SOFAR

Improving forecasts at the air-sea interface

through coupled atmosphere-wave-ocean modeling, coupled data assimilation, and Sofar's unique global network of Spotter buoys

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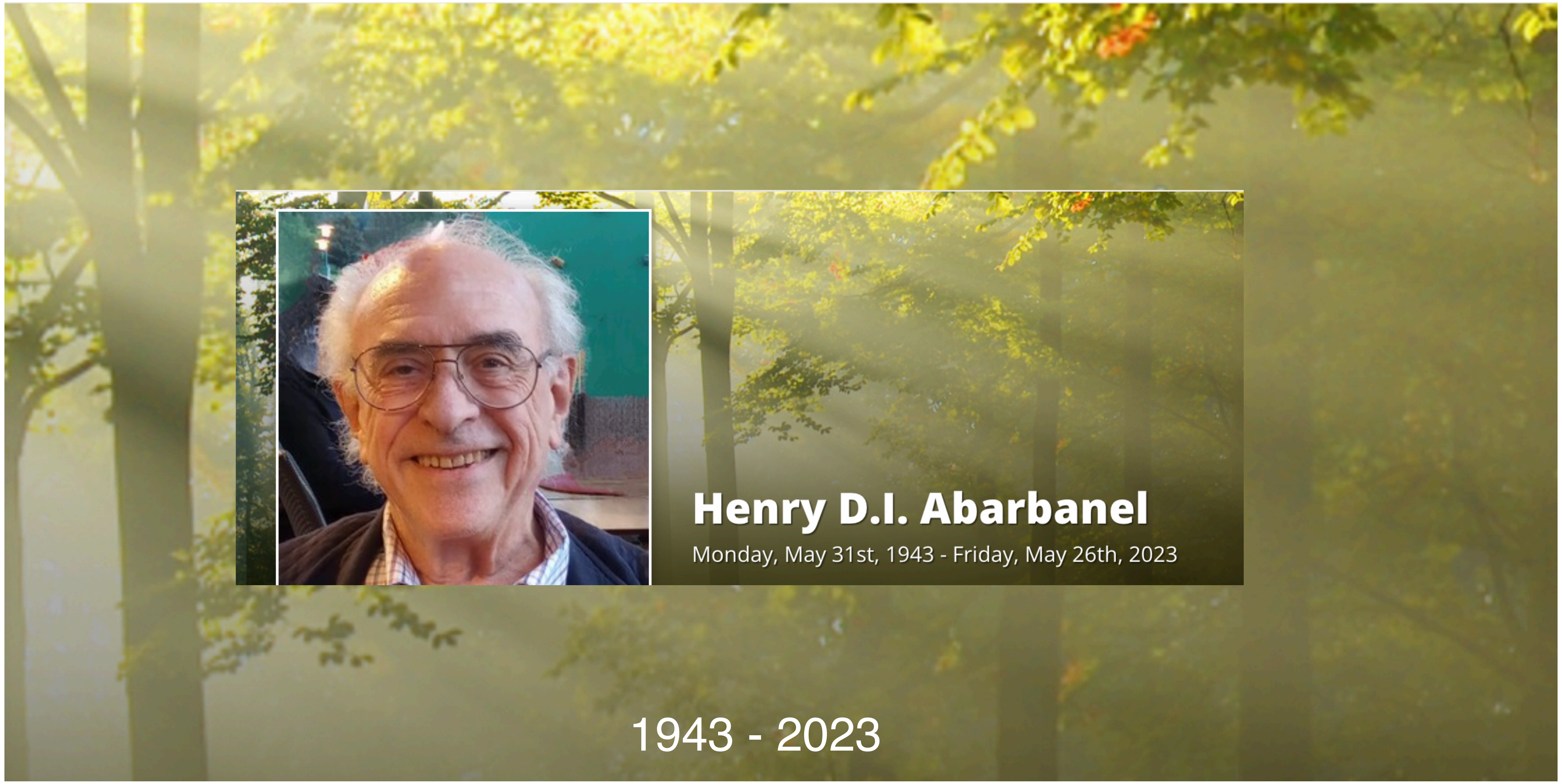
UNIVERSITY OF MARYLAND

13 JUNE 2023

Sofar Forecast Development team:
Steve Penny, Isabel Houghton, Christie Hegermiller, Pieter Smit, Camille Teicheira, Moriah Cesaretti

A moment to remember



https://www.amisraelmortuary.com/memorials/henry-abarbanel/5200839/index.php#wall

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CIRES

University of Colorado Boulder

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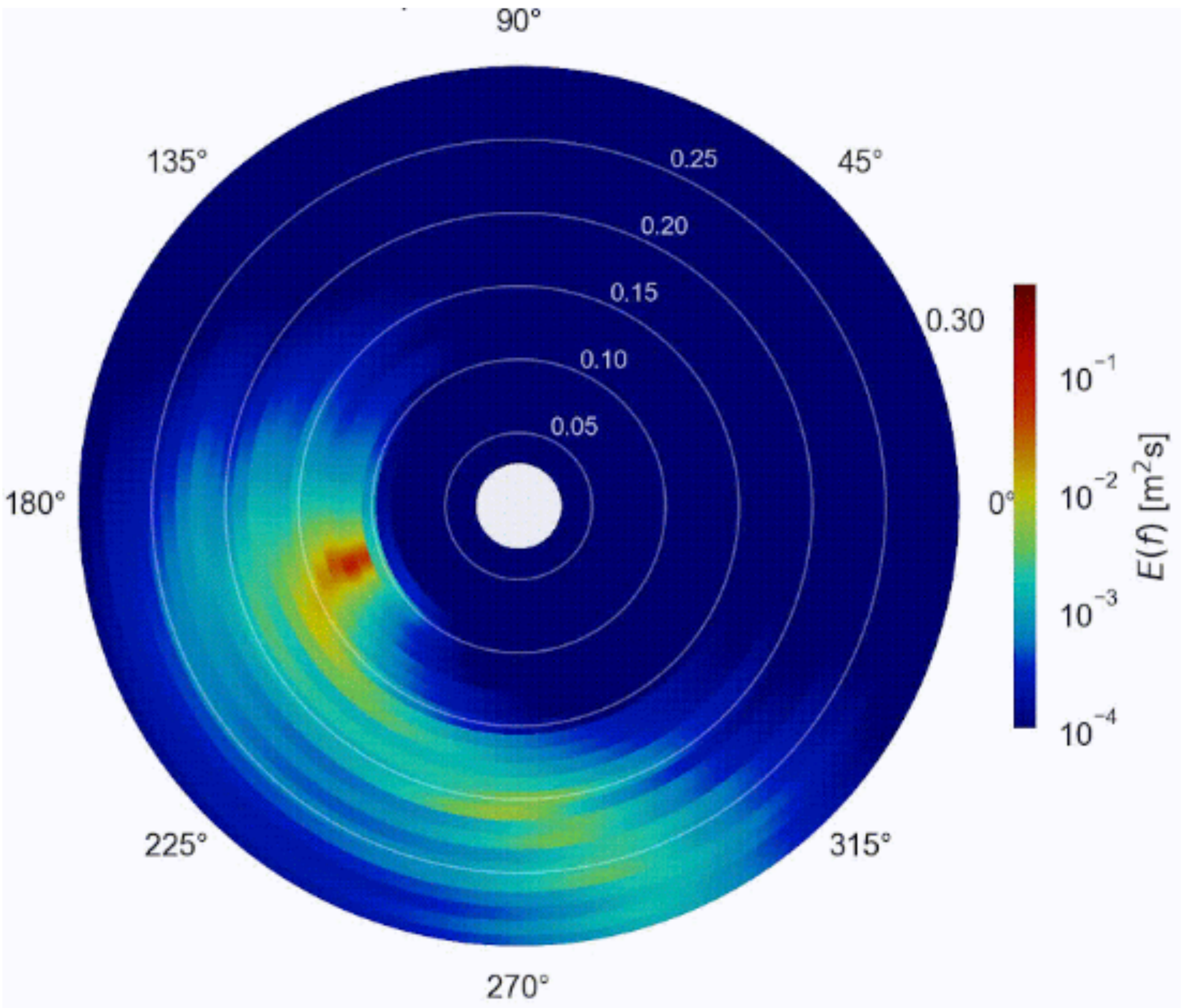
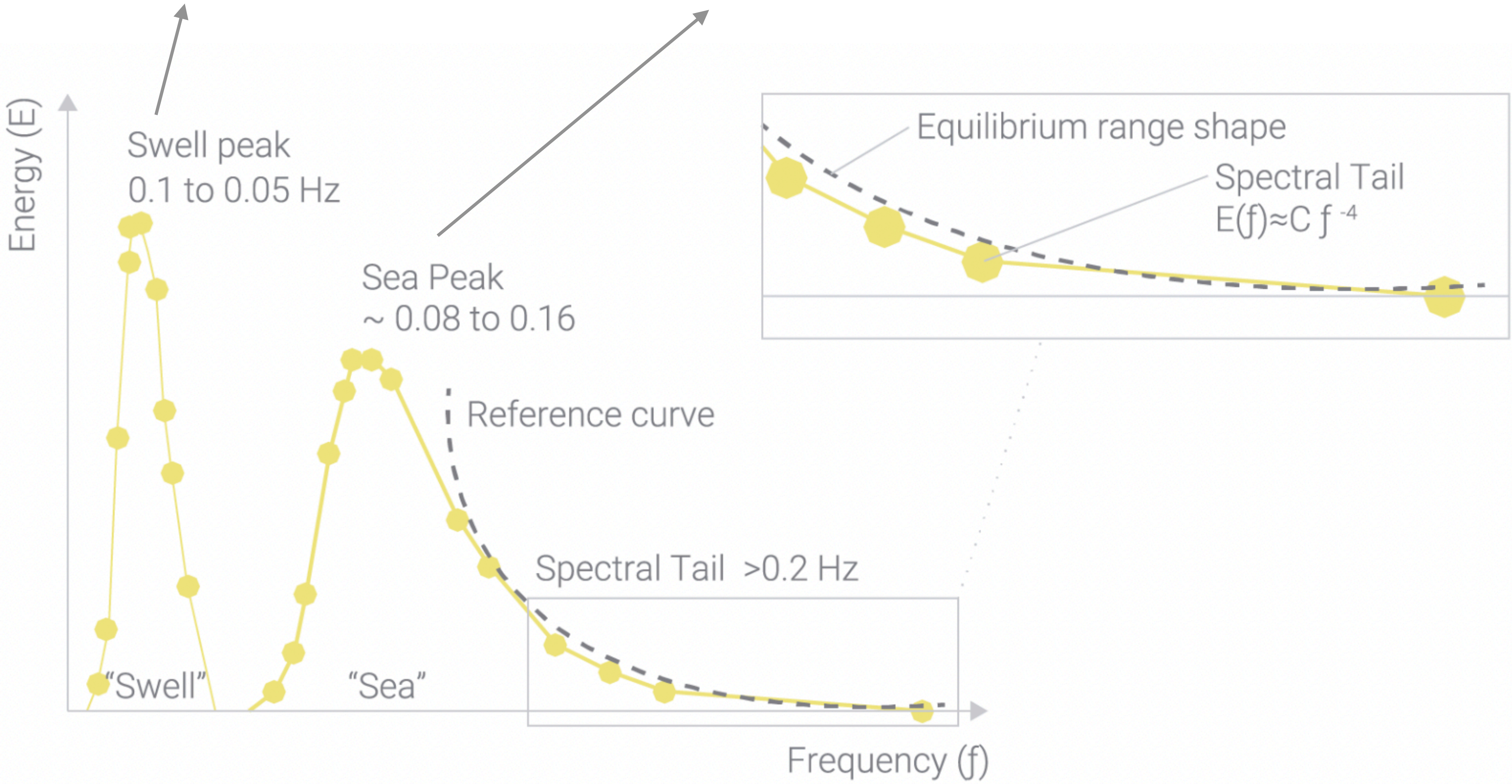
Background:
surface wave impacts
on ocean circulation and climate

Directional wave spectra



(Swell) waves generated by distant storms and undelated to local winds.

(Sea) waves generated by local winds.



Surface waves influence: the upper ocean and the lower atmosphere

- Non-breaking wave-induced mixing
- Turbulent Reynolds Stress in the upper ocean
- Air-sea momentum flux
- Air-sea heat flux

See review from Babanin (2023):

Babanin, A. V. (2023). Ocean waves in large-scale air-sea weather and climate systems. *Journal of Geophysical Research: Oceans*, *128*, e2023JC019633. https://doi.org/10.1029/2023JC019633

Non-Breaking Wave-Induced Mixing: Bv

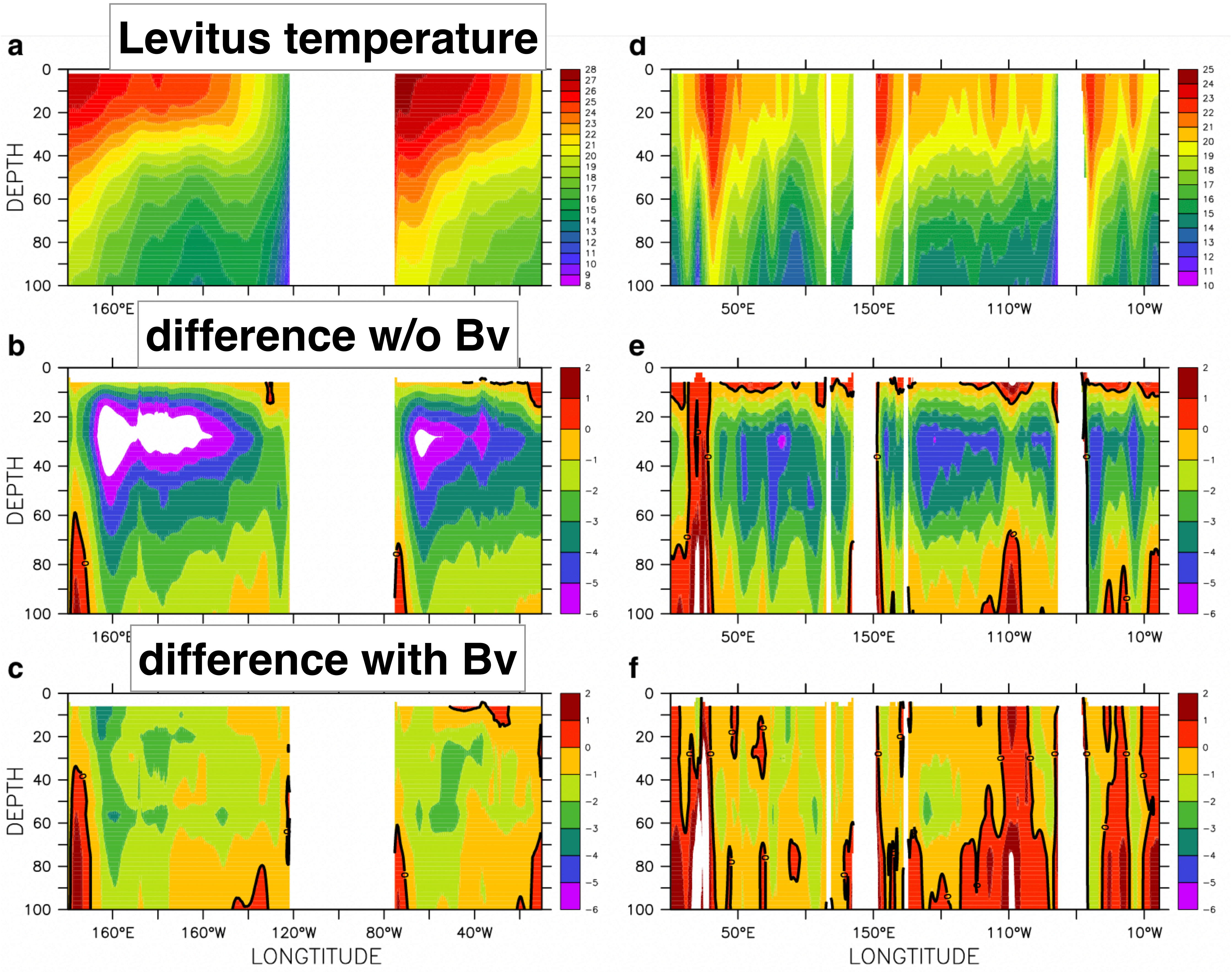


Fig. 4 The *upper panel* shows the temperature distribution of the Levitus data; the *middle panel* is the temperature difference between the model calculations without B_V and the Levitus climatology; the *lower panel* is the temperature difference between the coupled wave–circulation model results and the Levitus data. The *left column* is along 35° N in July and the *right column* is along 35° S in February

Qiao et al. (2010)

- Surface wave-induced mixing is not just due to wave breaking. *Turbulence produced by wave orbital motion extends vertically at the scale of the wavelength*, potentially hundreds of meters into the ocean.

- This directly impacts the mixed layer depth (MLD) and sea surface temperature (SST). Including this process in climate models can reduce common biases:
  - Bv can increase SST in the eastern tropical Pacific and *improves the too cold tongue in the tropical Pacific* (Song et al., 2012);
  - Bv *deepens the summer MLD, and shoals the MLD in winter* (Chen et al., 2018), addressing common MLD biases
  - Bv *can increase global ocean heat content* (Huang et al., 2008; Stoney et al., 2018) which can be a climate drift problem for some models.

