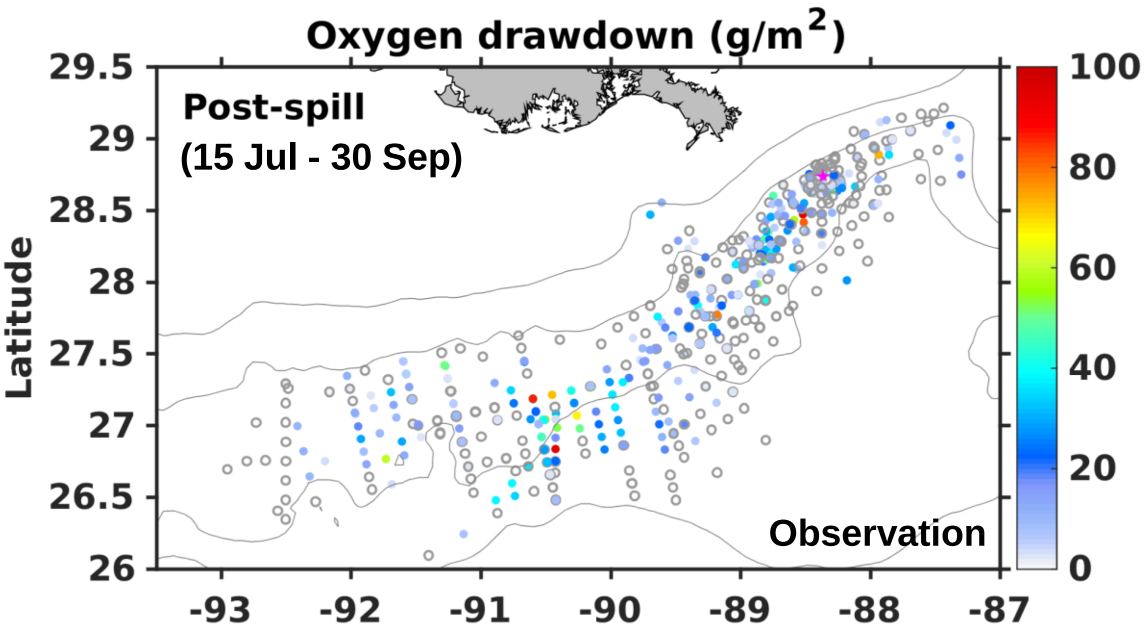


➔ DA has strong impact on the simulated plume distribution especially during the post-spill period.

Q: Are the existing O_2 measurements sufficient to evaluate whether the assimilation improves the simulated hydrocarbon plume?

II. Impact of DA on hydrocarbon plume distribution

- Validation against the observed O_2 drawdown



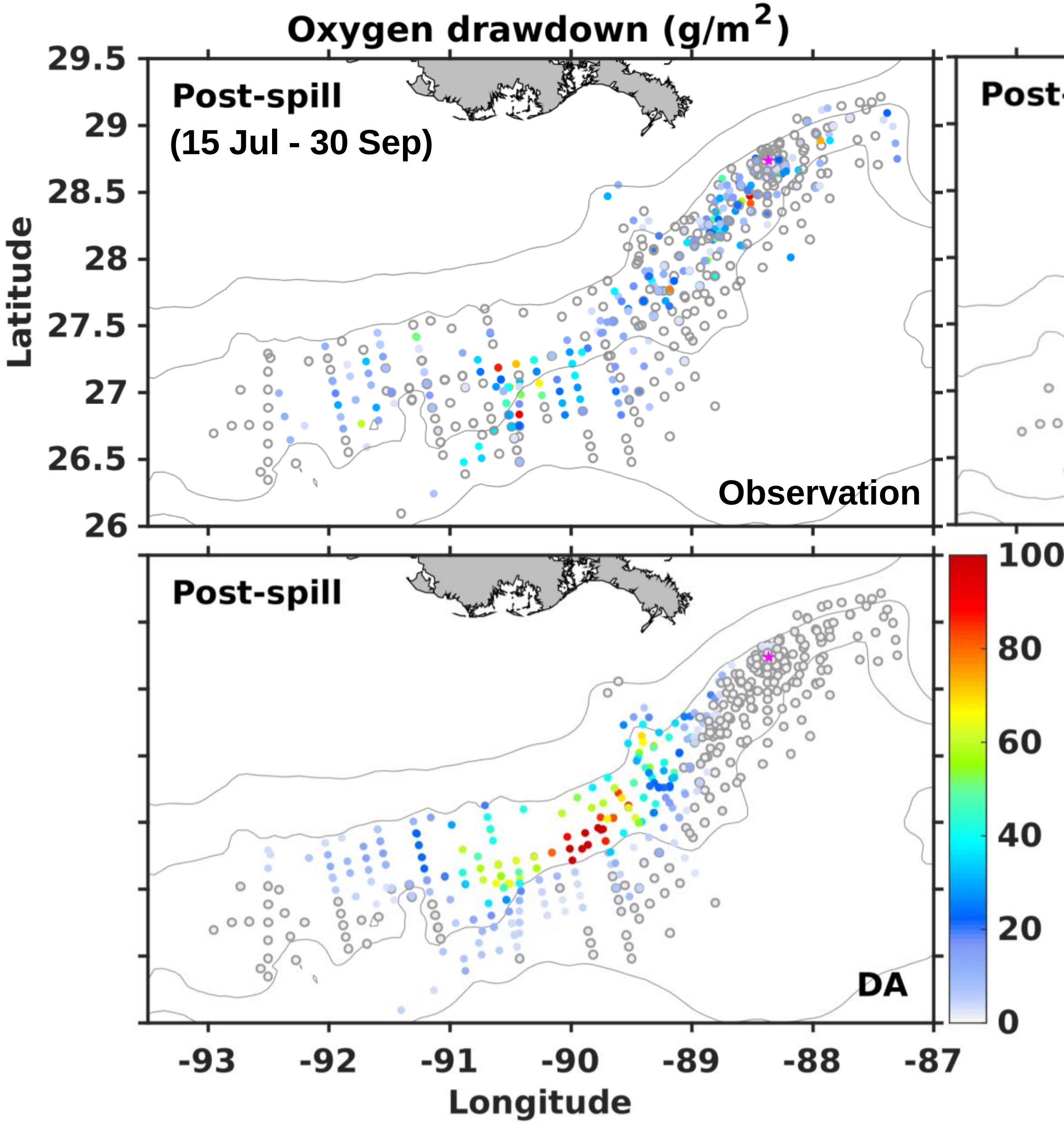
- Shipboard O_2 observations were collected mostly during Aug & Sept (the post-spill period)

→ incomplete in time and space

- Most O_2 drawdown occurred along western shelf region of the spill location

II. Impact of DA on hydrocarbon plume distribution

- Validation against the observed O_2 drawdown



→ **Assimilation run better reproduces the westward directed oil plume transport during the post-spill period**

However, few O_2 observations are available to validate the plume distribution during the spill time period (20 Apr - 15 Jul)

See backup slides for the during-spill observation

III. Sensitivity to hydrocarbon decay

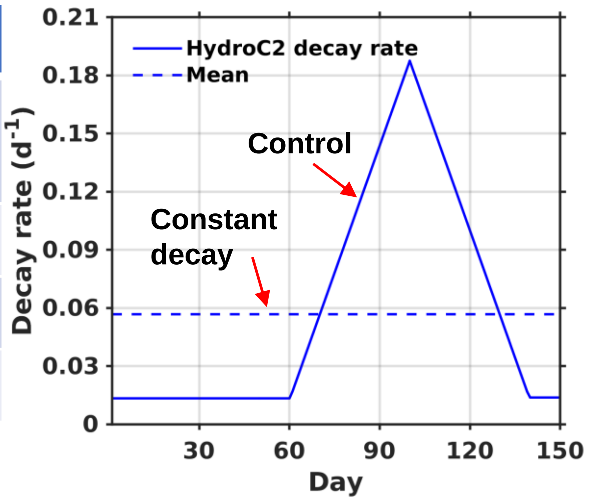
O_2 profile observations were mostly collected during the post-spill period and were limited in space. ➔

Will it bias the estimation of hydroC mass based on O_2 drawdown?

Can the available O_2 measurements constrain the hydrocarbon decay parameter?