Turbulent Reynolds Stress in the Upper Ocean

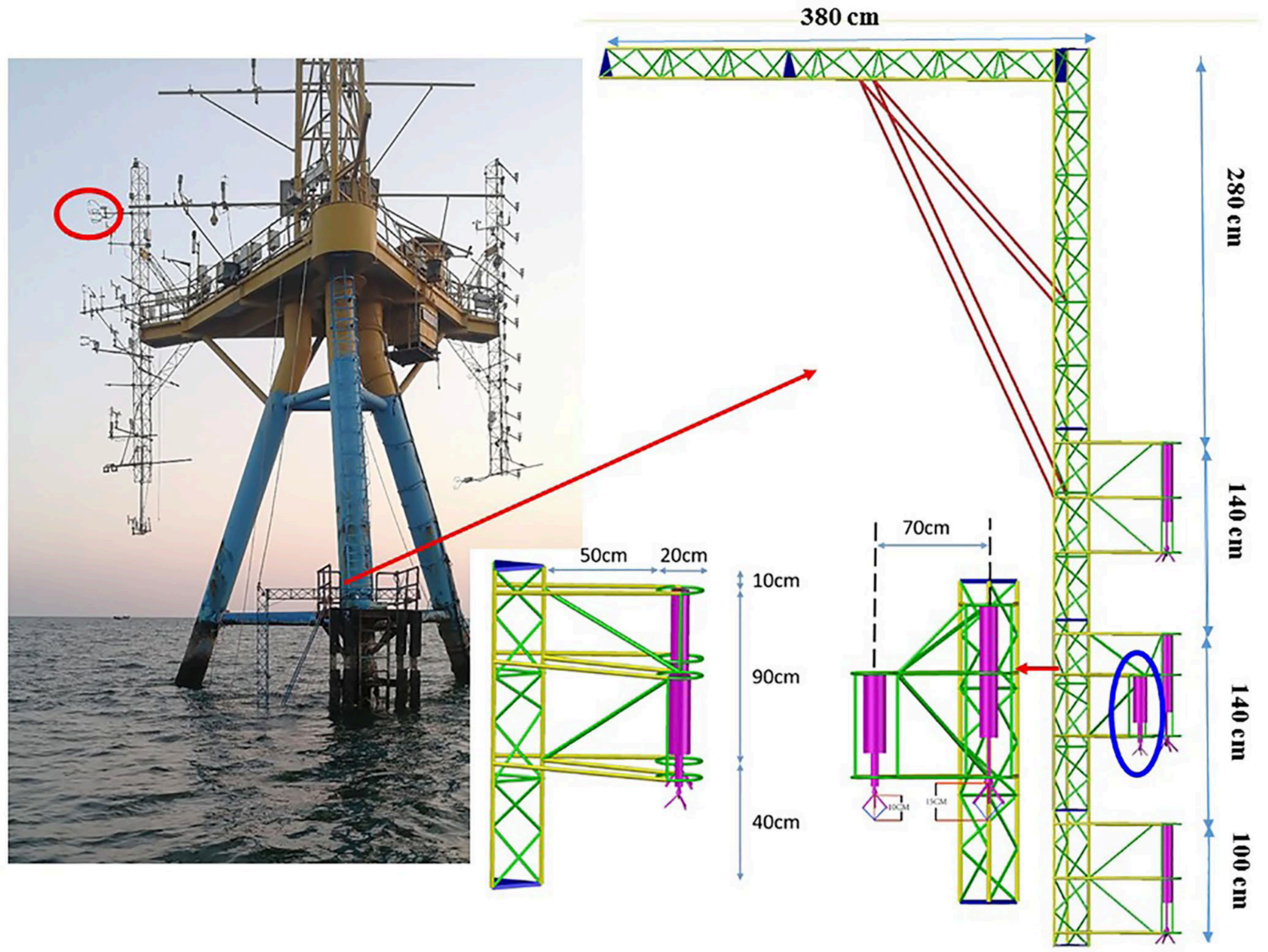


Figure 1. Observation platform of the marine meteorology tower in the northern South China Sea (viewed from the north), and the observational framework installed with the ADVs. The instrument highlighted by the red (blue) ellipse is the Campbell Scientific eddy covariance system (Vectrino). ADV, acoustic Doppler velocimetry.

Huang and Qiao (2021)

- **In wind-driven ocean circulation theory**, the oceans are directly (locally) driven by the sea surface wind through the friction force.

- Huang and Qiao (2021) determined from measurements that the turbulent stress in the ocean surface boundary layer (OSBL) *is dominated by turbulence produced by surface waves*, which can be several times larger than that due to the local atmosphere. I.e. the momentum gain by the ocean can be larger than the local wind stress input.

- **The effect is non-local**:
  - "*more than 90% of the wind energy input to the ocean is transferred by means of surface waves*, that is, the wind first generates waves which slowly grow under the wind action and then pass their kinetic energy to the upper ocean as they propagate over the ocean surface (e.g., Yuan and Huang, 2012)"
  - "Surface waves should be accommodated in all future studies that include air-sea interaction, as wave-induced stresses, which are *an integral of wind stress over large area and can be even uncorrelated with the local wind*, may have important impacts, and the present wind-driven ocean circulation theory would need corrections." Babanin (2023)

Air-Sea Momentum Flux: Wind Stress

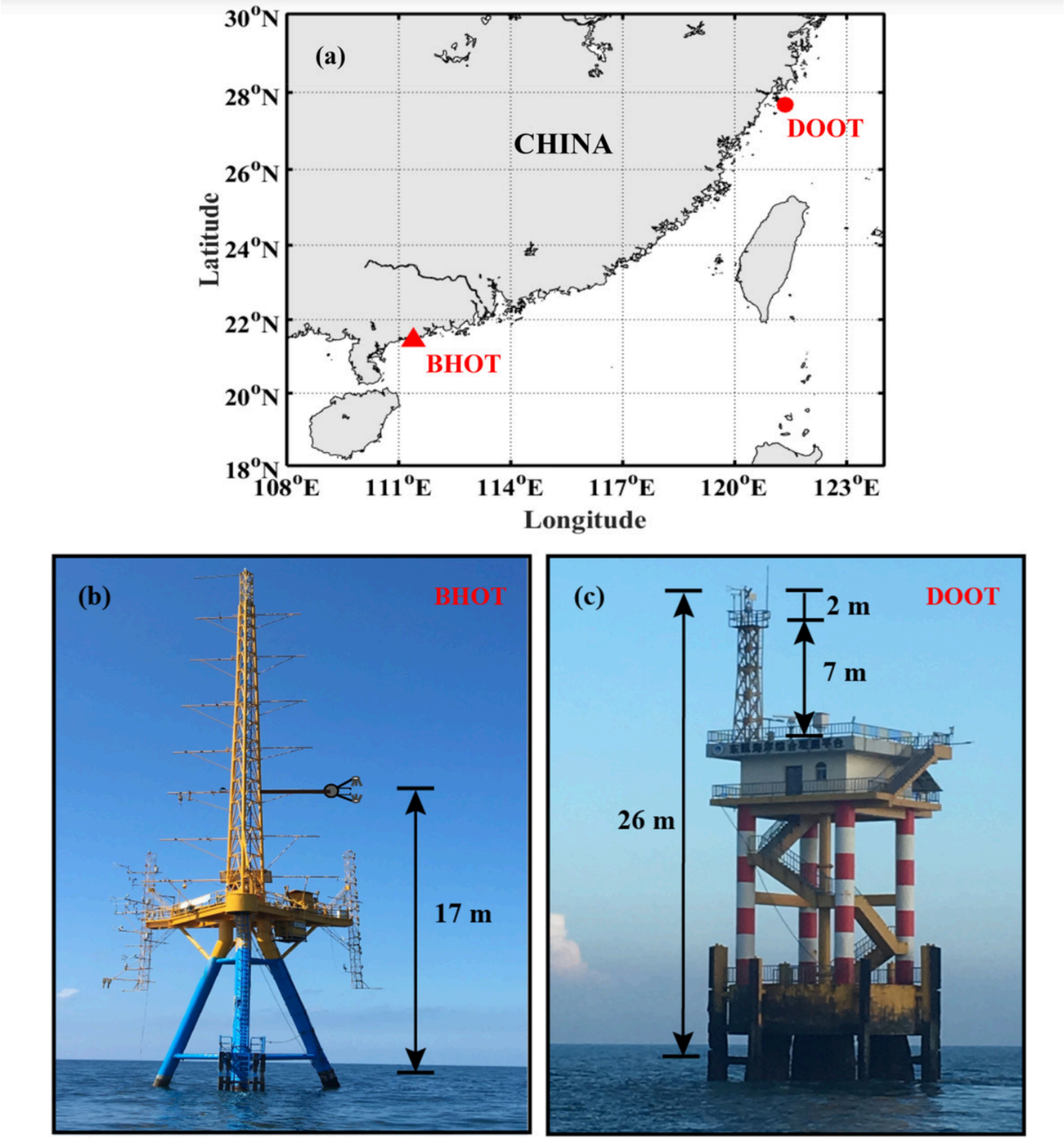


FIG. 1. (a) Regional map and locations of the BHOT and DOOT and photos of the (b) BHOT and (c) DOOT.

Chen et al. (2019)

- Ocean surface waves have different characteristics depending on wind speed and wave heights. E.g. for winds below ~7 m/s waves do not break, or above ~20 m/s spray is produced. Swell waves typically dominate the wind sea during light winds.

- Swells can cause changes to the marine atmospheric boundary layer:
  - Chen et al. (2019) and Chen, Qiao, Zhang, et al. (2020) showed that the swell influence on wind velocity spectra and wind stress can reach heights of >20m above the sea surface.
  - Rutgersson et al. (Nilsson et al., 2012; Rutgersson et al., 2010, 2012; Rutgersson & Sullivan, 2005) showed (both with measurements and direct numerical simulations) that the *air-sea interactions represented by waves have a significant impact on atmospheric processes such as mixing, turbulent kinetic energy, and boundary layer height*.

Air-Sea Heat Flux

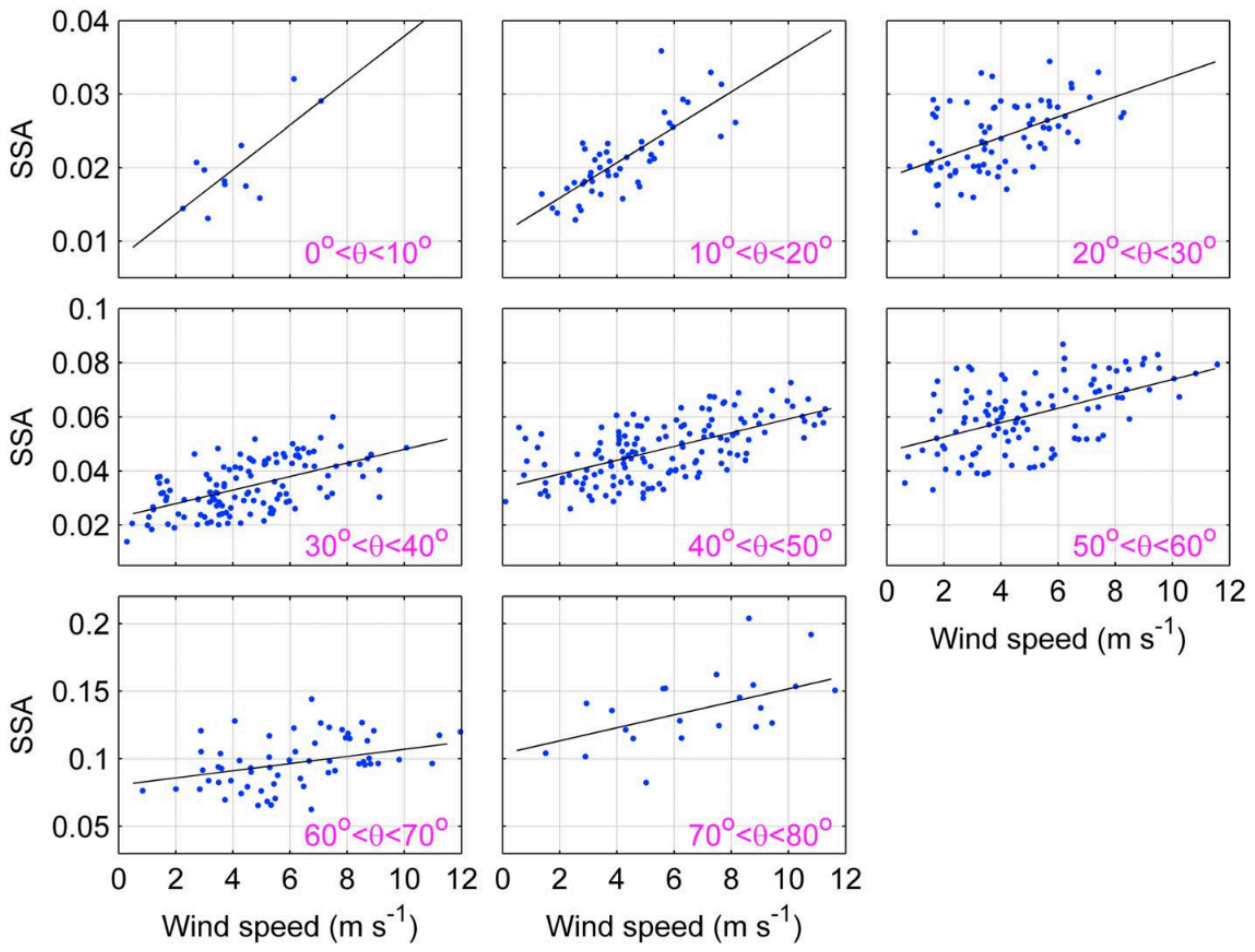


Figure 7. Scatter plots of the sea surface albedo (SSA) as a function of wind speed for different bands of the solar zenith angle under clear-sky conditions. The black line represents the linear fit to the SSA in each panel.

Huang et al. (2019)

- The air-sea heat flux can be modulated by surface waves through:
  - Sea spray from wave breaking
  - Stokes drift
  - Changes to albedo

- Wave breaking can disrupt the surface skin layer and cause an air-sea temperature gradient (Jessup et al., 1997) that drives a heat flux. This is also associated with sea spray and hence aerosol production

- Huang et al. (2019) found that *albedo increases when winds or surface waves increase* (see figure at left) and decreases with increasing water vapor pressure at the sea surface.

- Large surface waves can break sea ice, causing abrupt change of albedo. The warming seawater can trigger a positive feedback loop and further summer sea-ice melt.

Sofar Spotter network

The Spotter

SPOT-30000R

Weather Conditions

Download Spec Sheet →

WAVE HEIGHT 8.2 m	WAVE DIRECTION NNE	PEAK PERIOD 17.3 s	MEAN PERIOD 11.6 s
WIND SPEED 24 kts	WIND DIRECTION SSW	BAROMETER 1013.21 mbar	SST 17°C

Sofar Spotter: a scalable ocean sensor platform

Spotter is a rapidly deployable and extensible ocean sensor platform. Spotter provides power, two-way communication, and a suite of native sensors. Other sensors can readily be added (e.g. Bristlemouth).

OCEAN WEATHER (NATIVE)
Waves, wind, SST, surface currents, barometric pressure

COASTAL SENSING (NATIVE)
Water level and temperature stratification

Ocean Data as a Service: Sofar and OOT

Persistent network:	**600+ sensors**
Distribution:	**global**
Daily data points:	**200K+**
Data collected:	**> 2Gb**
Data points collected:	**> 100 million**
Device ocean hours:	**> 10 million**

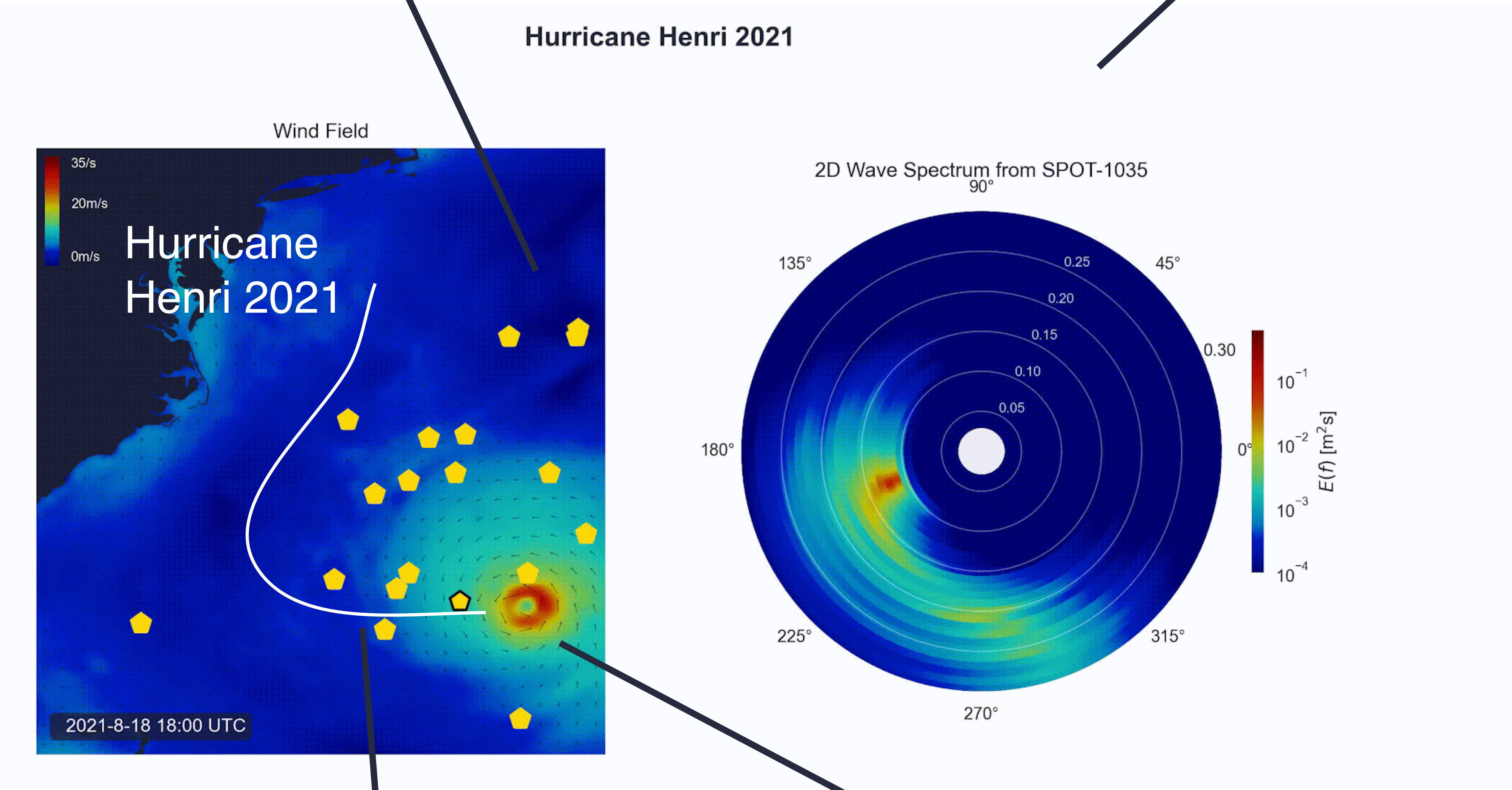
Measure: **directional wave spectra, wind, currents, sound, temperature, pressure**

Launched Bristlemouth
www.bristlemouth.org

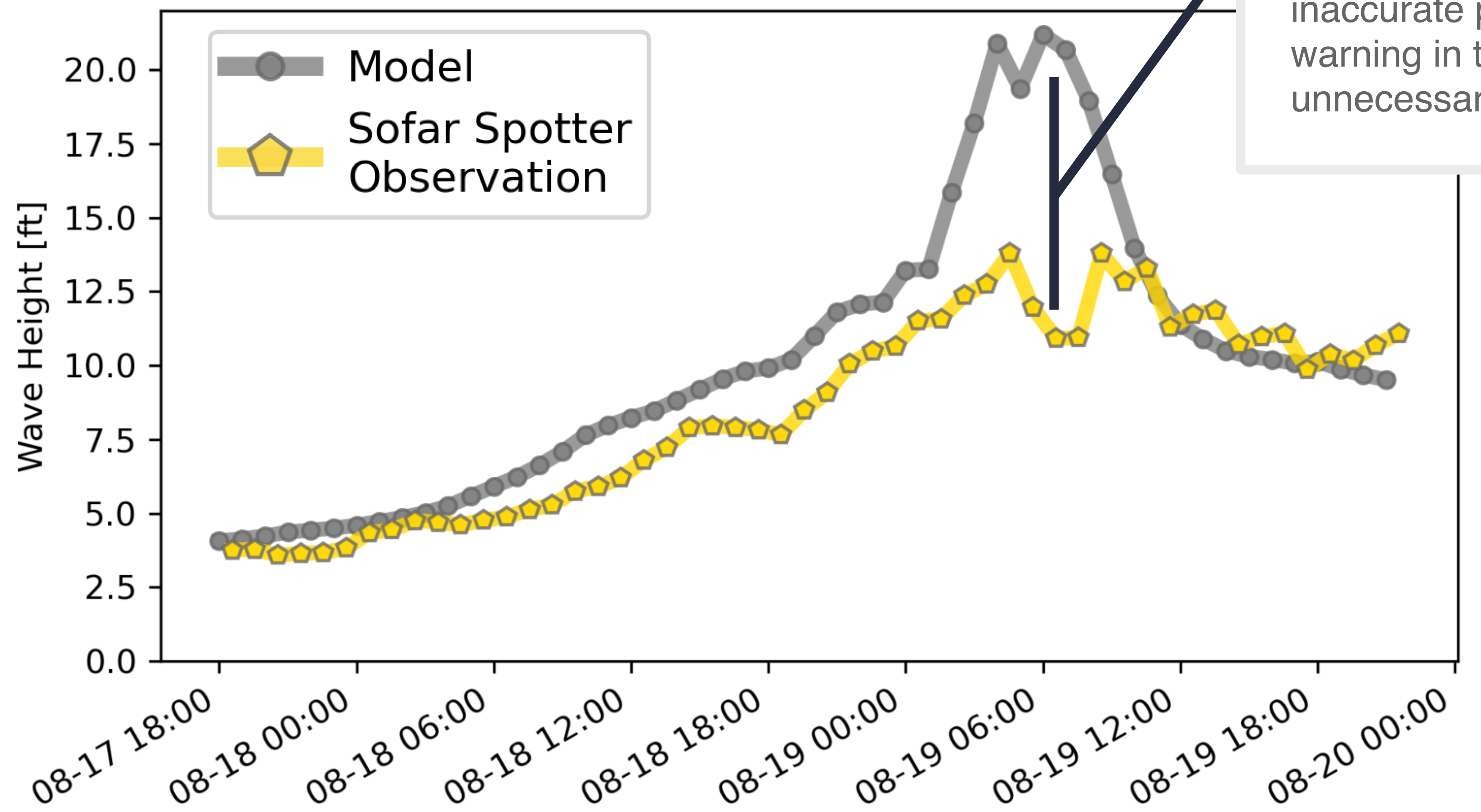
Measuring directional wave spectra, temperature, derived winds, etc.

Spotter Network
Every yellow icon is an independent buoy reporting in real time.

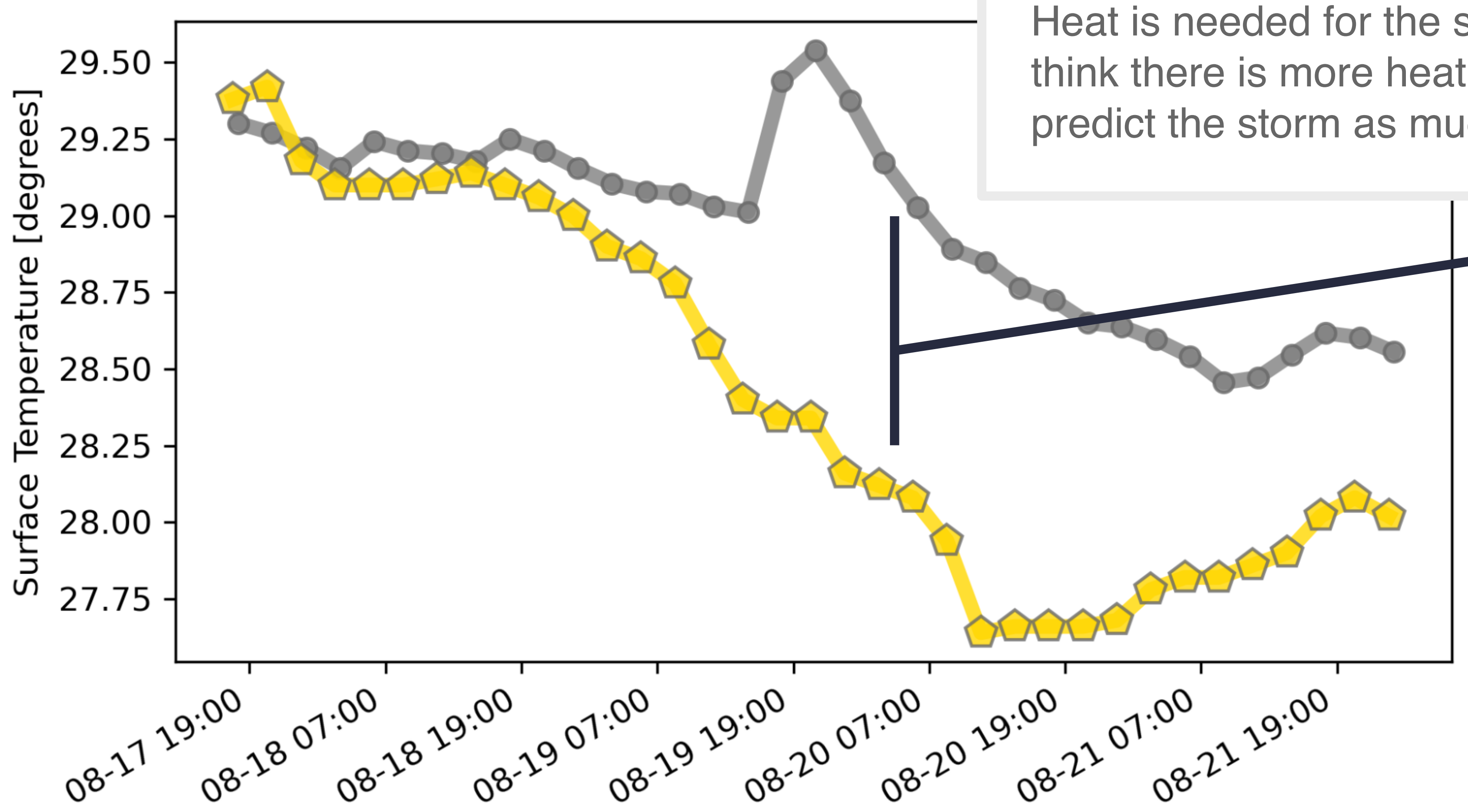
Wave Spectrum
Spotters collect full information about the direction and period of waves - e.g. the concentrated red region at 180° indicates big waves going to the west.



Wave height *error*
Waveheight in the model is substantially overestimated - meaning the models had the storm location or intensity (or both) incorrect - which in turn leads to highly inaccurate predictions and excessive warning in the wrong locations or an unnecessarily broad region.



Surface temperature *error*
Heat is needed for the storm to grow more intense. If you think there is more heat than there actually is, you will predict the storm as much more intense than it will be..



Hurricane Path
Seven buoys were proximate to the hurricane as it developed (in contrast to a single satellite overpass or reconnaissance flight).

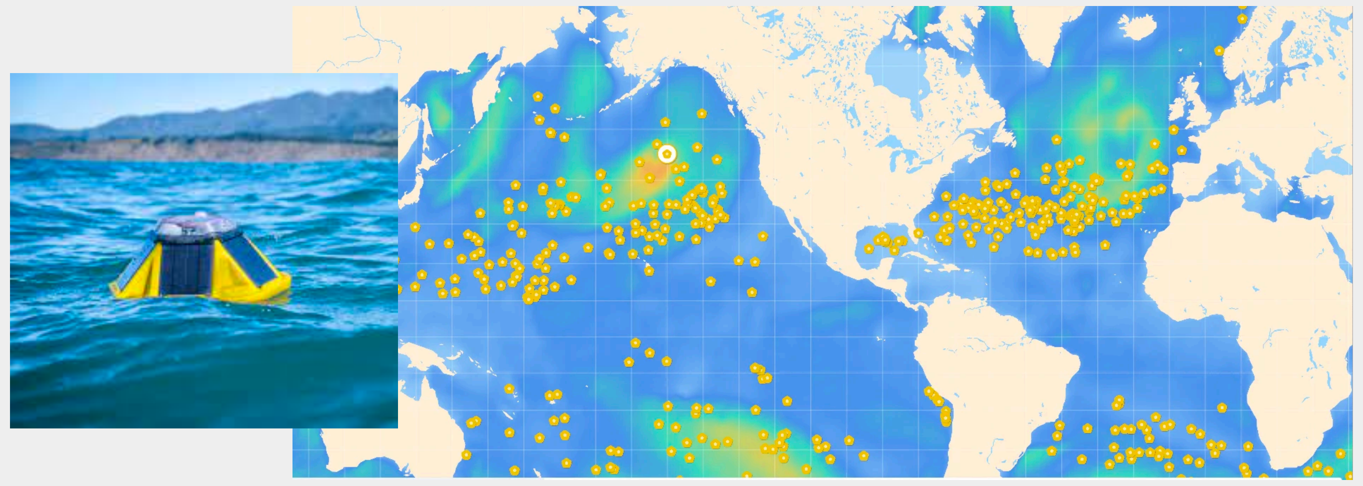
Winds
Red color indicates hurricane winds.

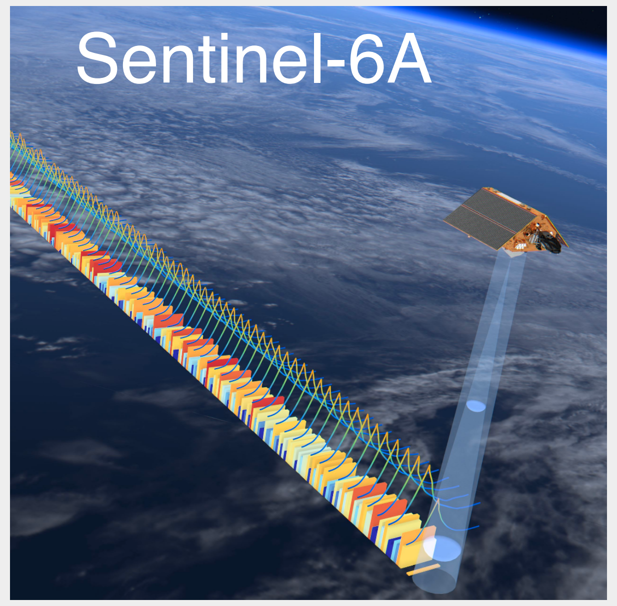
Sofar operational forecasts

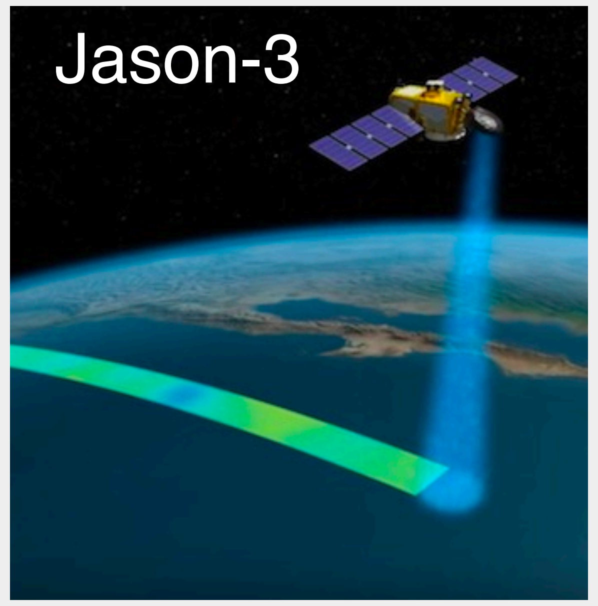
Sofar's Operational Wave Forecasting

Observations

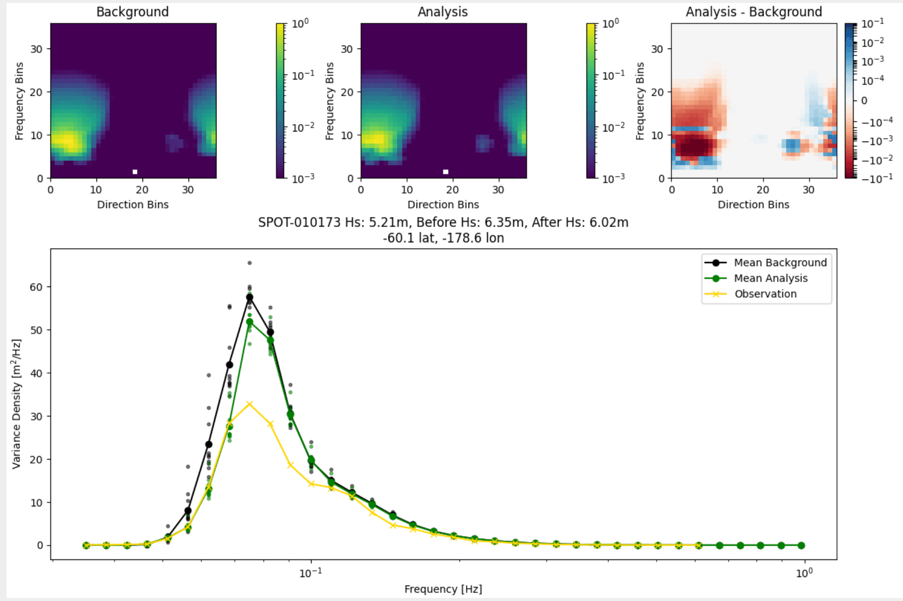
Sofar Spotter Network

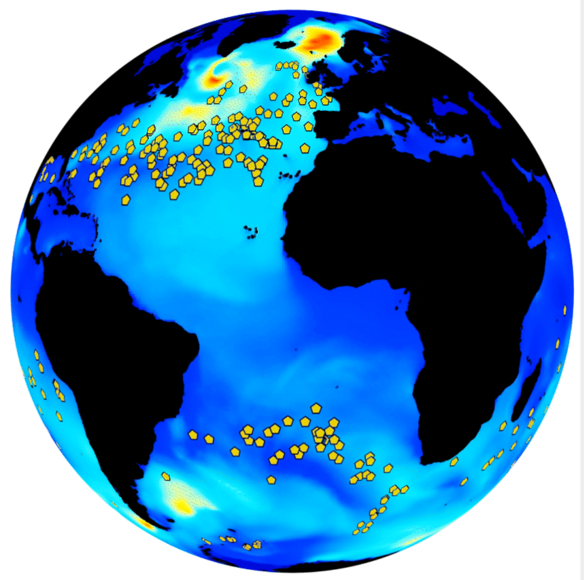






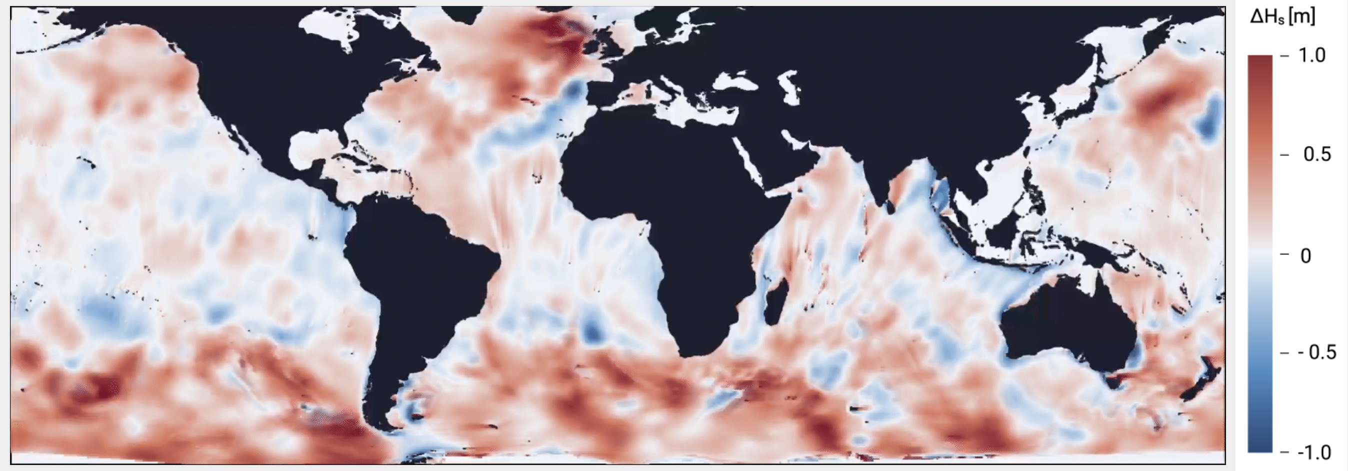
Data Assimilation (1-hourly)