➔ Conduct sensitivity tests in **a deterministic physical-hydroC model**, where physical fields are strongly nudged to DA run to obtain **as good physics as in DA run while saving computational resources.**

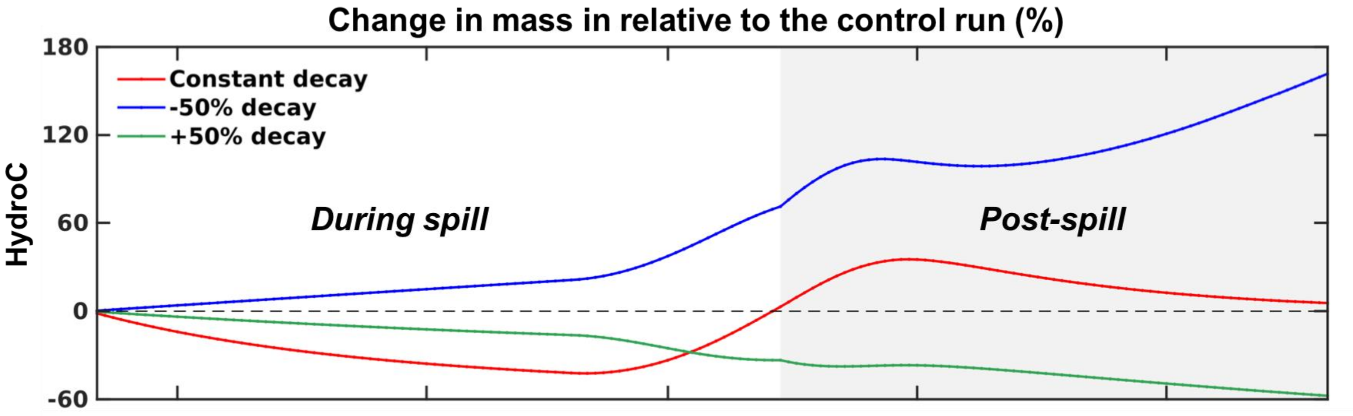
Experiments	
Control	Time-varying hydroC decay rates following Kessler et al. (2011)
-50% decay	-50% decay rates of control
+50% decay	+50% decay rates of control
Constant decay	Constant decay rate (mean value of control)



Kessler et al. (2011) A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico

III. Sensitivity to hydrocarbon decay

Time-series of **domain-integrated mass of HydroC and O_2 drawdown** relative to the control run.



The **HydroC mass** is very sensitive to the decay rate during the spill and in the post-spill period.

The **O_2 drawdown** is sensitive to the decay rate during the spill but not the post-spill period when most observations were collected.

➔ Similar O_2 drawdown but different HydroC mass in the post-spill period; hence, using observations of O_2 drawdown to estimate HydroC mass is problematic.

➔ The existing O_2 observations (mostly collected during the post-spill period) are insufficient to constrain hydrocarbon decay.

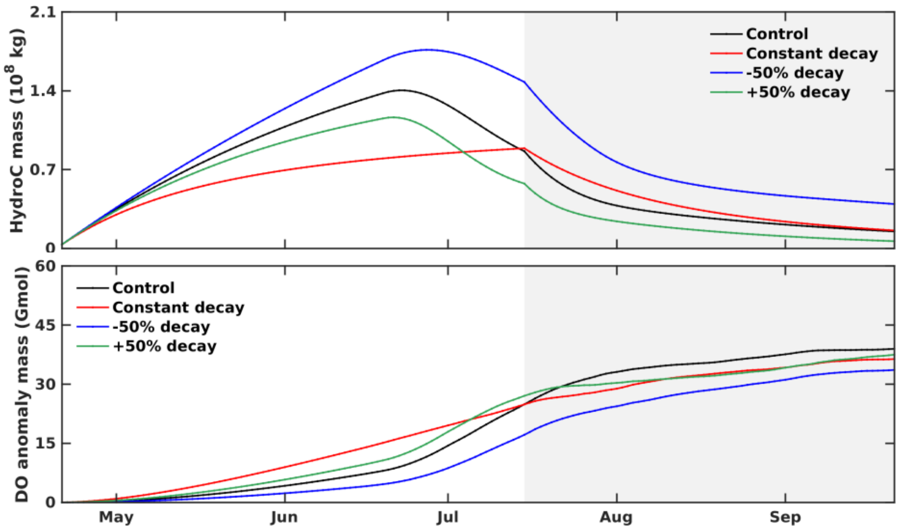
Summary

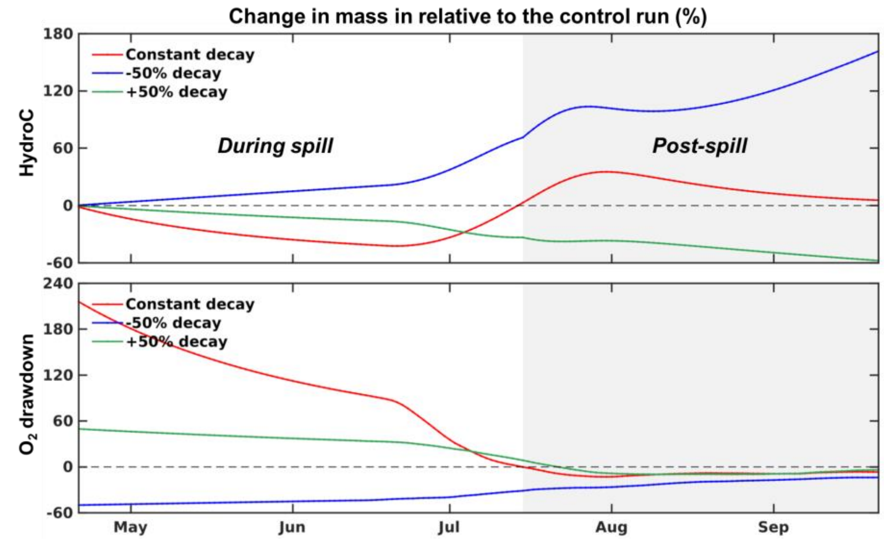
- Fraternal twin experiments show that DA improves the simulated subsurface circulation, especially the mesoscale patterns.

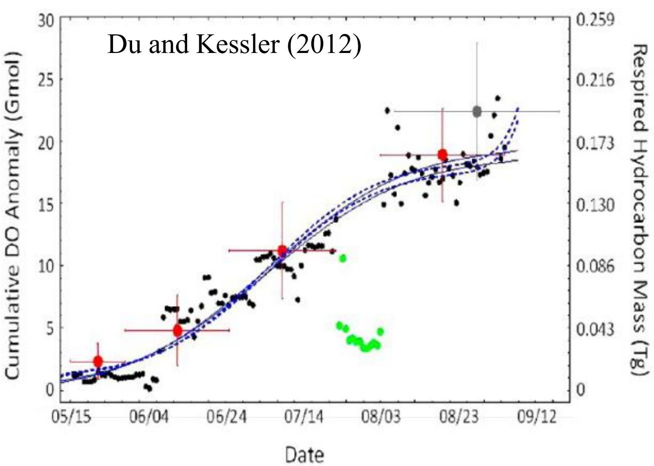
- The improved physical model fields help to better reproduce the observed westward O_2 drawdown associated with HydroC degradation.

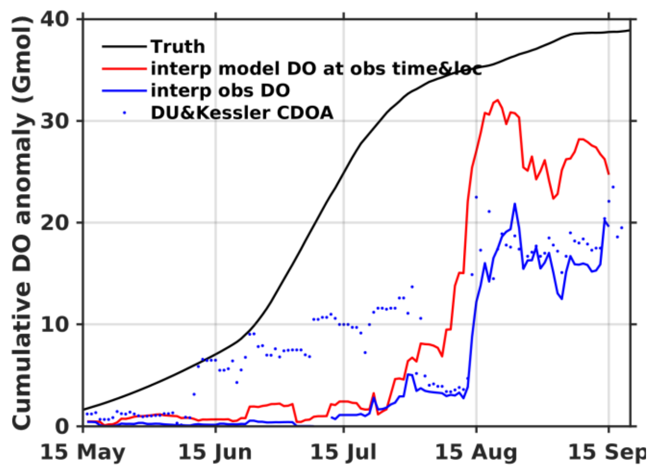
- While HydroC distribution is very sensitive to the decay rate throughout the simulation period, the O_2 drawdown is not sensitive to the decay rate post-spill when most observations were collected. That makes it hard to estimate HydroC mass and decay rate from these measurements.

- Need O_2 observations earlier (during the spill).