Modeling

ECMWF

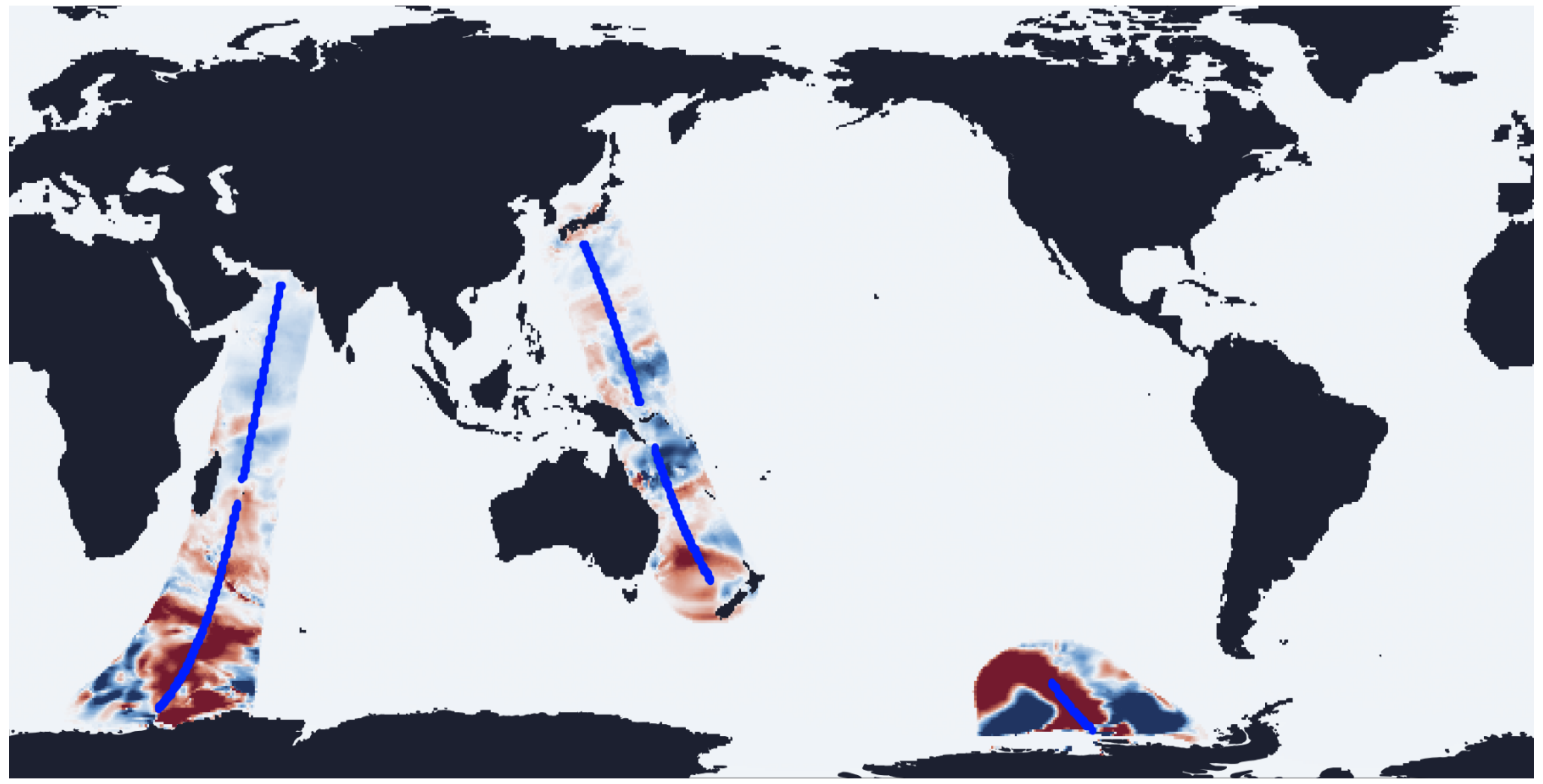


HYCOM

Delivery

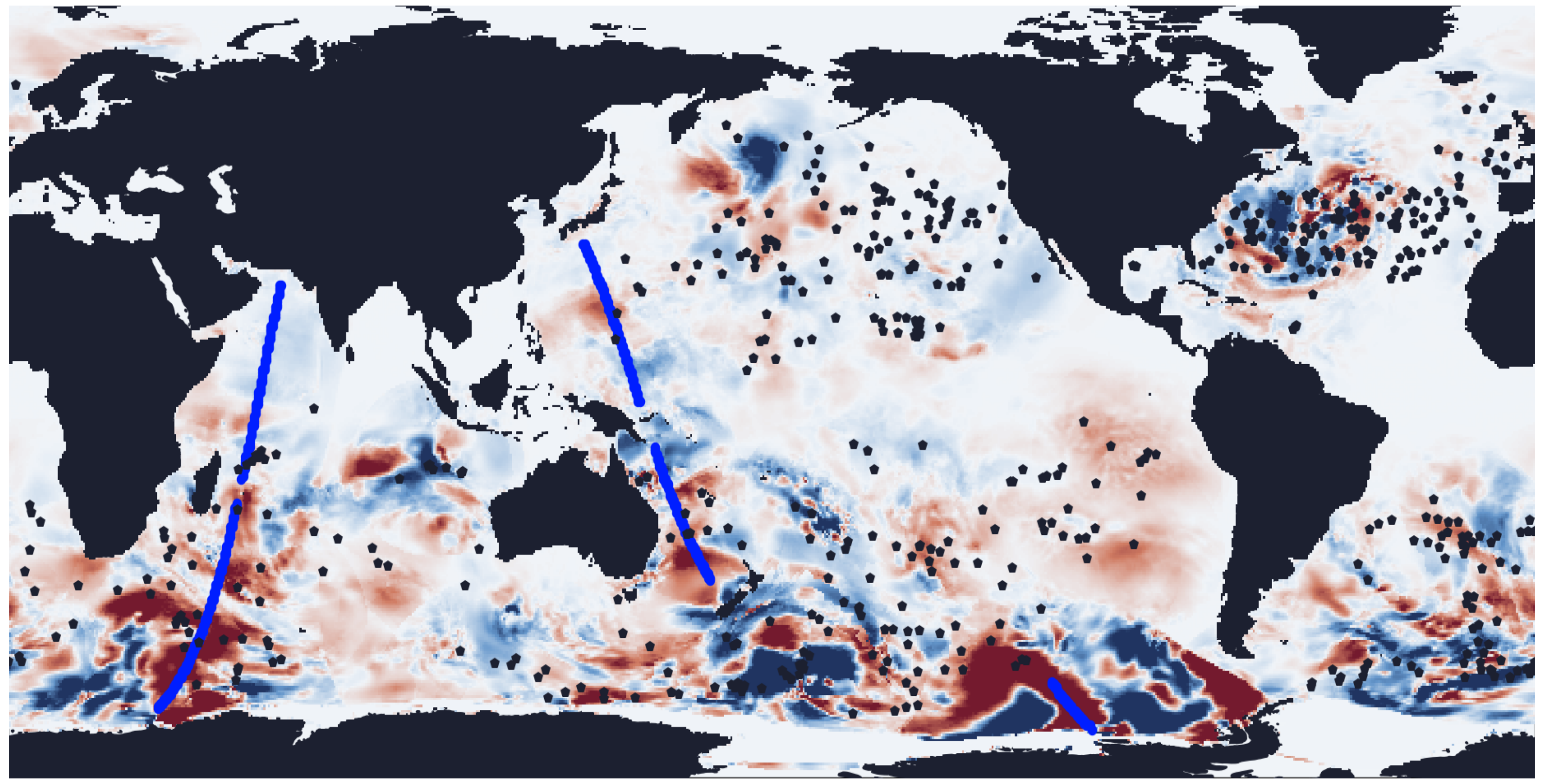
Lessons from global wave data assimilation: more is better

Assimilating complete wave spectra from over 650 live weather buoys combined with satellite altimeter data greatly expands the spatial impact of the hourly global analysis (see Houghton et al. 2022).



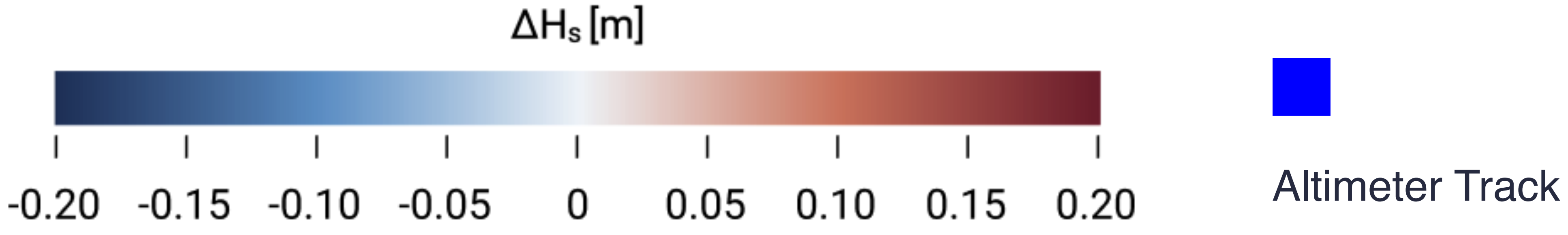
Altimeter

Altimeter model adjustments (1 hour)



Altimeter + Spotter

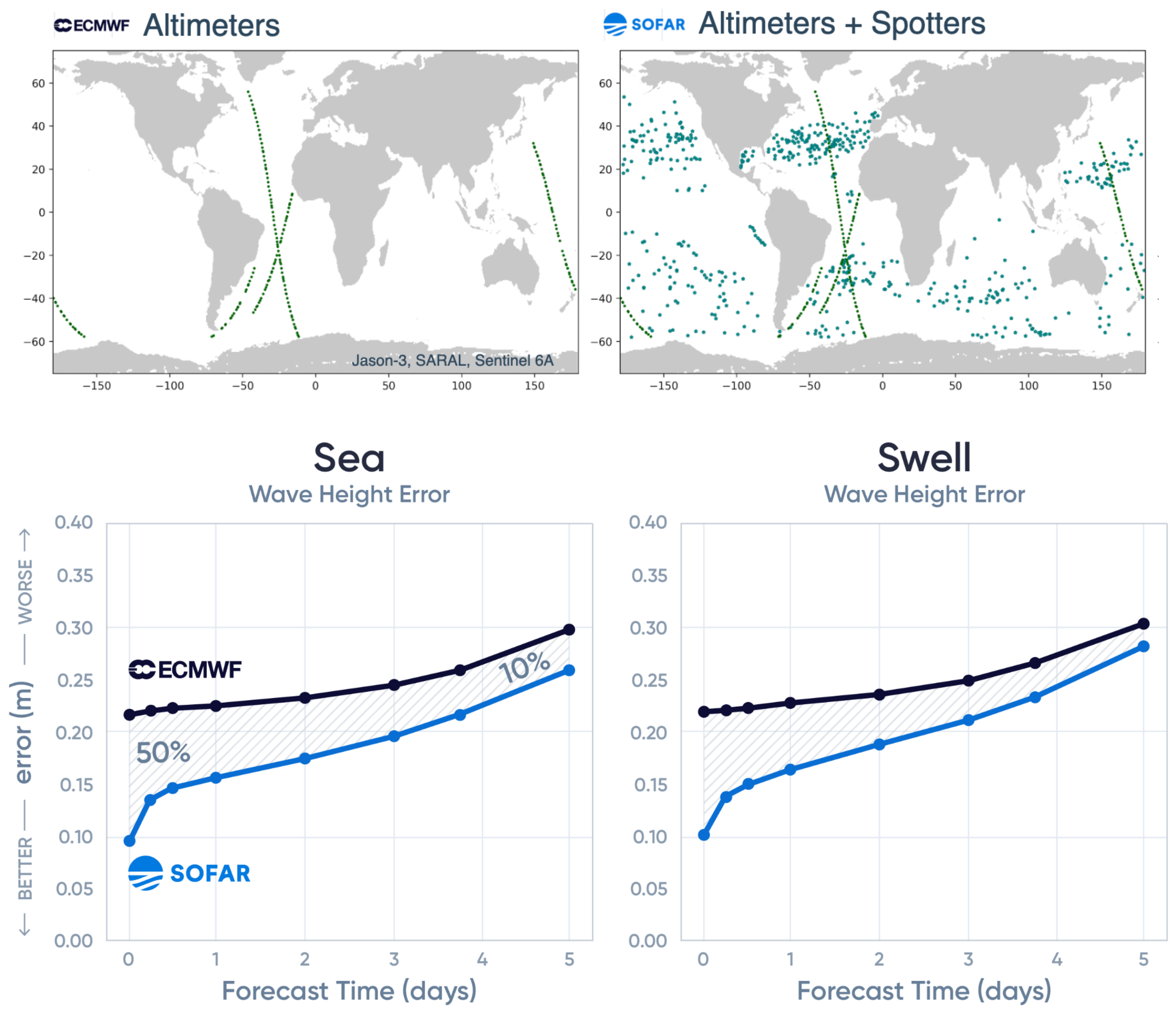
Altimeter + Spotter network model adjustments (1 hour)



Houghton et al. 2022, Geoph. Res. Letters, doi.org/10.1029/2022GL098973

Lessons from global wave data assimilation: the benefits of observing directional wave spectra

Assimilation of wave spectra adds detailed information about how energy is distributed across frequencies, leading to more skillful forecasts of sea and swell.



May-June 2022

Houghton et al. 2022, Geoph. Res. Letters, doi.org/10.1029/2022GL098973

Cloud infrastructure

Orchestration with Airflow allows for seamless, automated pipelines without a human in the loop.

Containerized builds

Running on cloud compute (AWS Batch) allows deployment of experiments on production-ready infrastructure.

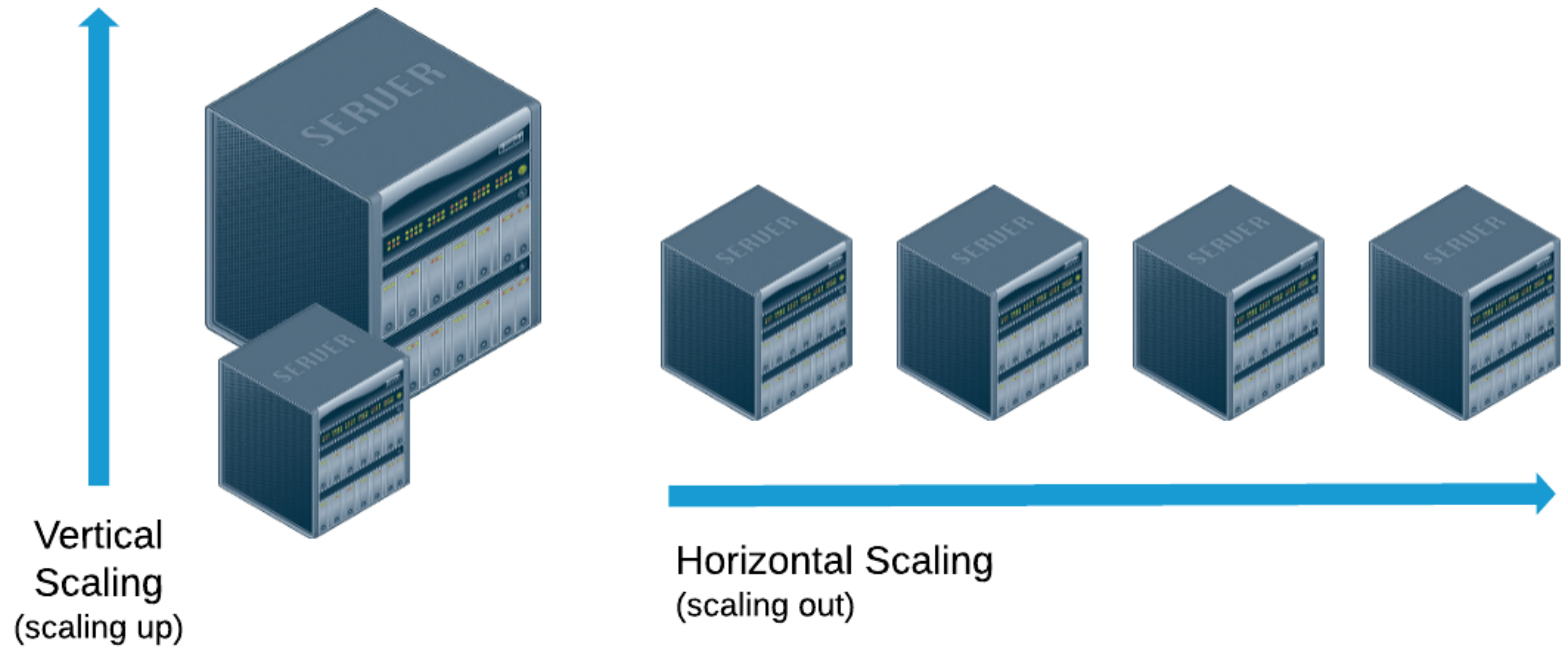
Data stored in final form on AWS S3.

Served to customers via an HTTP API hosted on AWS ECS with a load balancer and autoscaling.

Scalability

Horizontally scaling forecast system is a large collection of small compute instances

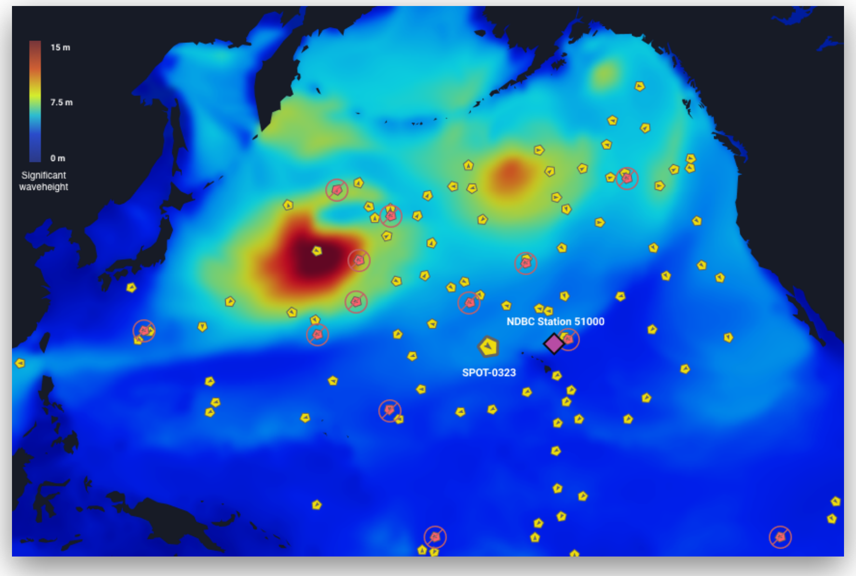
- Only pay for compute time used
- Simple configuration changes:
  - node instance size: `c6i.xlarge`
  - node group size: `6` → `12` → `48`
- Ephemeral storage



AWS Batch | AWS ECS | AWS EC2 | AWS EFS | AWS S3 | AWS CloudFormation | AWS CloudWatch

Sofar R&D: Coupled modeling and data assimilation

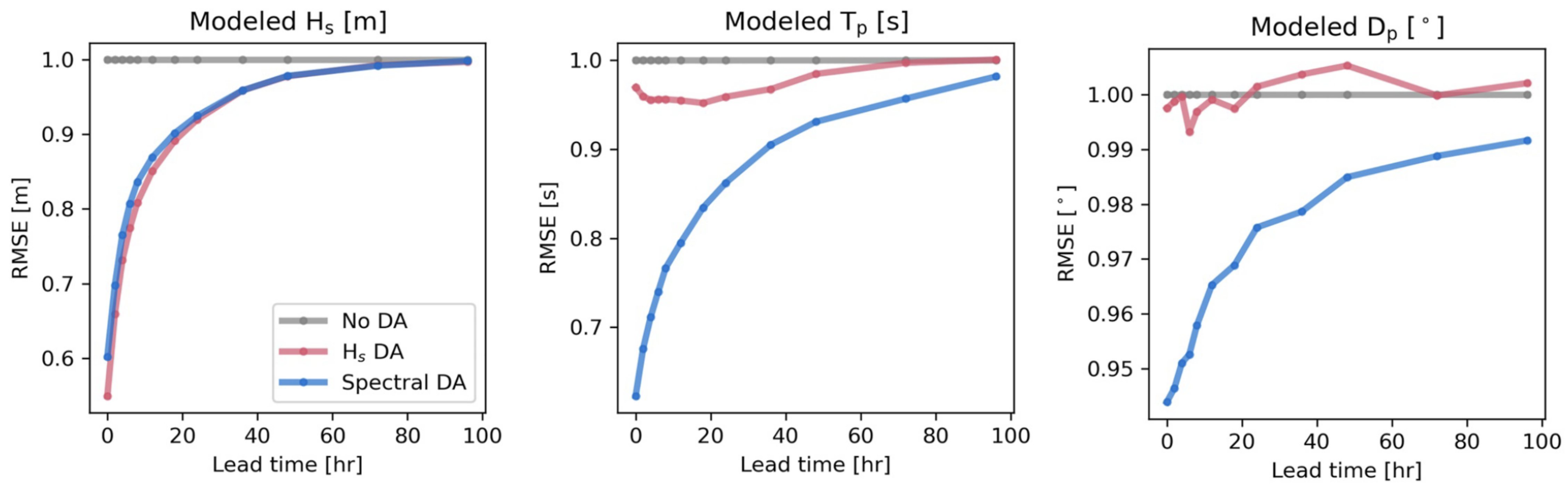
Assimilation of the Sofar Spotter Network



2020

Optimal Interpolation (OI) of Spotter significant wave height

Smit et al. (2021). Assimilation of significant wave height from distributed ocean wave sensors. *Ocean Modelling*, 159, 101738.



2021

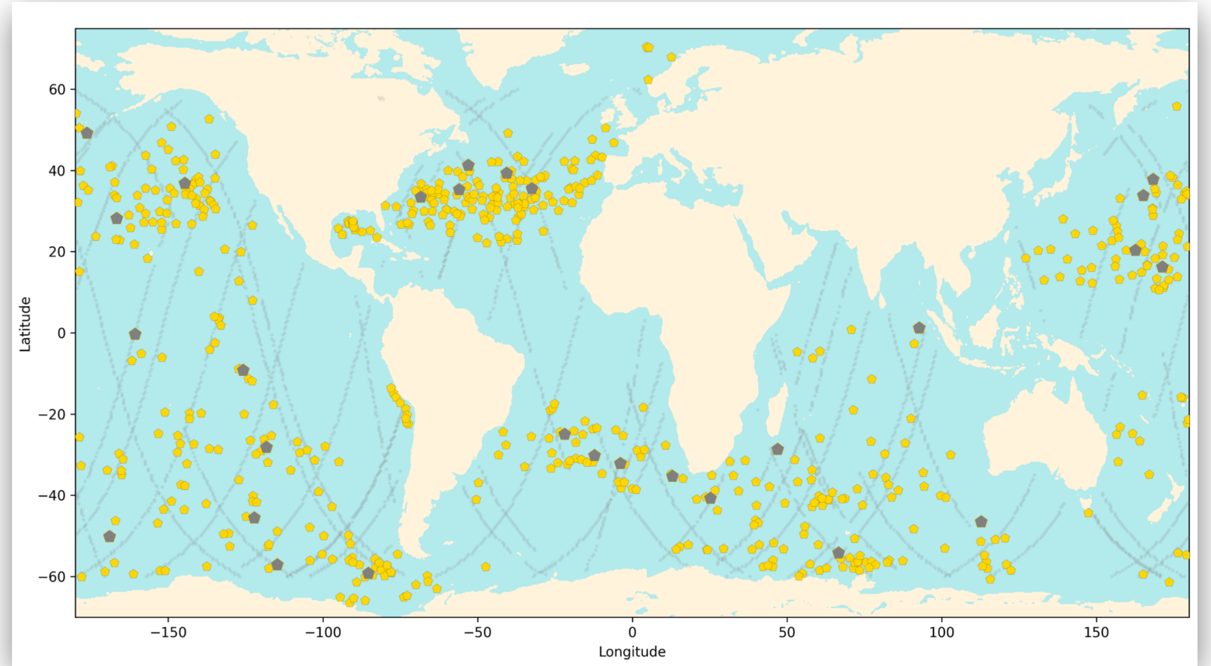
OI of Spotter directional wave spectra

Houghton et al. (2022). Operational assimilation of spectral wave data from the Sofar Spotter network. *Geophysical Research Letters*, 49.

2022

Ensemble-based DA of Spotter significant wave height

Houghton et al. (2023). Ensemble-Based Data Assimilation of Significant Wave Height from Sofar Spotters and Satellite Altimeters with a Global Operational Wave Model, *Ocean Modelling.*



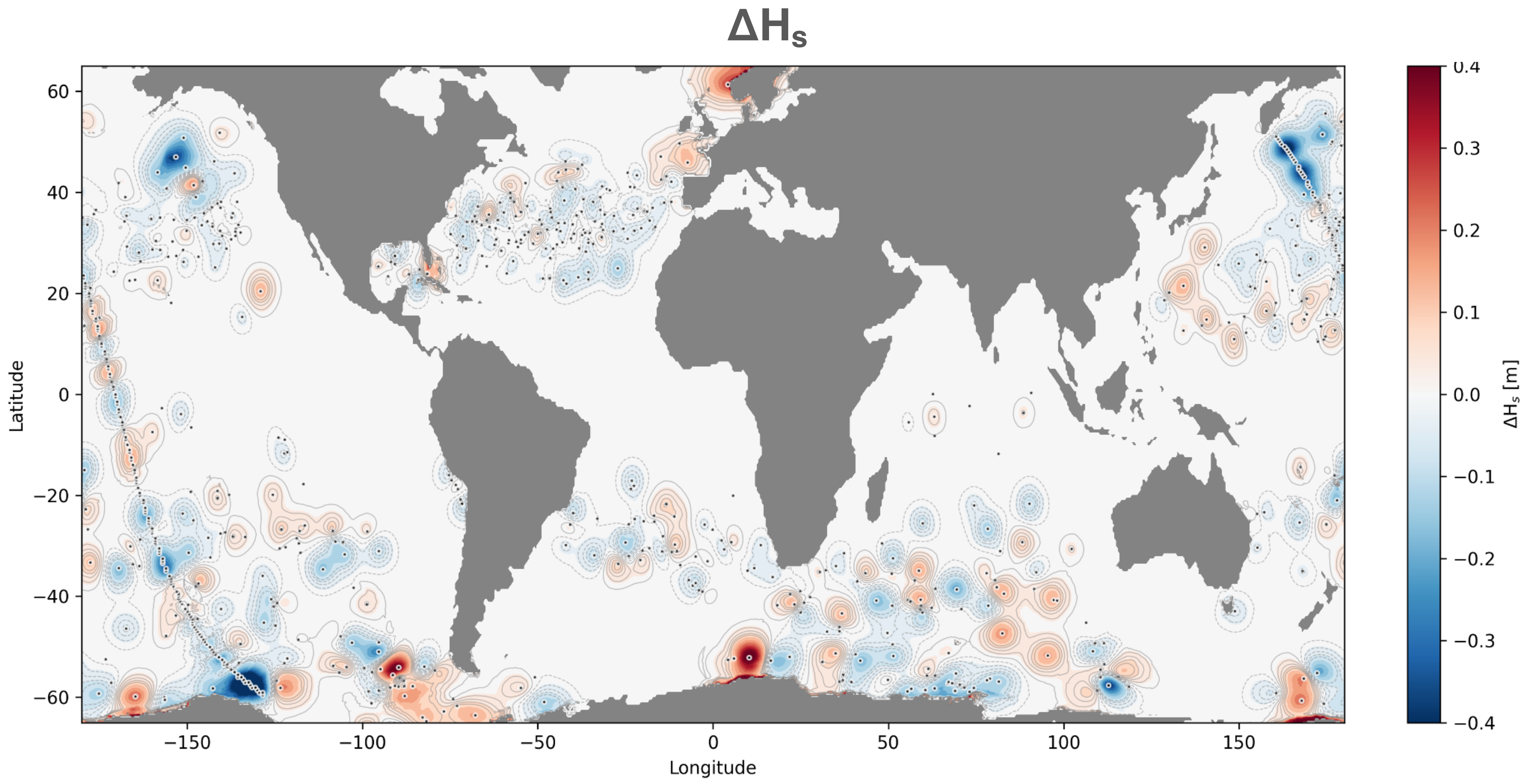
2023

Ensemble-based DA of Spotter directional wave spectra

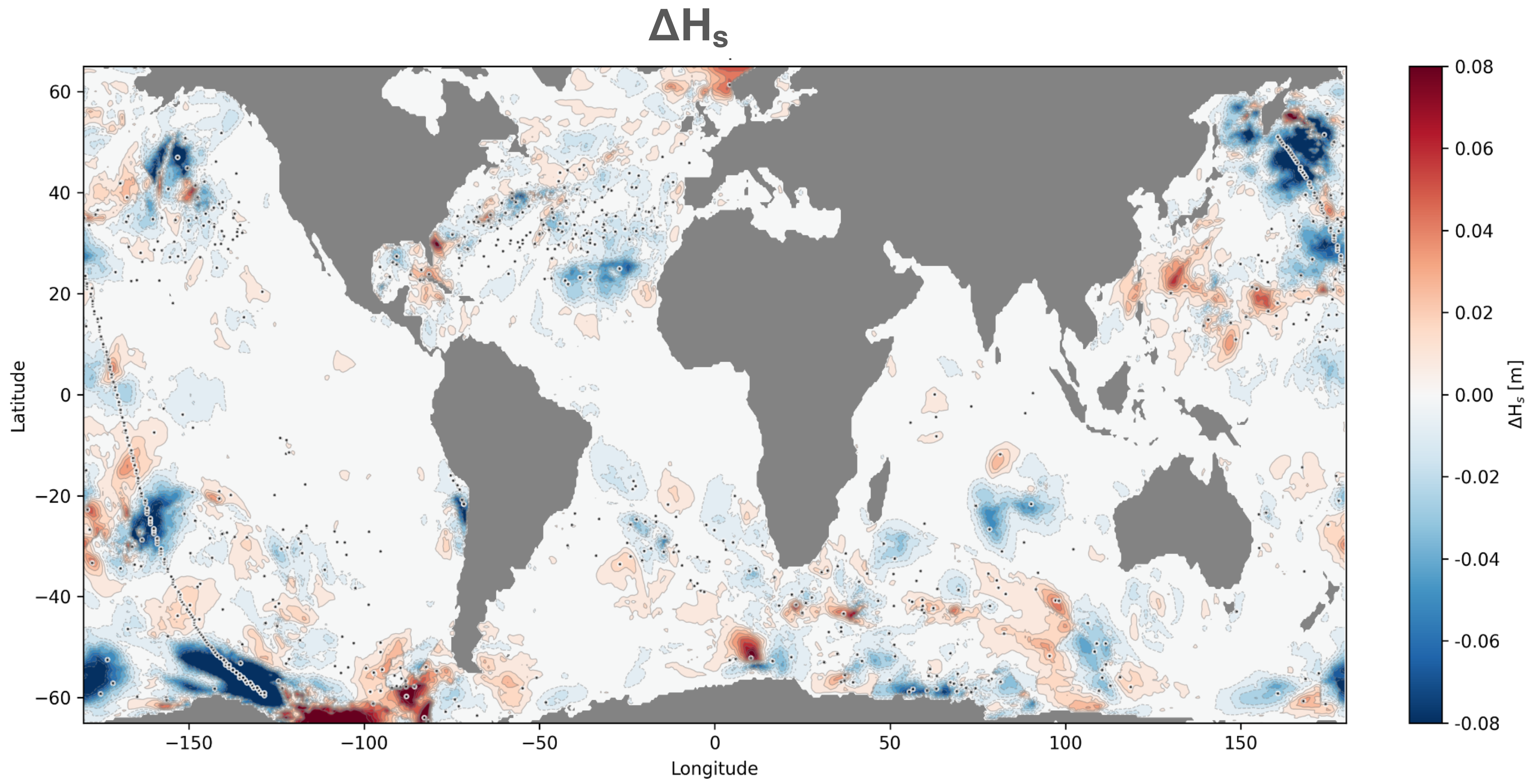
(In progress)

The value of ensemble-derived error covariances

- Handles diverse observations (Altimeter Hs + Spotter wave spectra)
- Localized by grid point: Enables potential coupled DA across atmosphere-ocean-wave models
- Informs analysis update far from observations



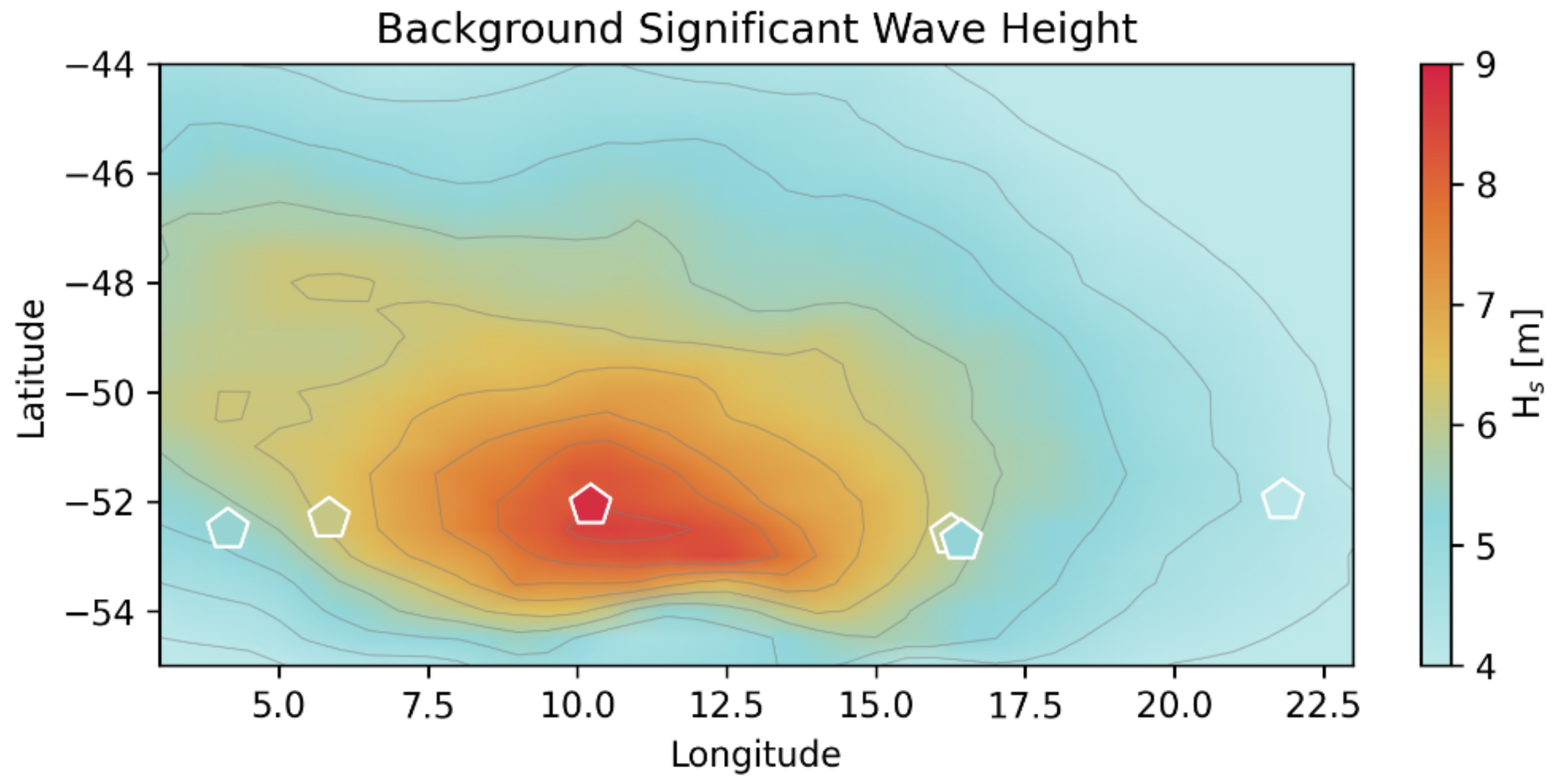
***Optimal Interpolation**: Blobby, local updates out of balance with wave model and wind forcing*