Our **DO anomaly mass** is essentially the same as the **Cumulative DO anomaly** in Du & Kessler (2012)

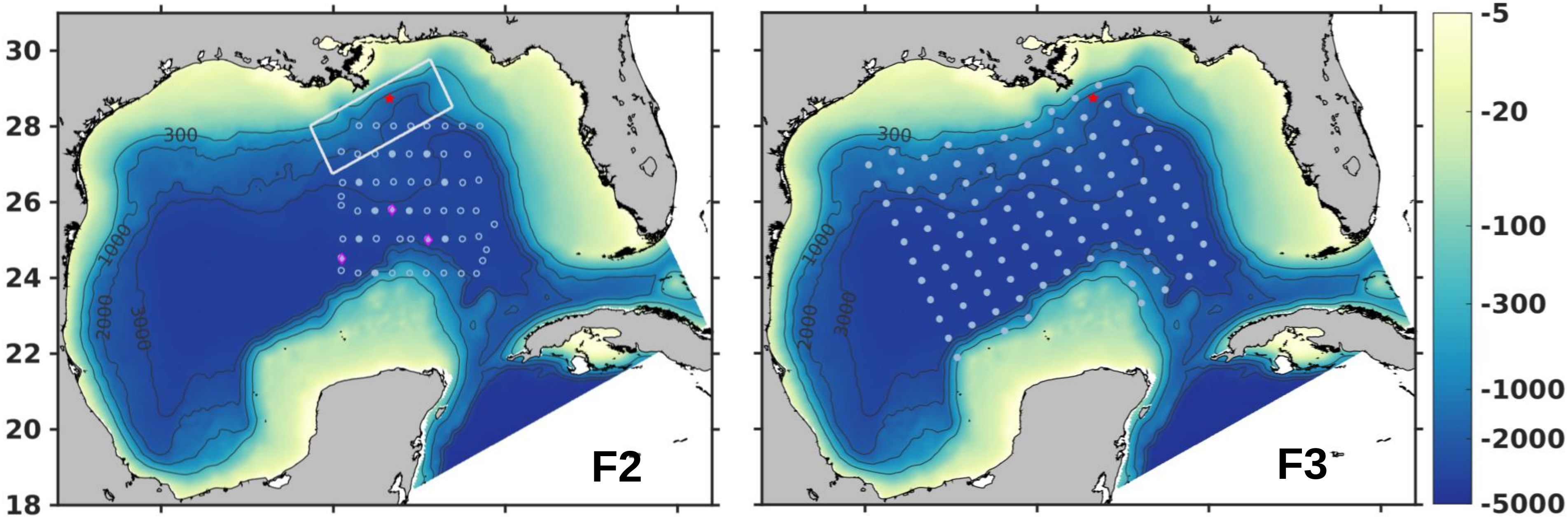
1. Impact of DA: *fraternal twin*

Reference (truth) run

Free run

Data assimilation runs

F1	Weekly SSH (bathymetry > 300m) and SST (> 10m)
F2	Weekly SSH and SST as in F1; T (mostly<400m) & few S profiles on 9 sampling dates from May to Jul (Shay et al. 2011)
F3	Weekly SSH, SST as in F1; Weekly T&S profiles that extend to 1000 m

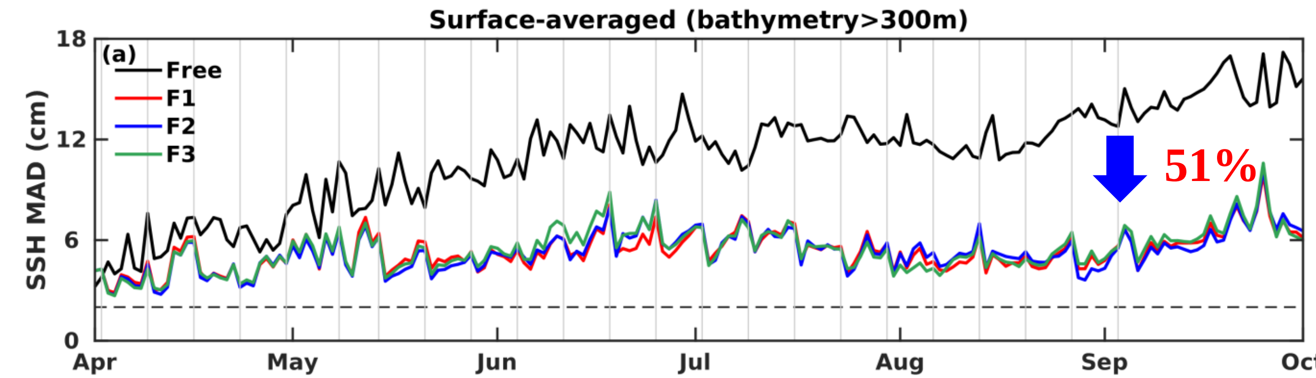


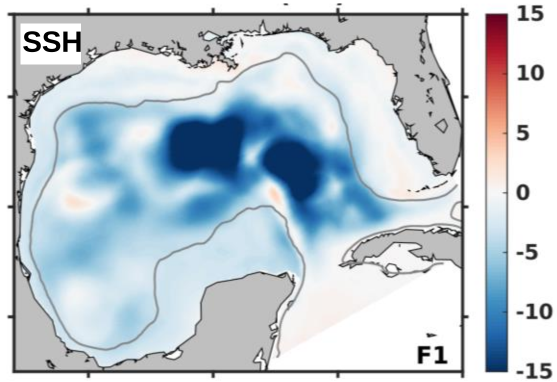
1. Impact of DA: *fraternal twin*

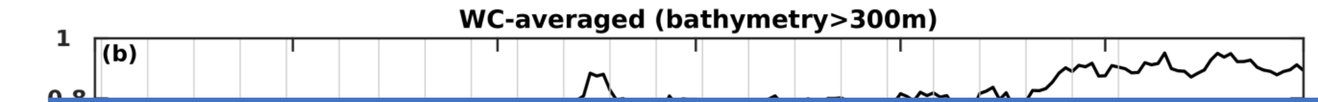
- *mean absolute deviation* (MAD)

(DA run-free) MAD

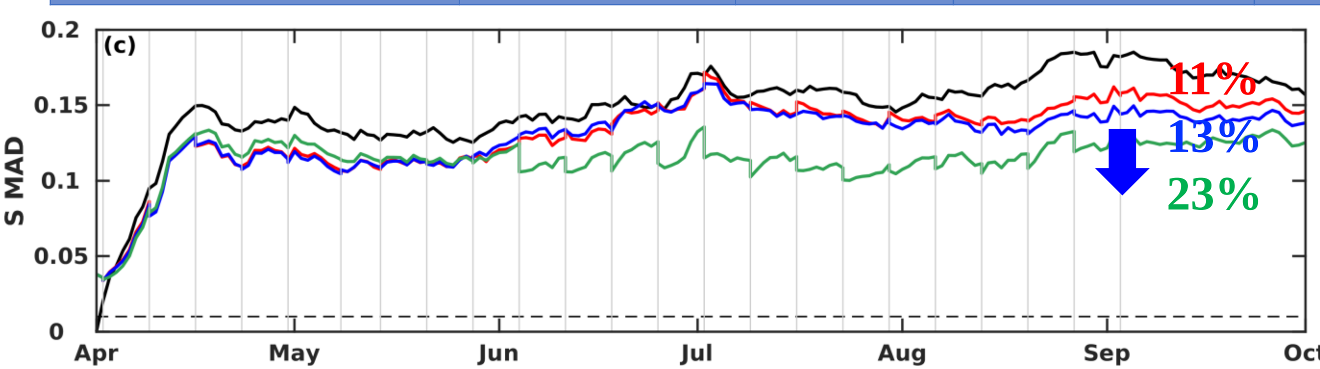
Blue ➔ improvement

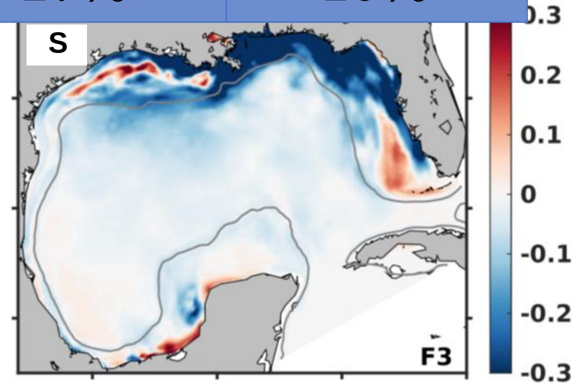




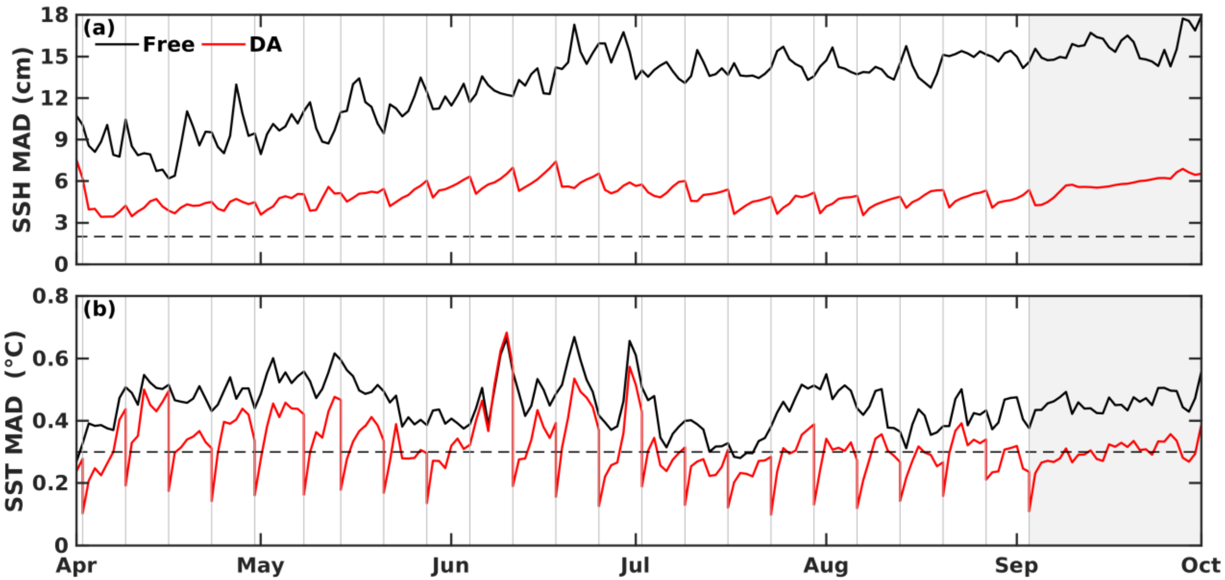


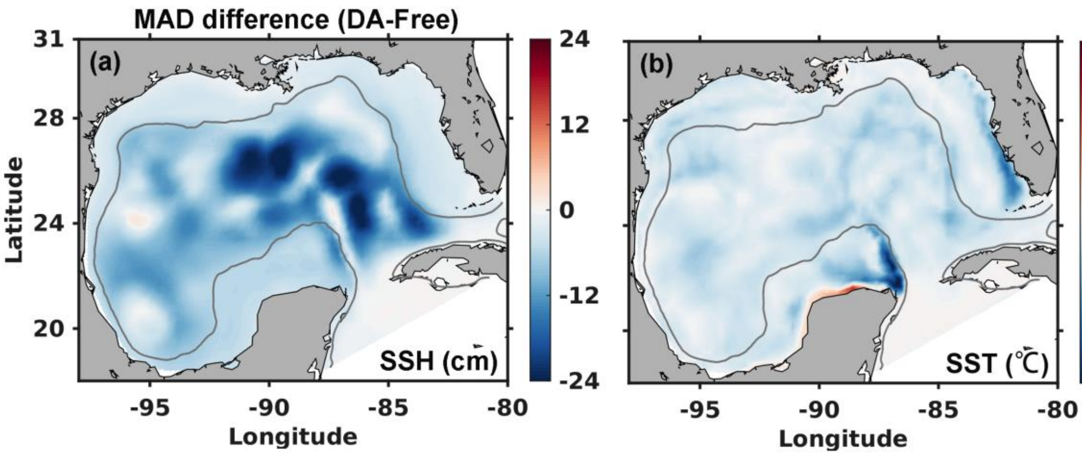
MAD reduction	SSH	T	S	u	v
F1	51%	29%	11%	**25%**	**25%**
F2	52%	30%	13%	**26%**	**24%**
F3	51%	33%	23%	**27%**	**26%**

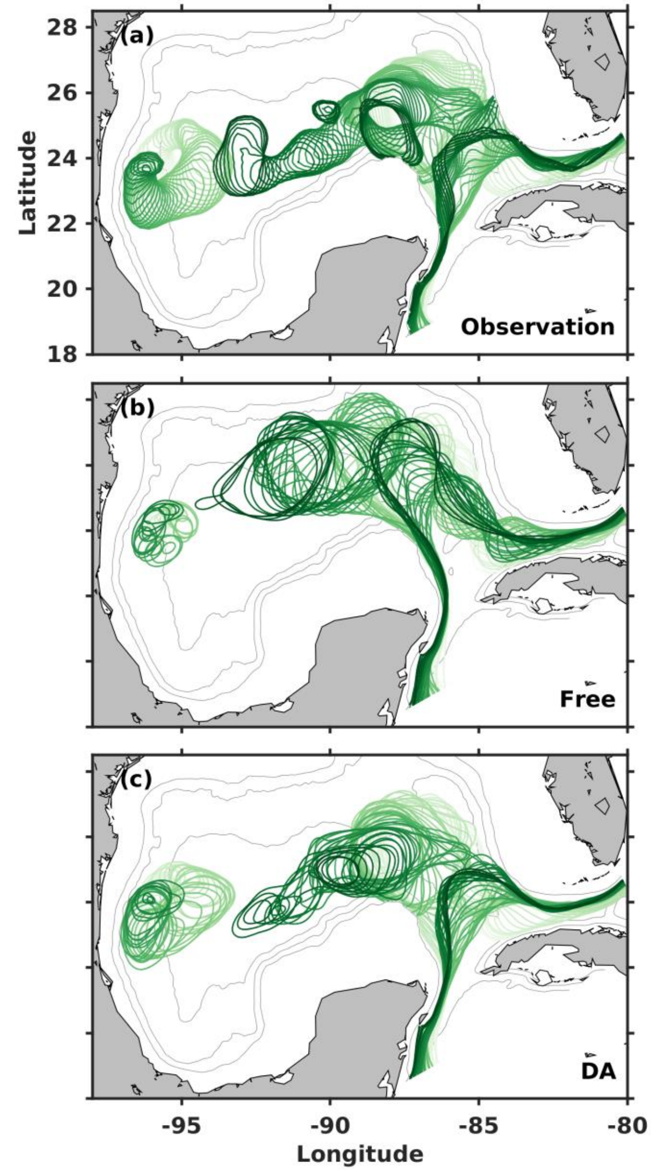




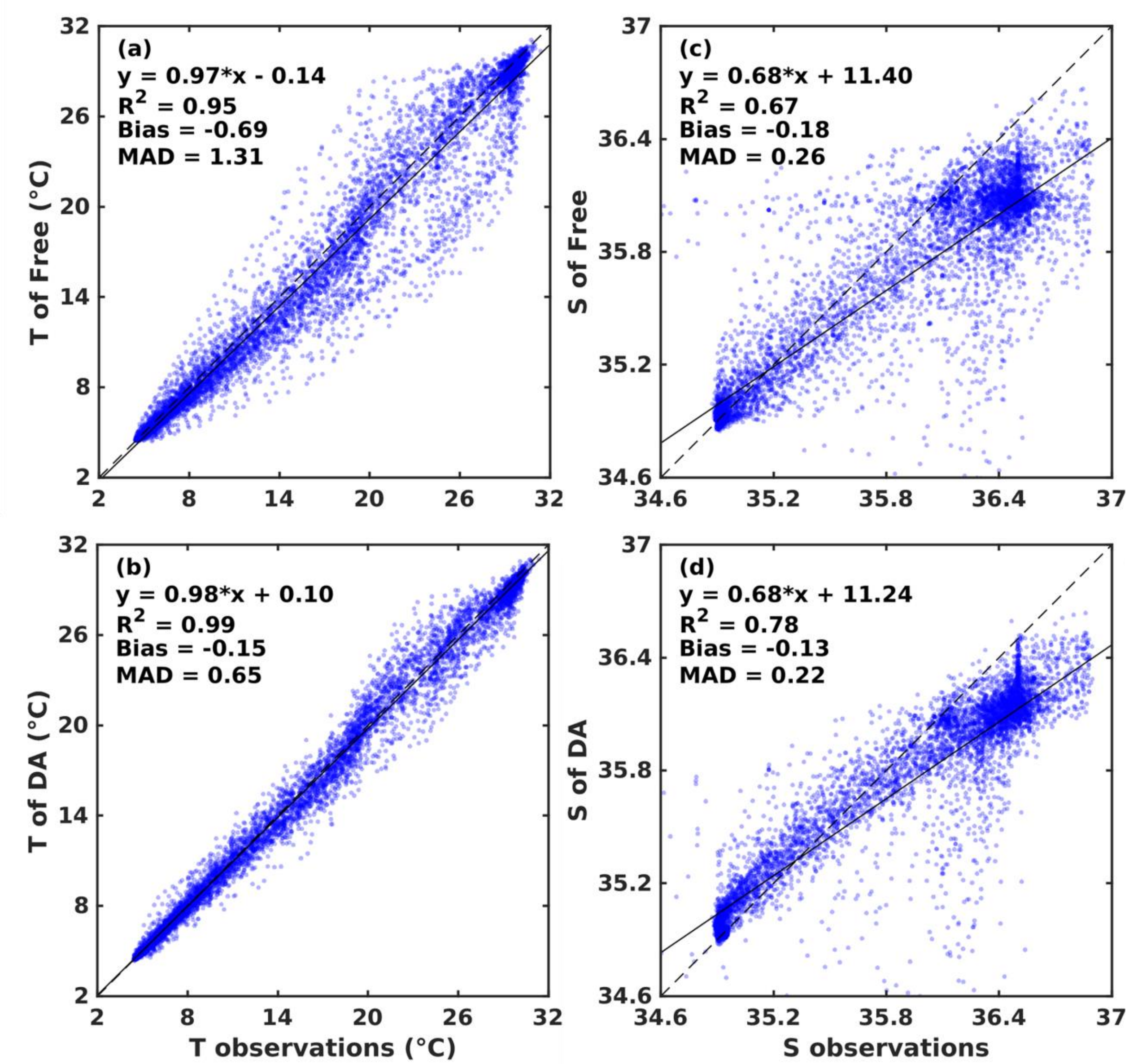
2. Impact of DA: *assimilating real observations*