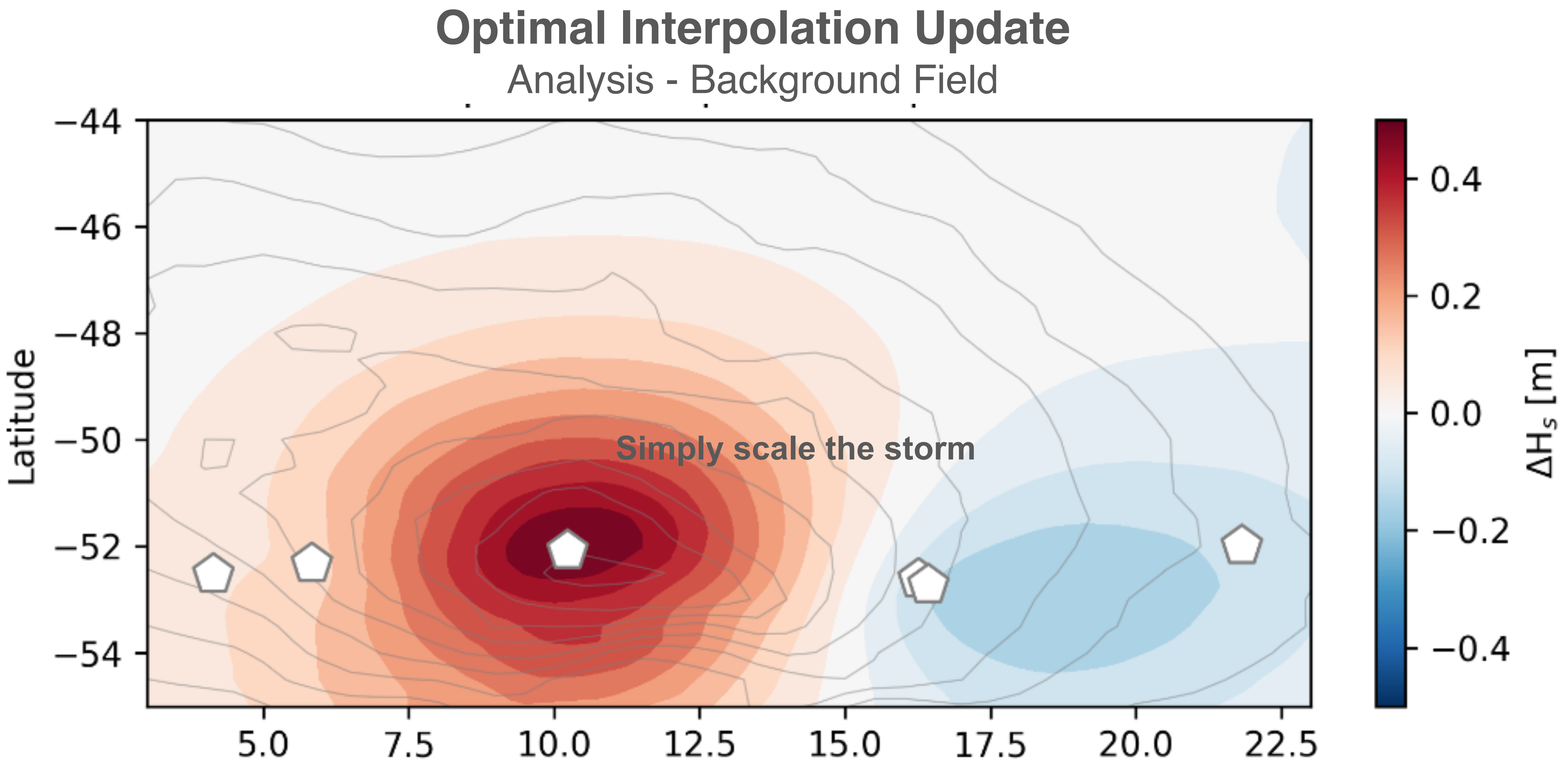


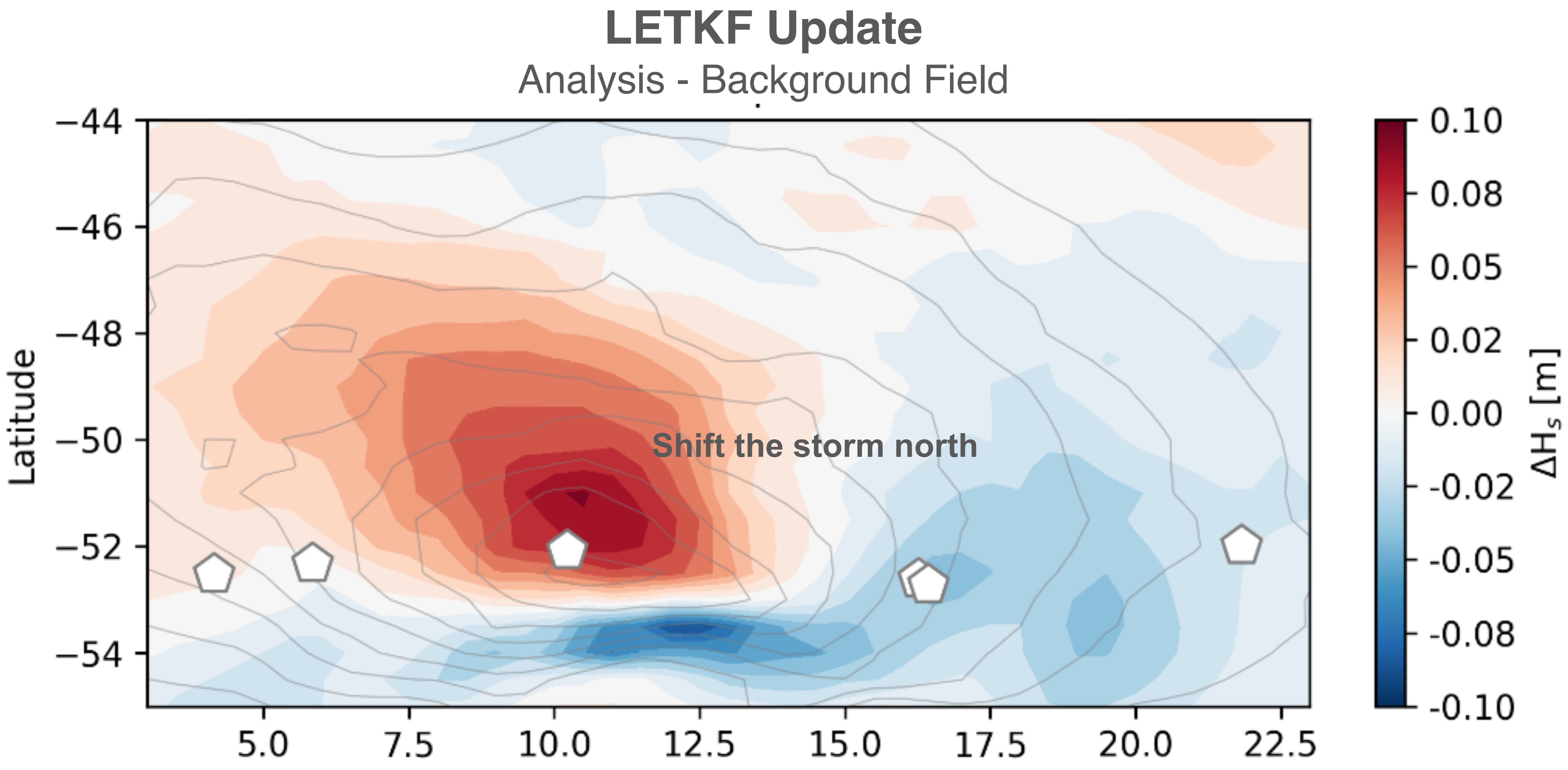
***LETKF**: Coherent, physically realistic updates balancing model uncertainty with observations*

Ensemble-based DA Update

Ensemble provides a more physically realistic update to the wave field and an understanding of the uncertainty.



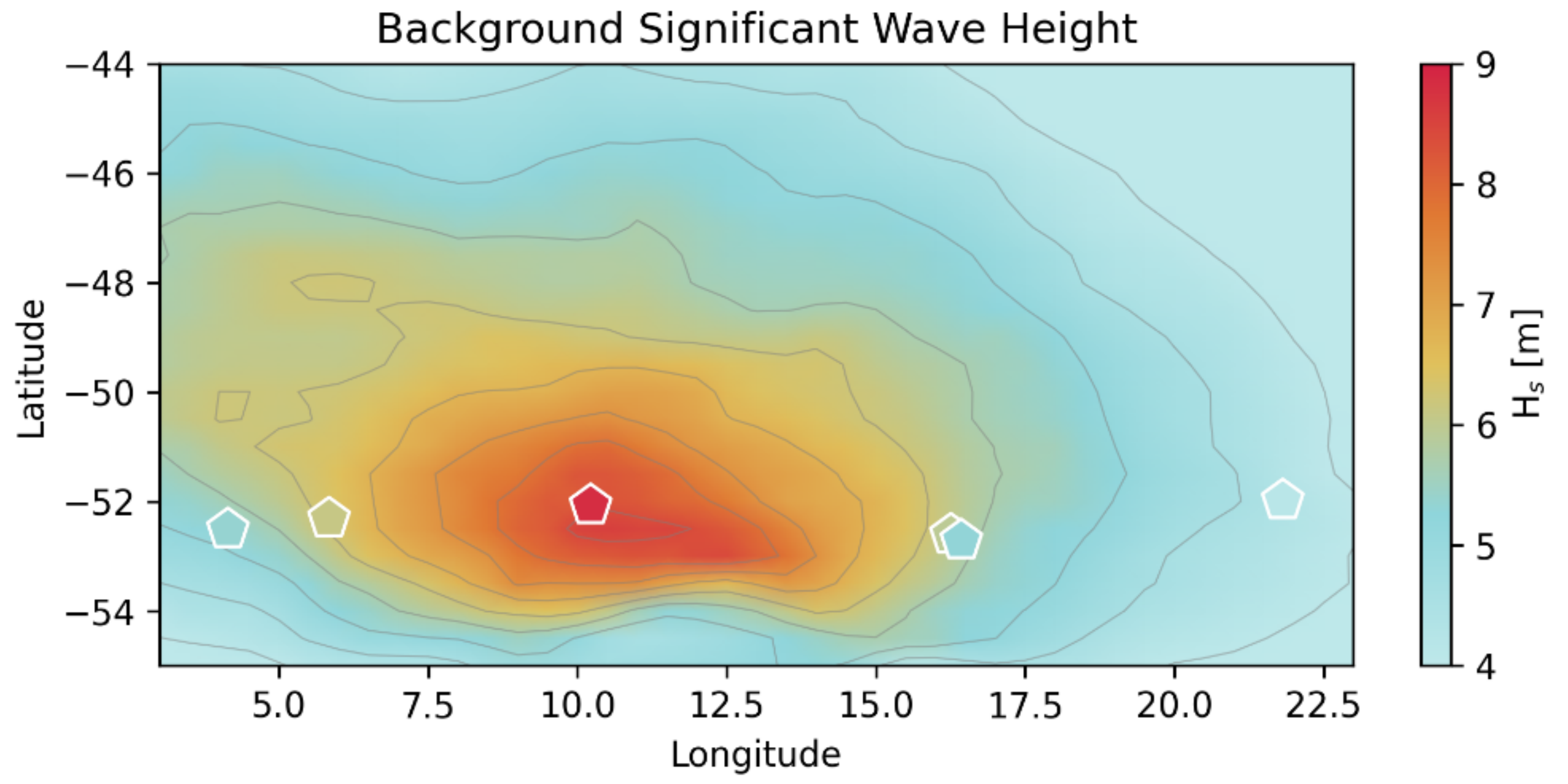




Houghton, et al. (2023). Ensemble-Based Data Assimilation of Significant Wave Height from Sofar Spotters and Satellite Altimeters with a Global Operational Wave Model, *Ocean Modelling*.

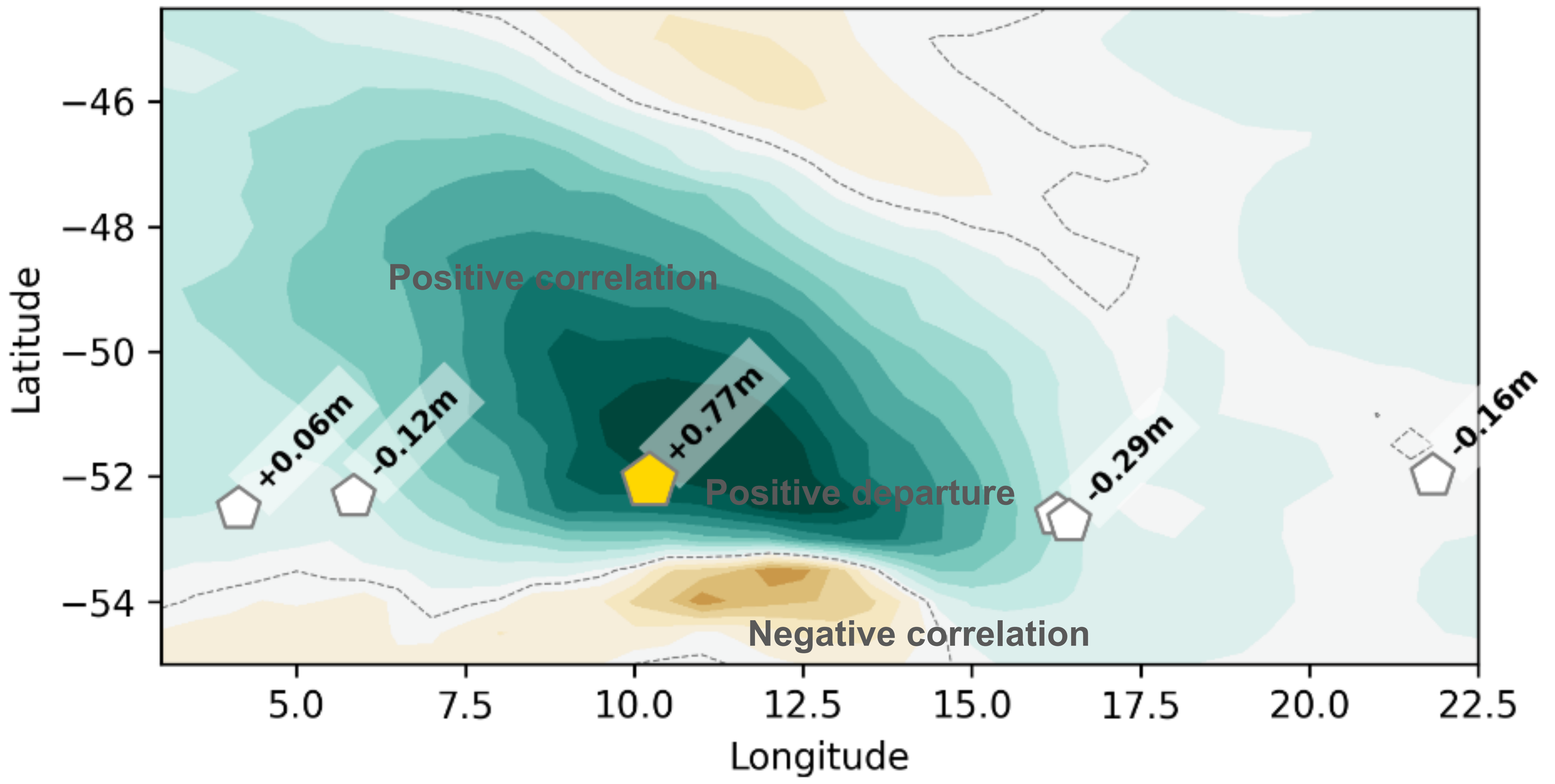
Ensemble-based DA Update

Wave model ensemble provides estimate of error covariances between all locations.