II. Impact of DA: *assimilating real observations*

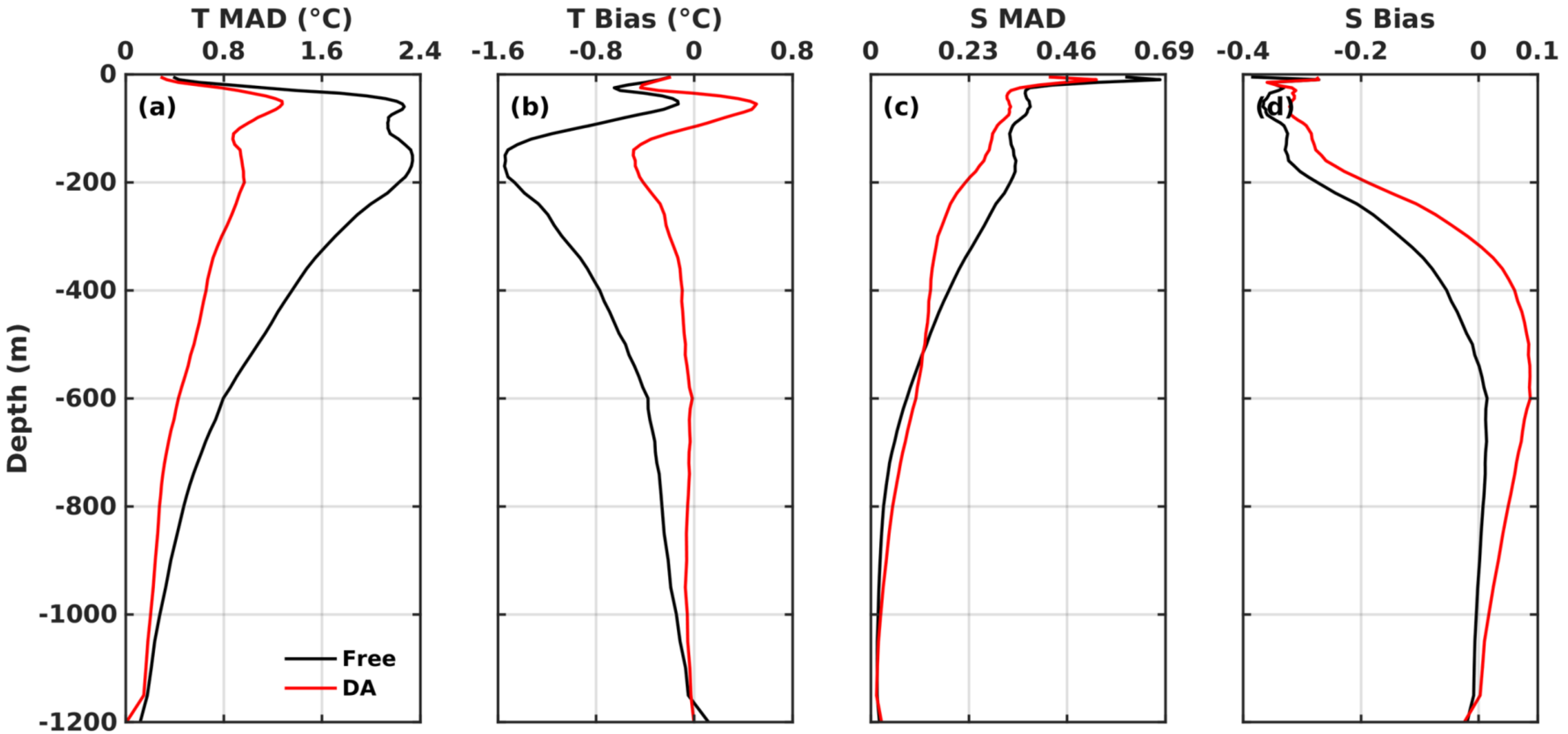


Independent observations

- Comparison against Argo T&S profiling data

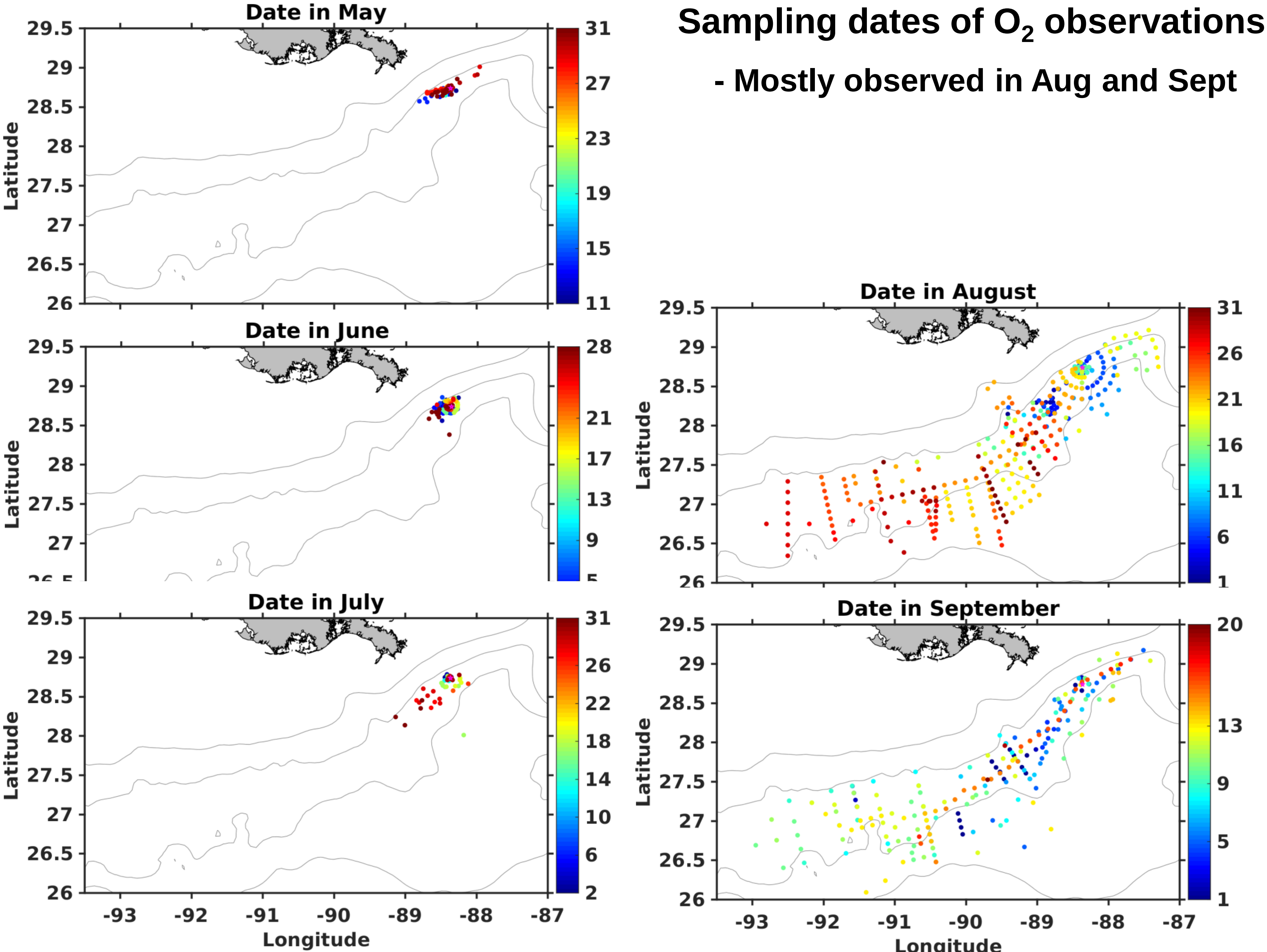
2. Impact of DA: *assimilating real observations*