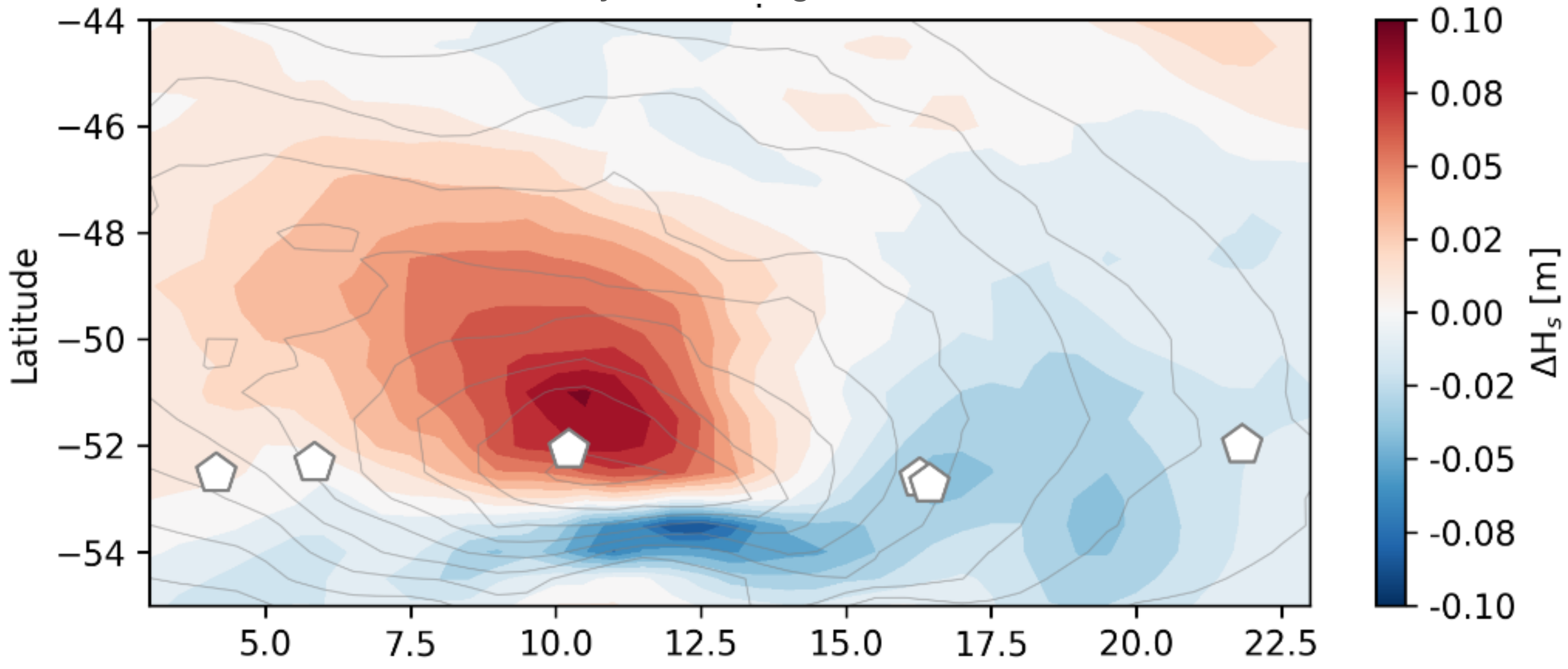


Model Error Covariances
Derived from wave ensemble

$$\mathrm{cov}(X, Y) = \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{N}.$$



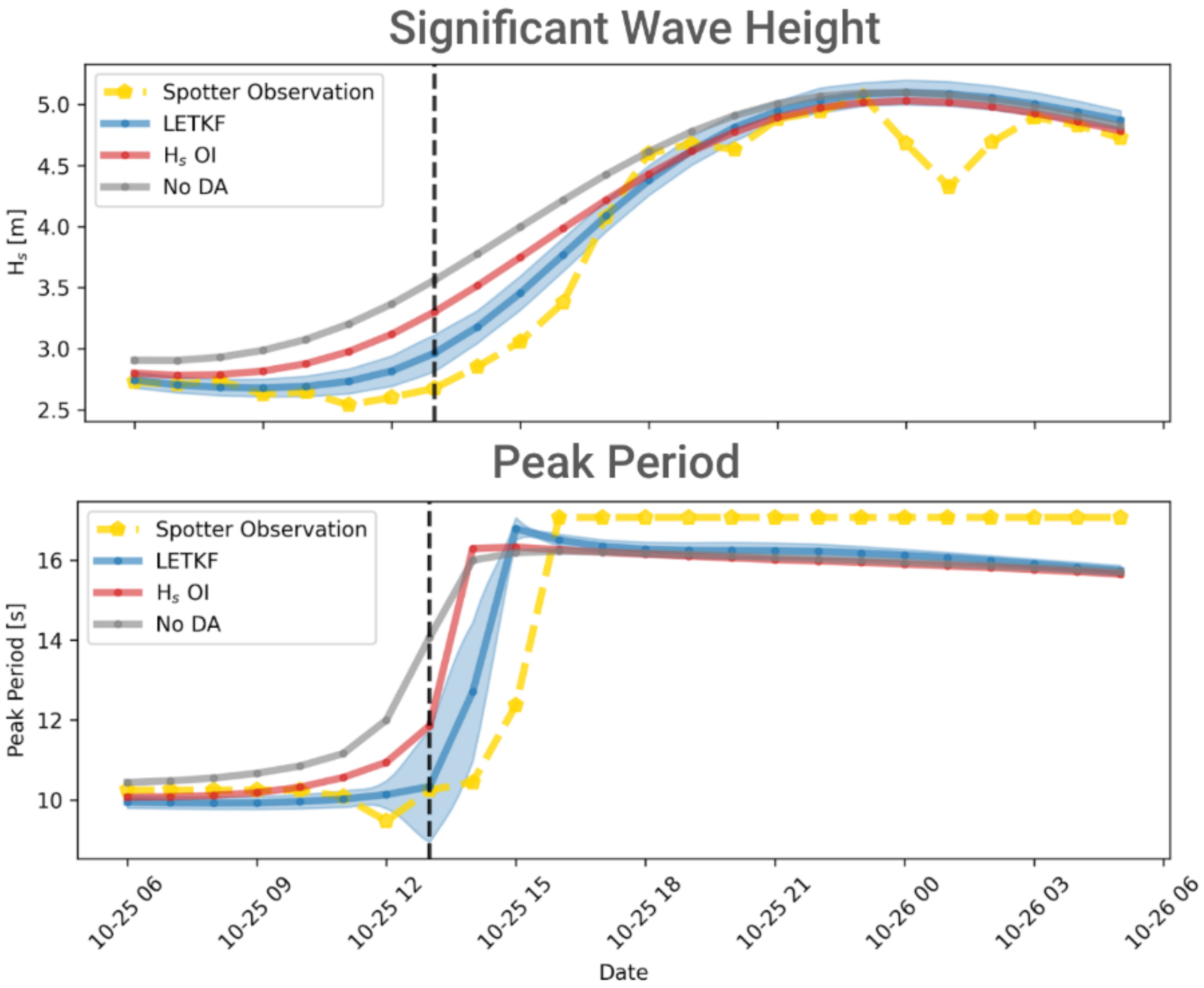
LETKF Update
Analysis - Background Field

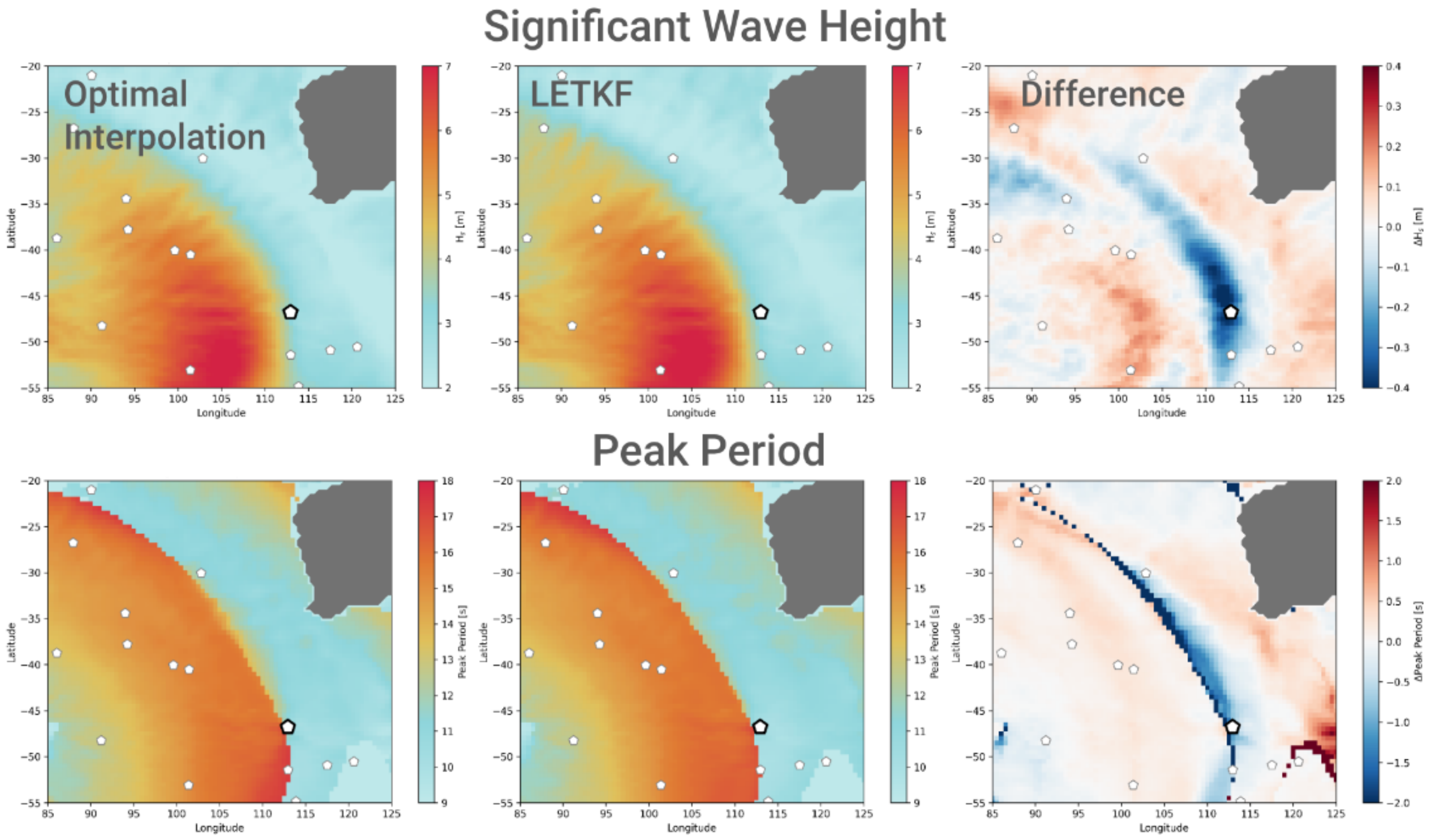


Houghton, et al. (2023). Ensemble-Based Data Assimilation of Significant Wave Height from Sofar Spotters and Satellite Altimeters with a Global Operational Wave Model, *Ocean Modelling*.

Ensemble-based DA → global, operational forecasts

Effective for discrete events with sharp gradients.



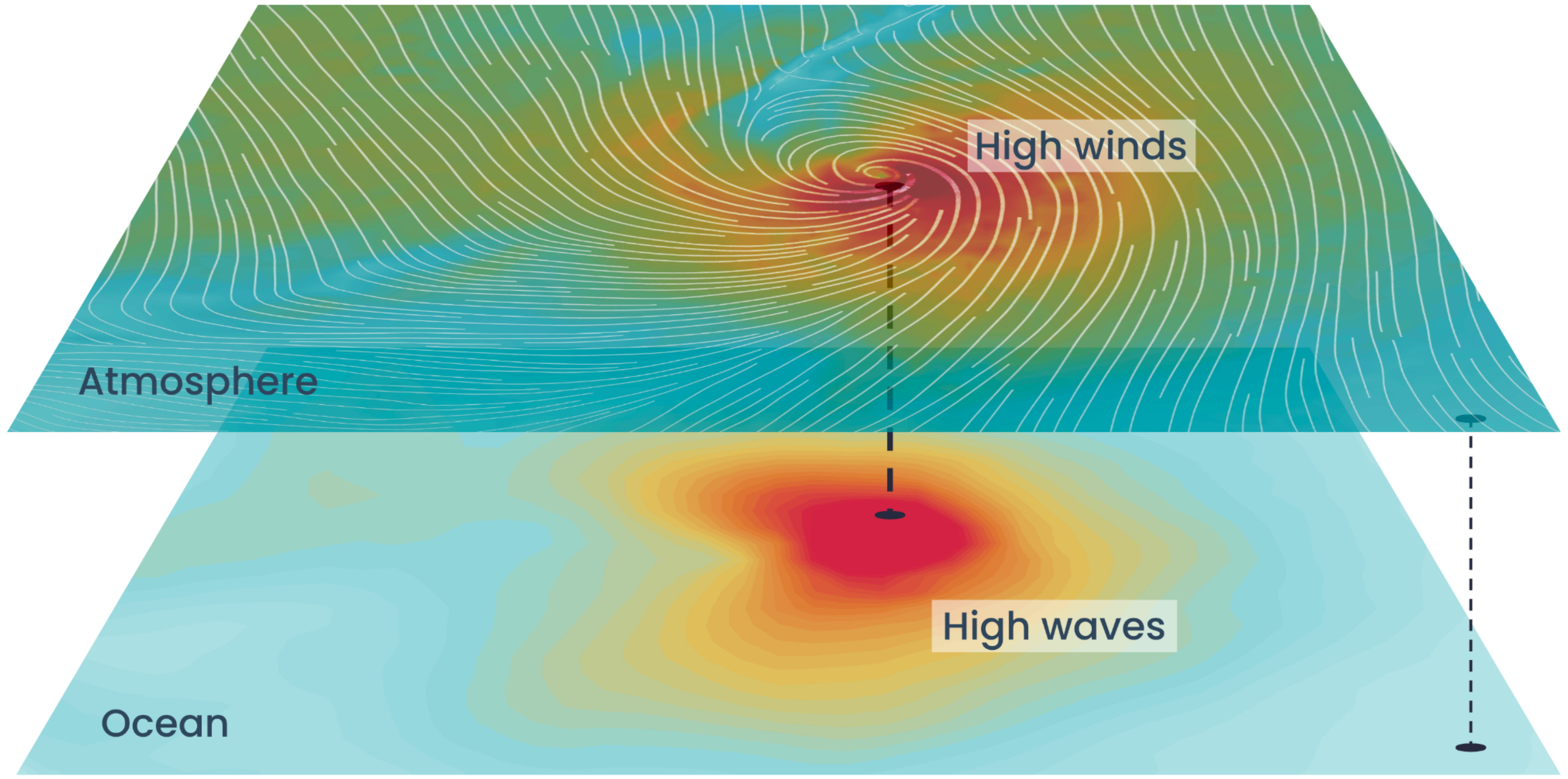


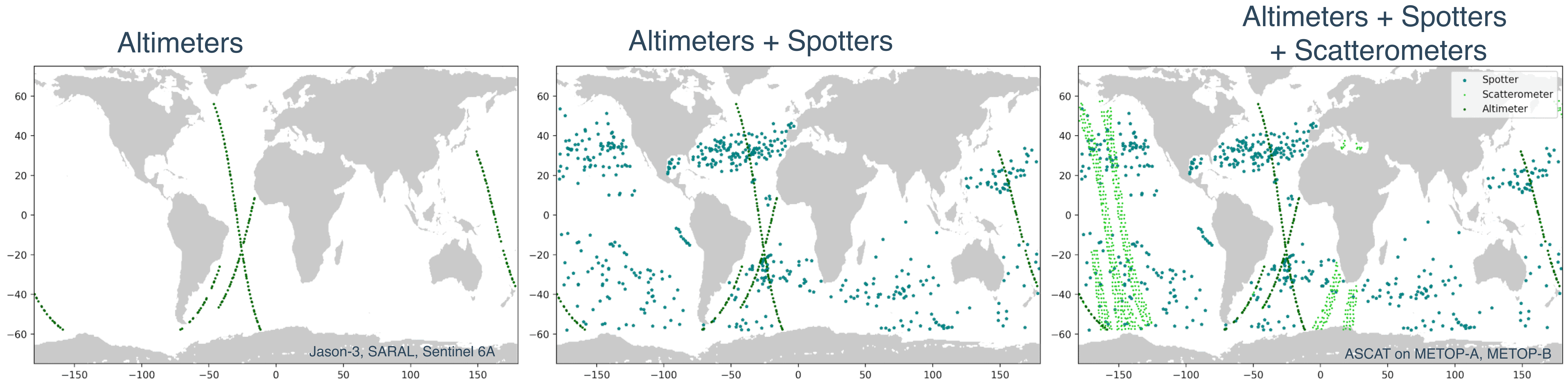
Houghton, et al. (2023). Ensemble-Based Data Assimilation of Significant Wave Height from Sofar Spotters and Satellite Altimeters with a Global Operational Wave Model, *Ocean Modelling*.

Expanding the available data

Errors between the atmosphere and underlying wave conditions should be correlated to some degree.

“Cross-covariances” between wave and atmosphere ensemble perturbations (X^b) permit the transfer of information from observation innovations (y^o - Hx^b) to unobserved variables (projected via the Kalman Gain matrix K).