- Comparison against Argo T&S profiling data

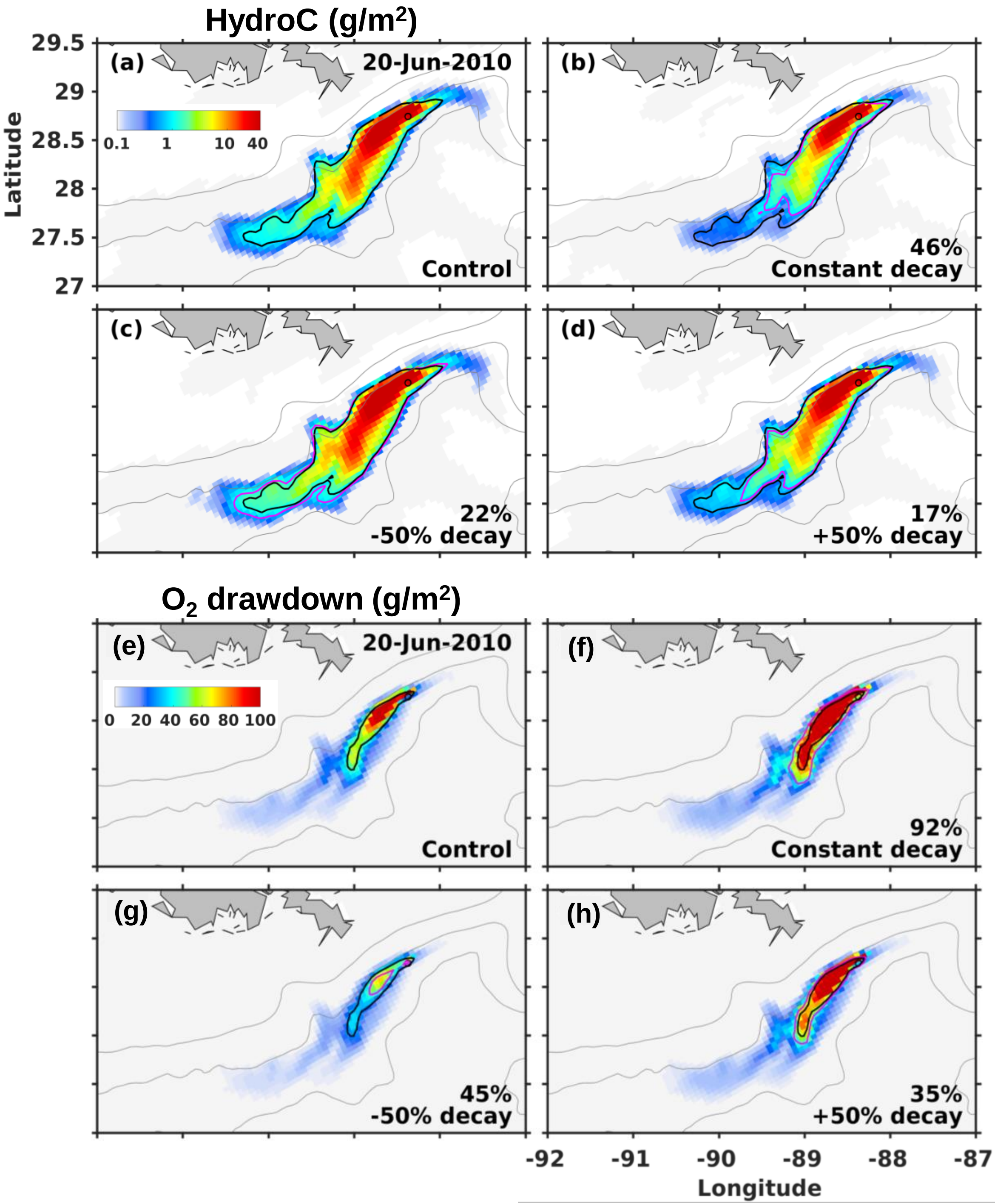


Sampling dates of O_2 observations

- Mostly observed in Aug and Sept



A snapshot of HydroC and O_2 drawdown on 20 Jun (during the spill period)

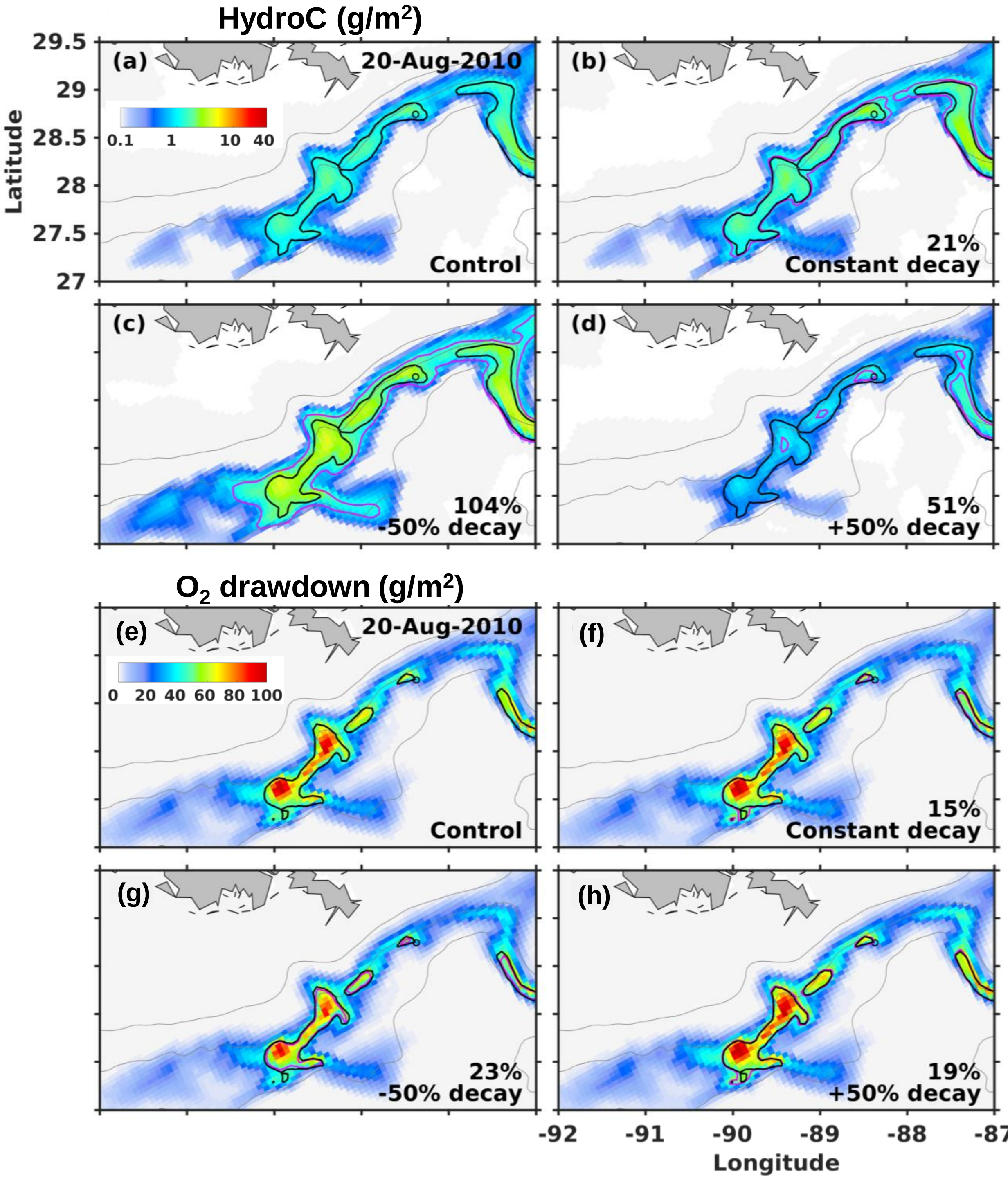


- Percentage change in relative to the control run is listed in each panel

Contour line is 1g/m²

➔ During the spill period, both the HydroC and O2 drawdown mass and spatial distribution are sensitive to the decay rates

Contour line is 50 g/m²



A snapshot of HydroC and O_2 drawdown on 20 Aug (post-spill period)

- Percentage change in relative to the control run is listed in each panel

Contour line is 1g/m^2

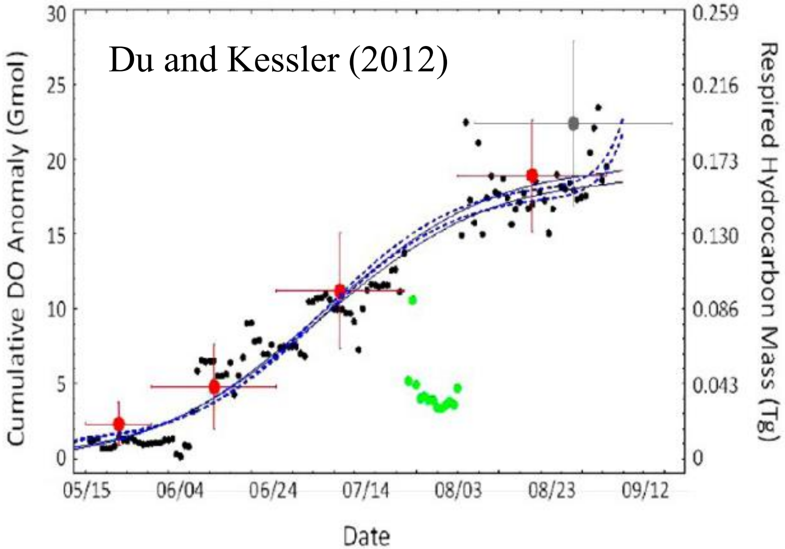
➔ During the post-spill period, while HydroC mass and spatial distribution are sensitive to the decay rates, the O_2 drawdown among different runs are very similar.

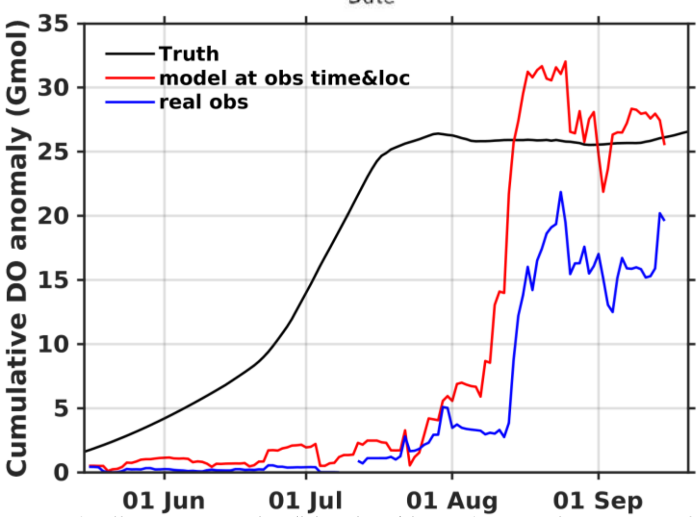
(because O_2 drawdown is the cumulative product of the hydroC mass remaining in water and the decay rate; during post-spill period, there is no 'new' oil source. larger decay rate→ less HydroC remained in water while the O_2 drawdown would be similar under different decays)

Contour line is 50 g/m^2

V. Improve O_2 profiles sampling strategy

- The shipboard measurements of O_2 profiles were used to track the deep-water HydroC distribution and estimate HydroC mass (Reddy et al., 2011; Du and Kessler 2012).





← HydroC mass was estimated from the Cumulative DO Anomaly (CDOA)

- Each CODA snapshot is calculated by interpolating the observed DO anomaly values centering at 11-days time window

Using the 3D physical-hydroC model (T&S fields nudged to the DA run to obtain reliable physics),

- We can calculate the 'true' CDOA at each date
- We can also calculate the 'model-observed' CODA following the actual sampling locations and date.
- Release Lagragian floats to find more efficient O_2 profile sampling scheme that could estimate CODA closer to the 'truth'.
  - Isobaric floats (constant pressure)
  - Released at different depths (0:200:1200m), and then calculate the average to represent the potential float track.

Note: ideally we want the 'blue line' based on real O2 anomaly observations to reproduce Du & Kessler 2012's results, but the Krigging method they used for interpolation was not detailed in their paper that I couldn't obtain same interpolation result as theirs (theirs looks 'too perfect' considering how few observations we had during May-Jul). In the end I used the linear interpolation for my CODA calculation. Nevertheless the point is that the CODA estimation based on the existed O2 observations were far away from the 'truth' and had high uncertainties dependent on the interpolation method.

V. Improve O_2 profiles sampling strategy

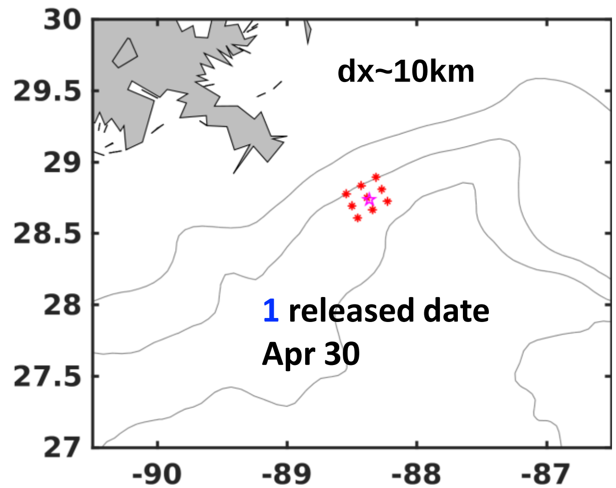
- Is temporal or spatial resolution more important?

Schemes 1~4 have 9 floats

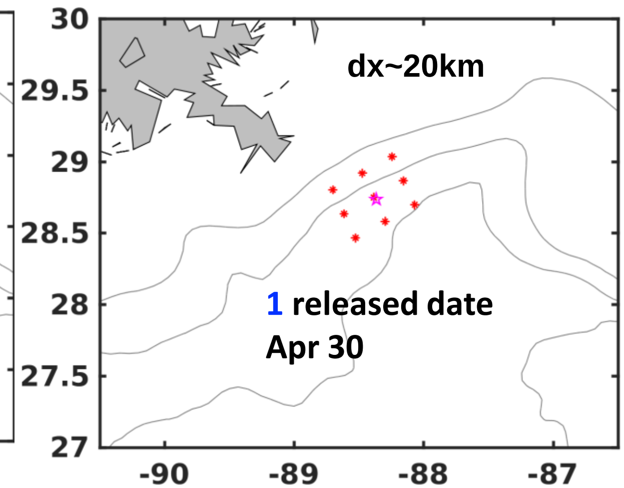
Scheme1

Spill site only
9 released dates from **Apr 30 to July 17** at every 10 days

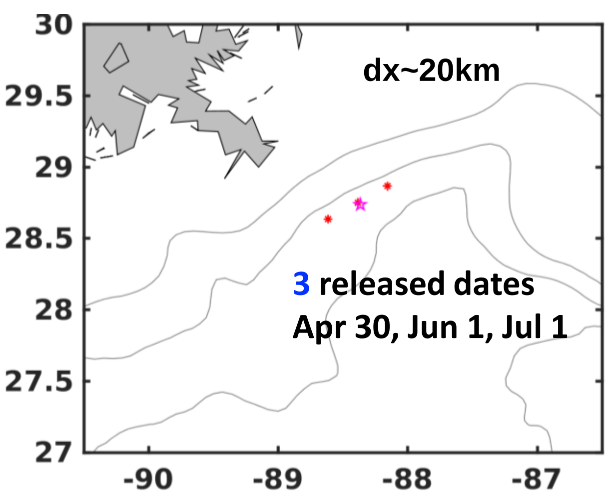
Scheme 2



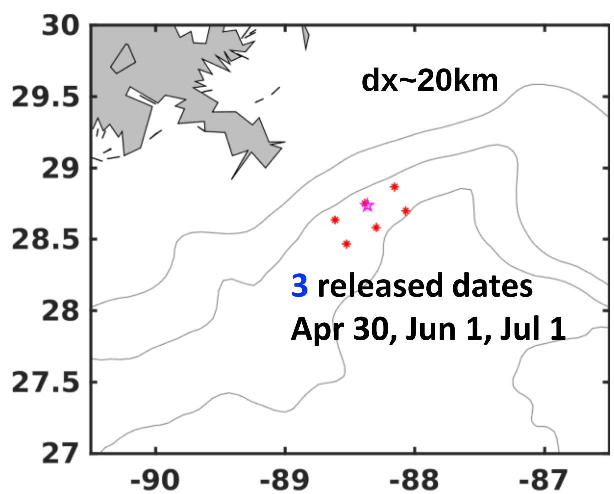
Scheme 3



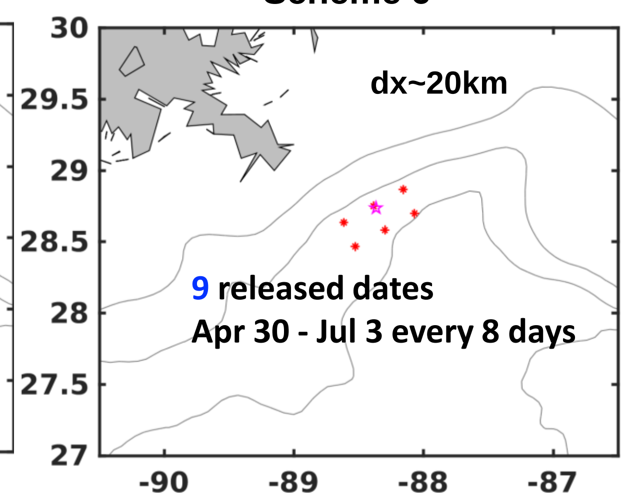
Scheme 4



Scheme 5



Scheme 6



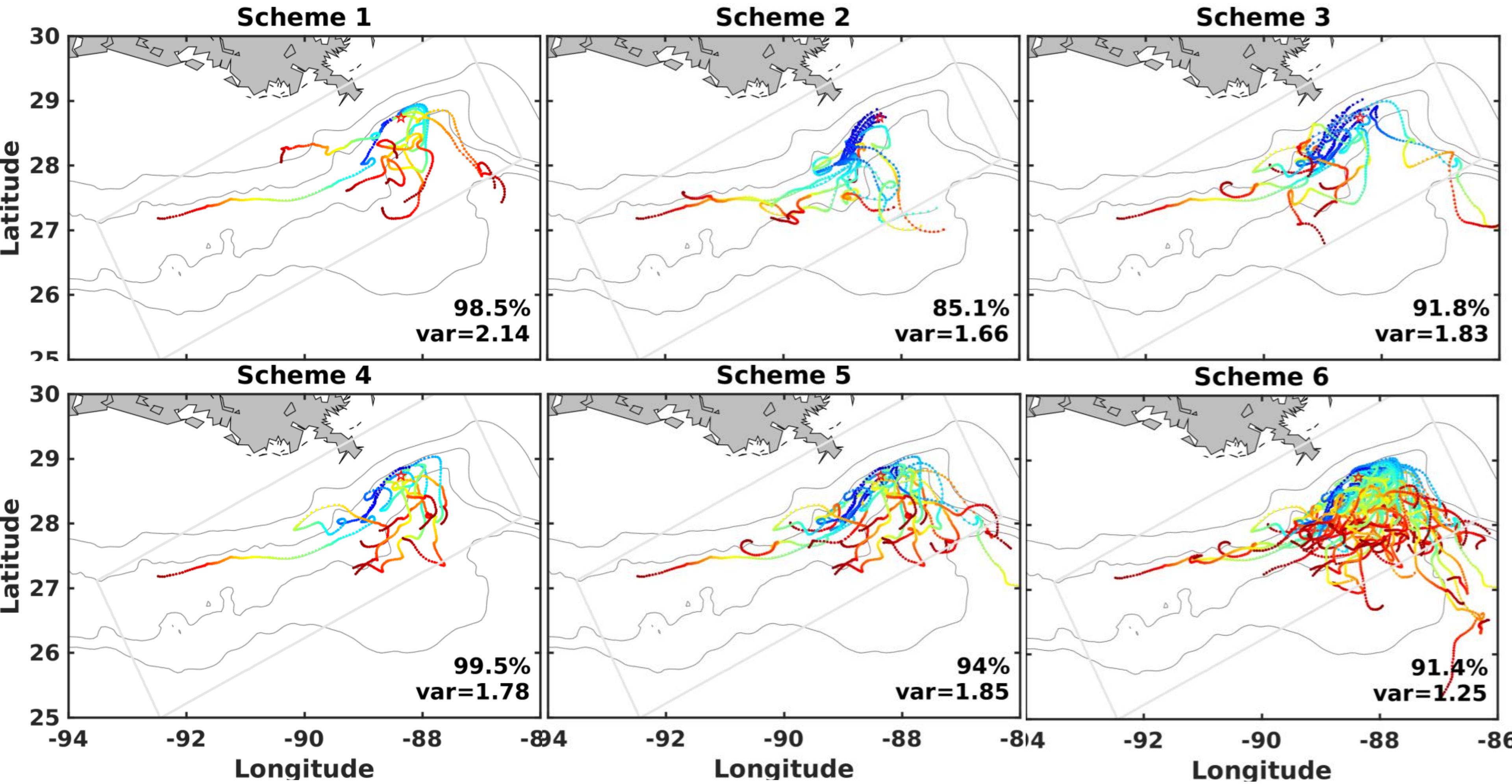
Scheme 5 has 18 floats

Scheme 6 has 27 floats

V. Improve O_2 profiles sampling strategy

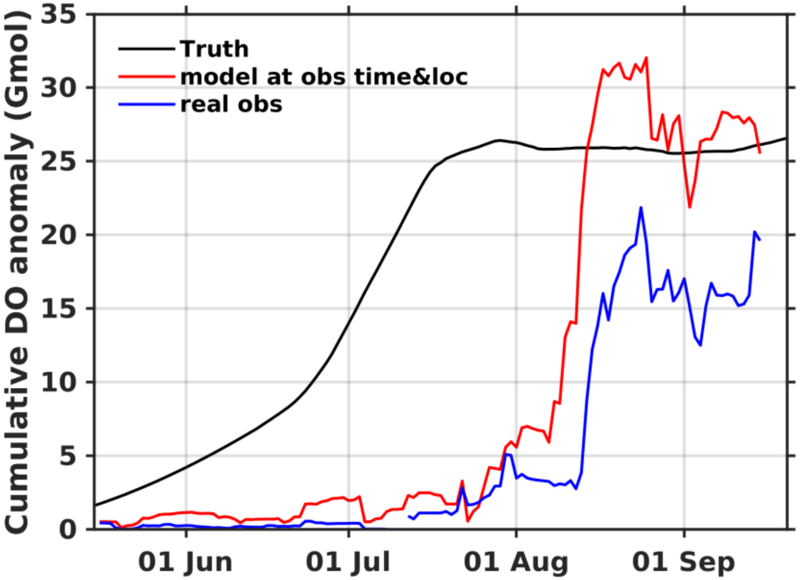
- Is temporal or spatial resolution more important?

Spatial distribution of floats on different dates, where blue to red colors represent the dates from 30 Apr to 30 Sept.



Releasing the same number of floats, scheme 1 covers the largest space (represented by largest variance)
➔ **Temporal resolution** is more important than spatial resolution as the

V. Improve O_2 profiles sampling strategy



Here I should have the CODA time series estimated by the 6 sampling schemes. We expect that

- the CODA based on scheme 1 is closer to the truth than schemes 2~4.
- Increased number of floats improves the CODA estimation. (Scheme 6 > 5 > 1)

This slide is not finish yet….

III. Sensitivity to hydrocarbon decay

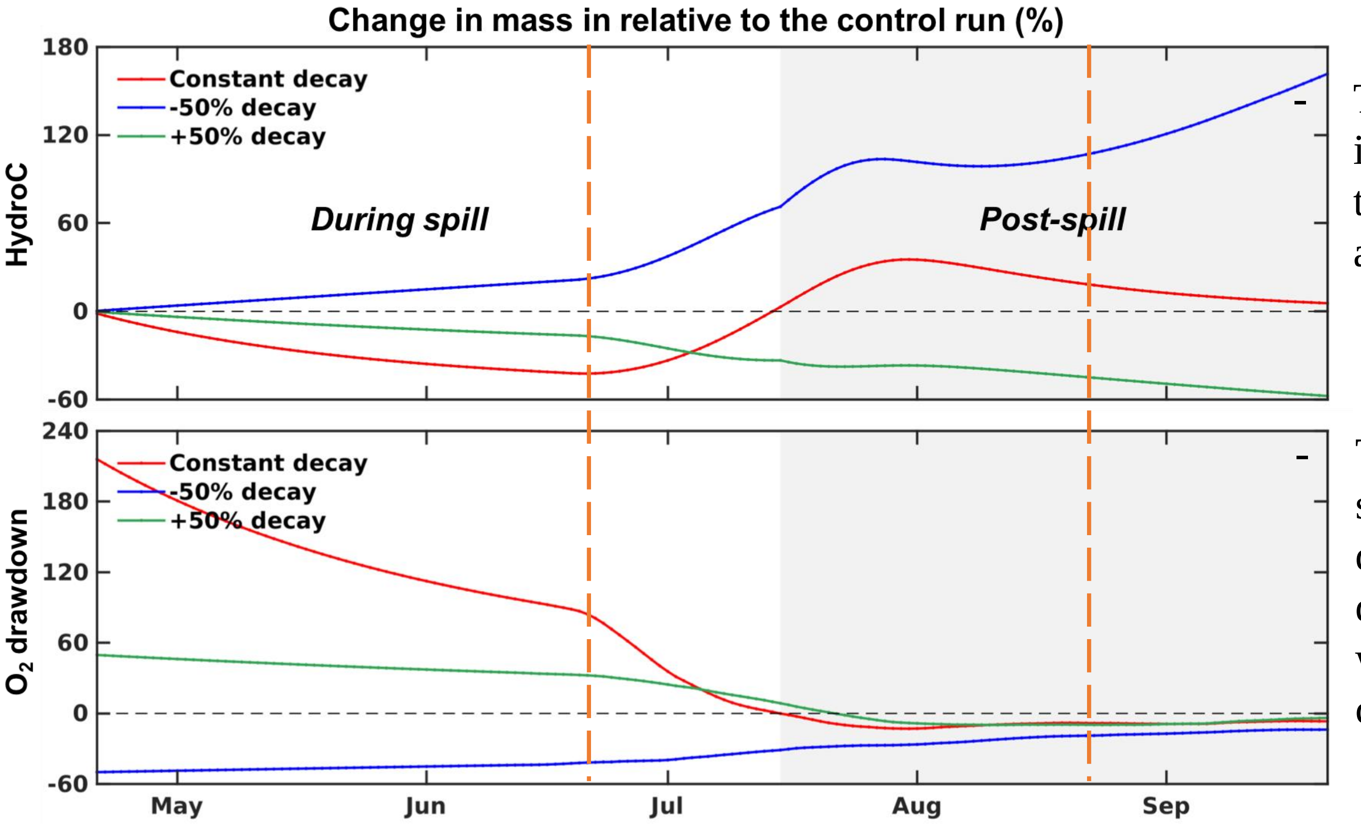
Time-series of percentage change in **domain-integrated mass of HydroC and O_2 drawdown** for the sensitivity runs in relative to the control run.

$$\frac{(m_{sen} - m_{ctl})}{m_{ctl}} * 100$$

- m (a scalar) represents the horizontally and vertically integrated mass of HydroC (O_2 drawdown) on each date
- 'sen' denotes each sensitivity run while 'ctl' denotes control run

III. Sensitivity to hydrocarbon decay

Time-series of percentage change in **domain-integrated mass of HydroC and O_2 drawdown** for the sensitivity runs in relative to the control run.



The **HydroC mass** remained in water is very sensitive to the decay rate during the spill and post-spill time periods.

The **O_2 drawdown mass** are sensitive to the decay rate during the spill period but not during the post-spill period when most observations were collected

➔ the fact that different sensitivity runs have similar integrated mass of O_2 drawdown but different HydroC mass during the post-spill period raises concern in the uncertainty of using the existed O_2 drawdown data to estimate HydroC mass.

➔ the existing O_2 observations (mostly collected during the post-spill period) are insufficient to distinguish the differences between the different hydrocarbon decay simulations; it follows that the current available O_2 observations are not sufficient to constrain the hydrocarbon decay rate.