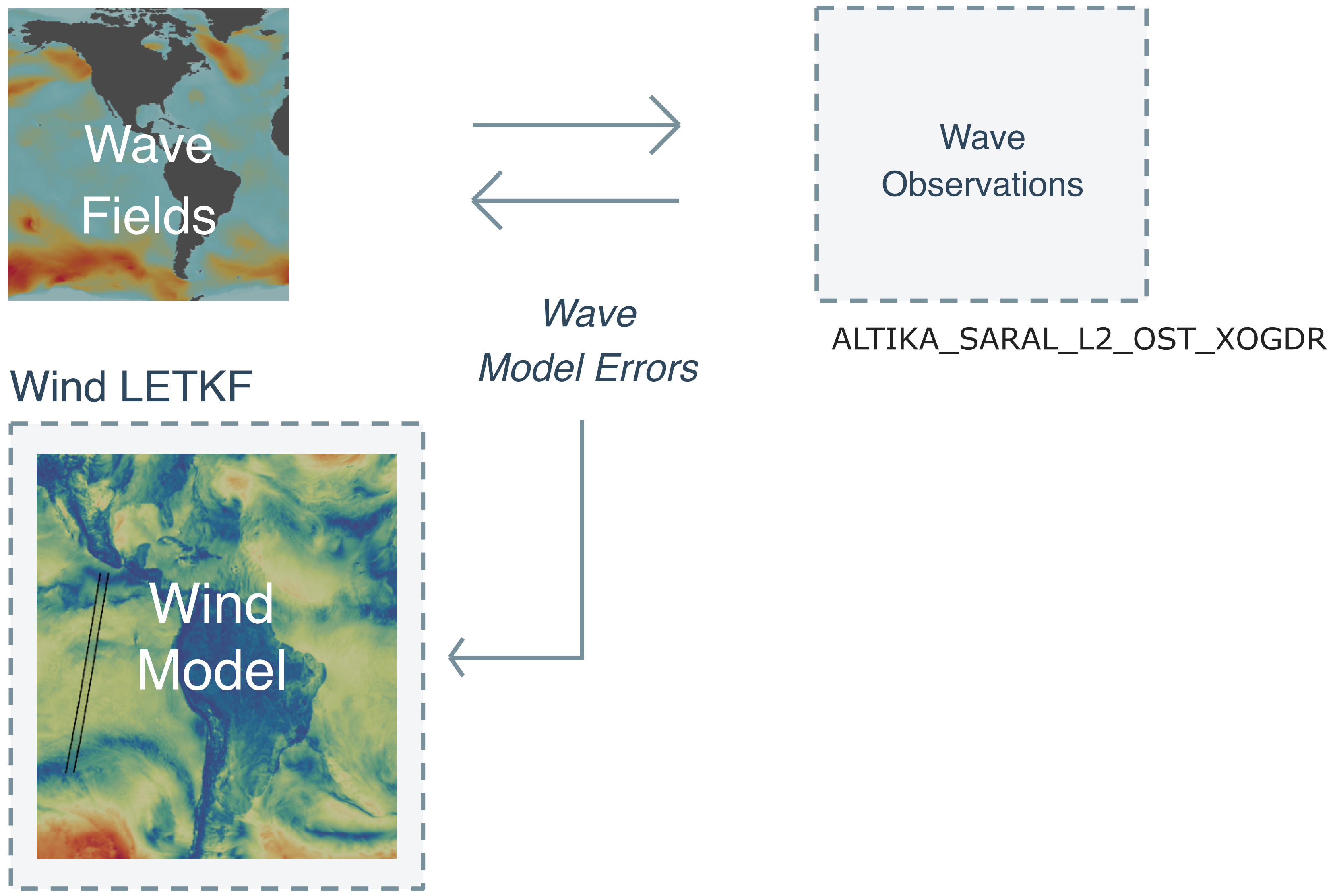


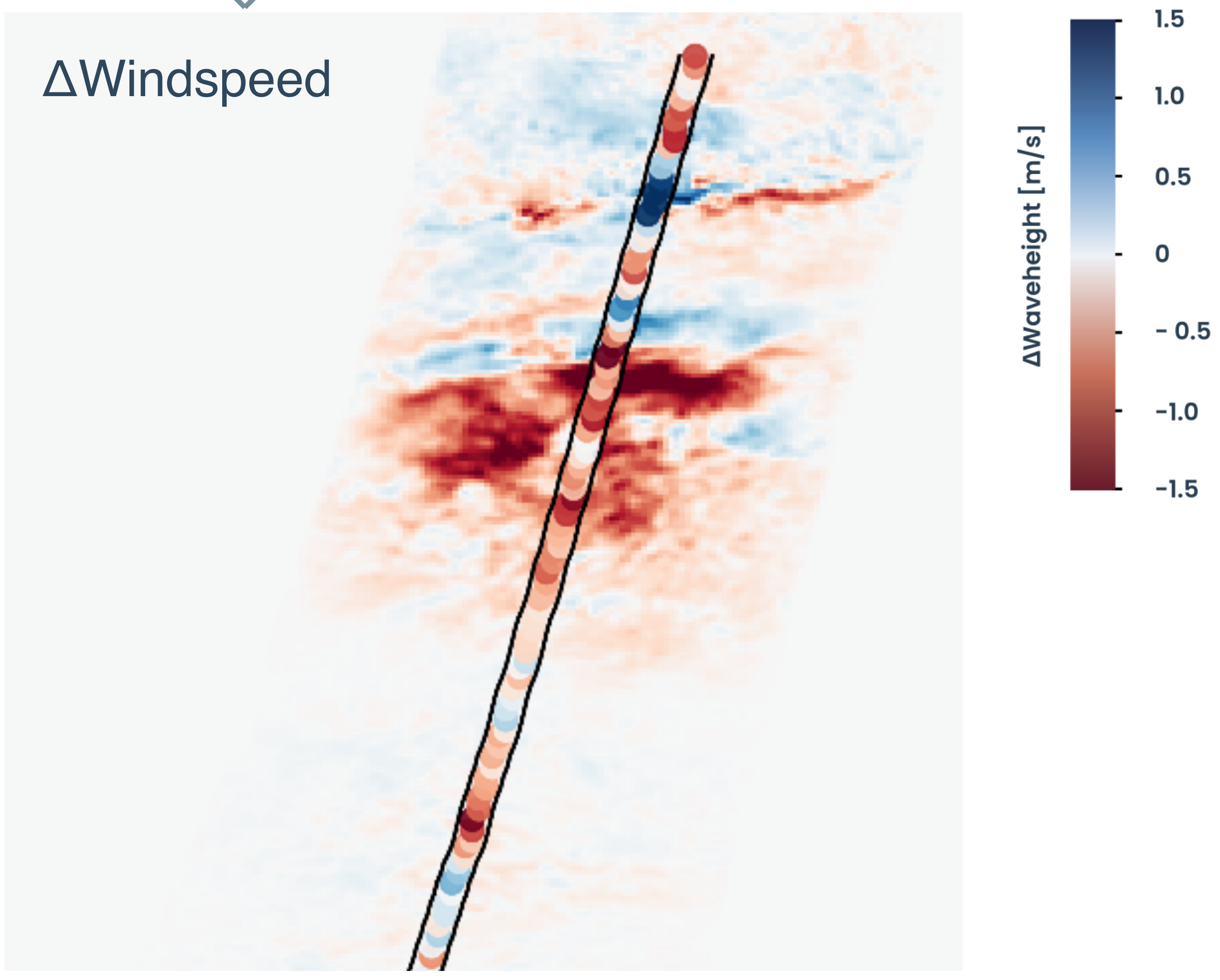


EXPERIMENT 01

Wind Update

from Wave Observations



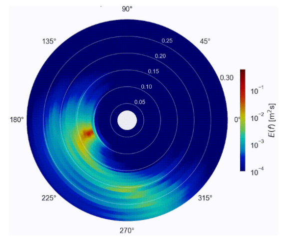


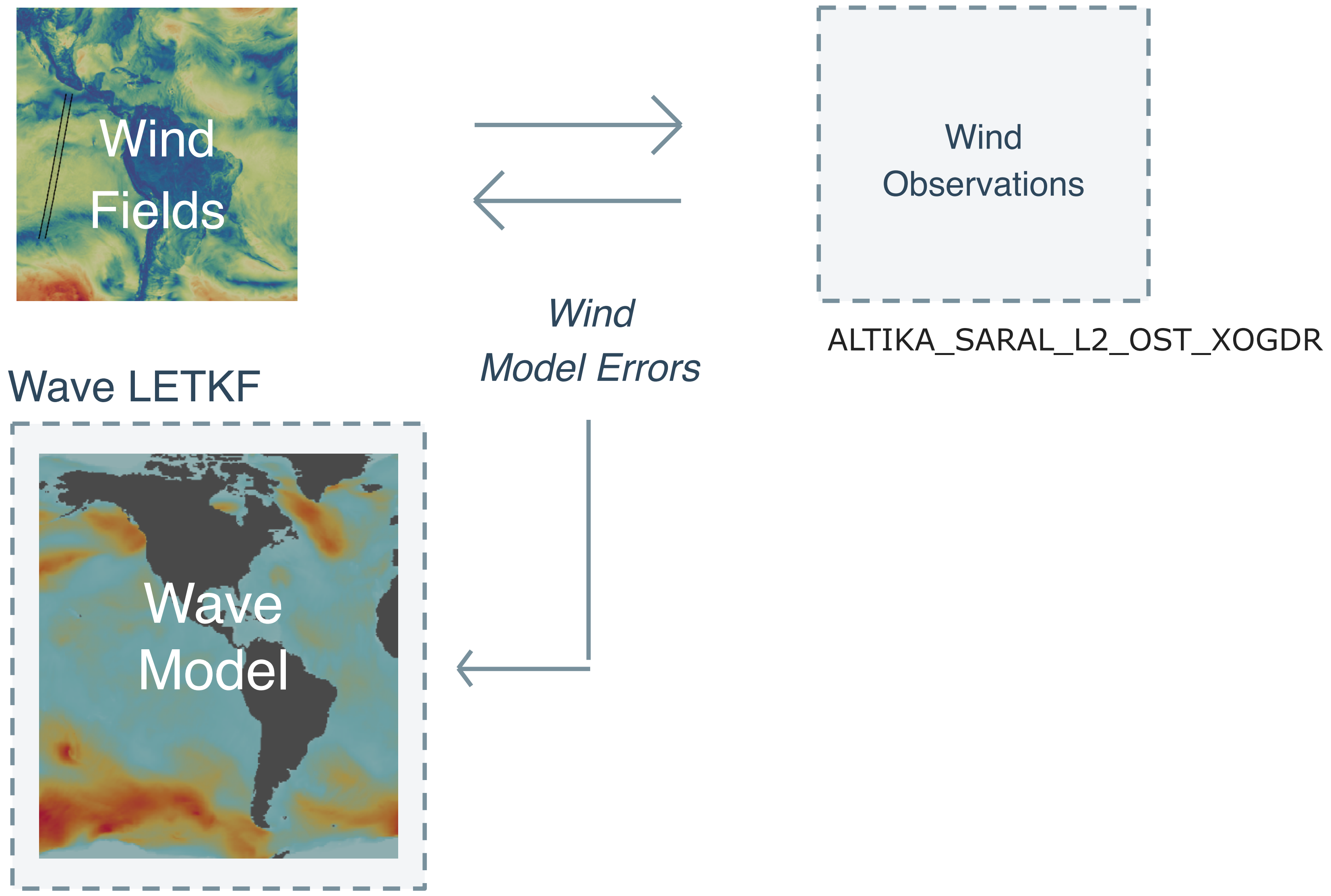
Streak indicates independent (unused) data to validate update. Matching colors indicates update agrees.

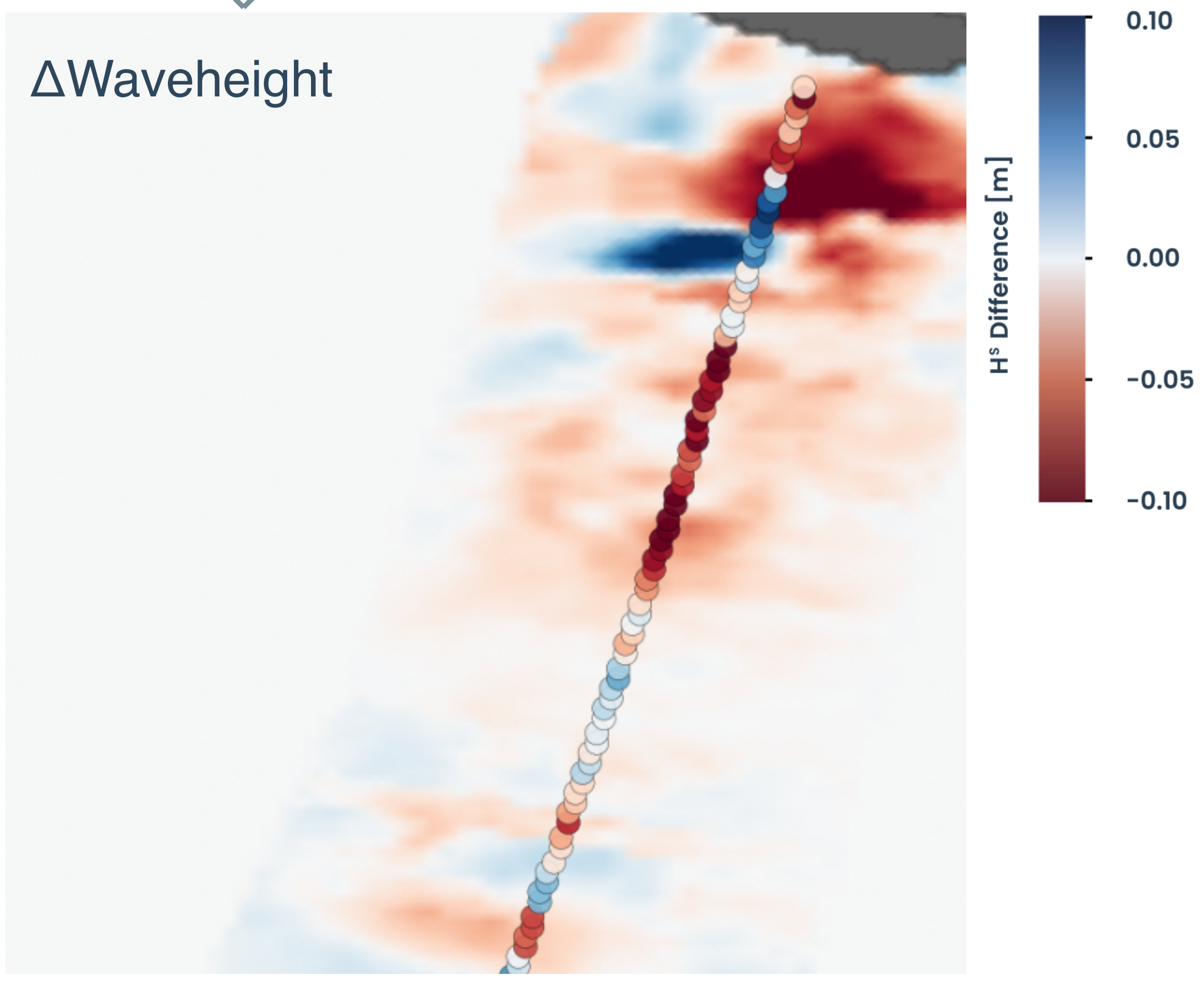
EXPERIMENT 02

Wave Update

from Wind Observations



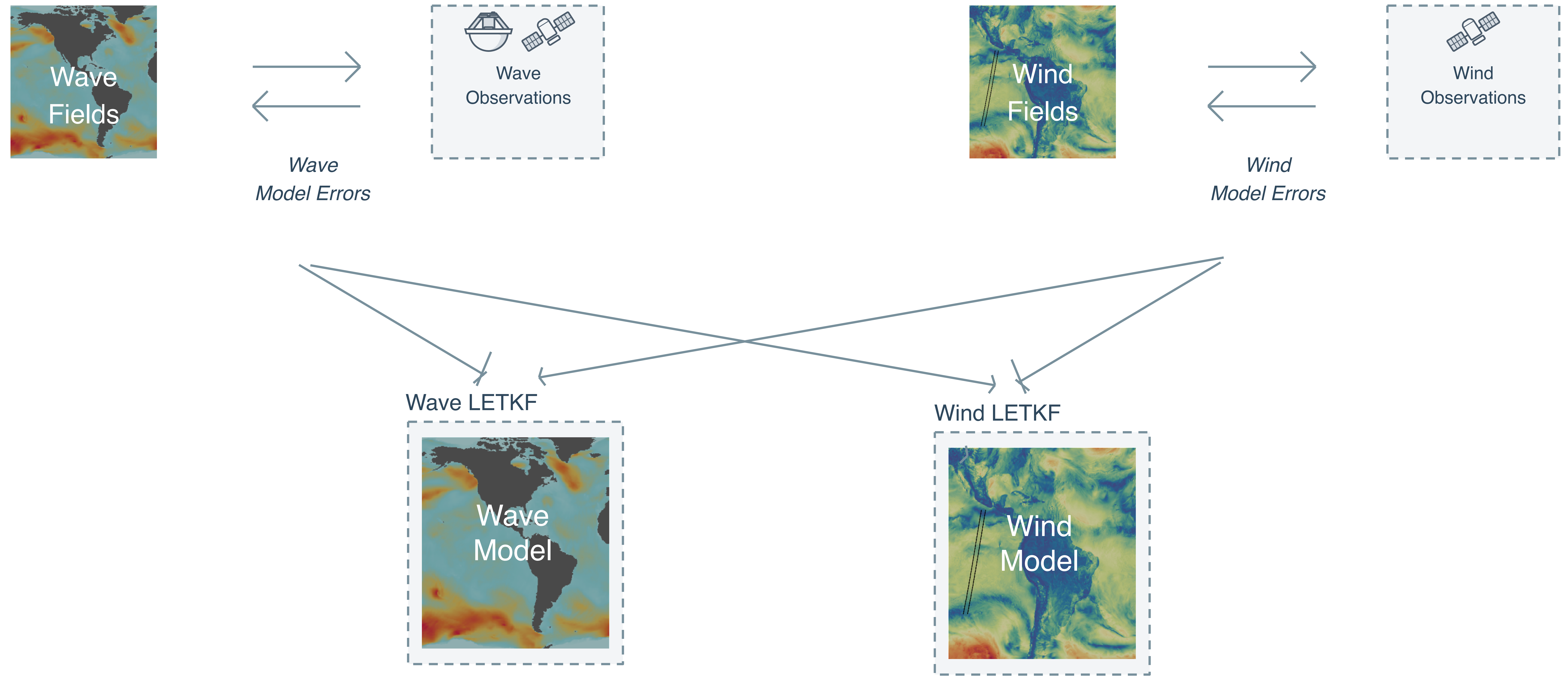




Streak indicates independent (unused) data to validate update. Matching colors indicates update agrees.

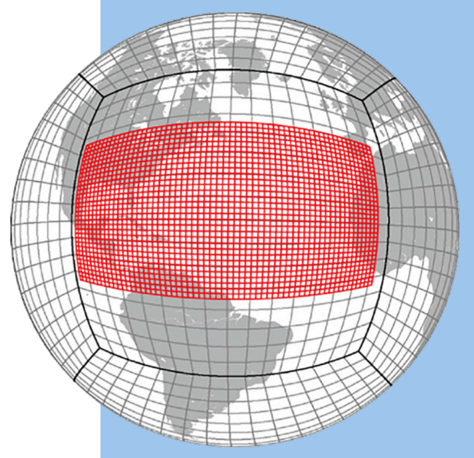
Assimilating observations across the air-sea interface

Can we use observations in one domain to correct for errors in another domain?



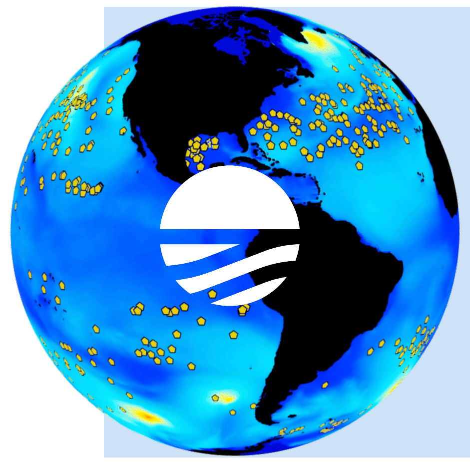
Coupled Modeling Framework

SHiELD



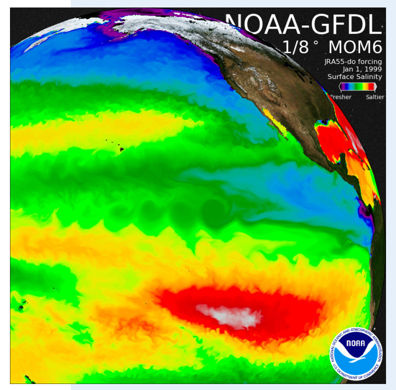
Atmosphere

We use the System for High-resolution modeling for Earth-to-Local Domains (SHiELD) with Finite Volume Cube Sphere dynamical core (FV3), developed at GFDL *(Harris et al., 2020)*.



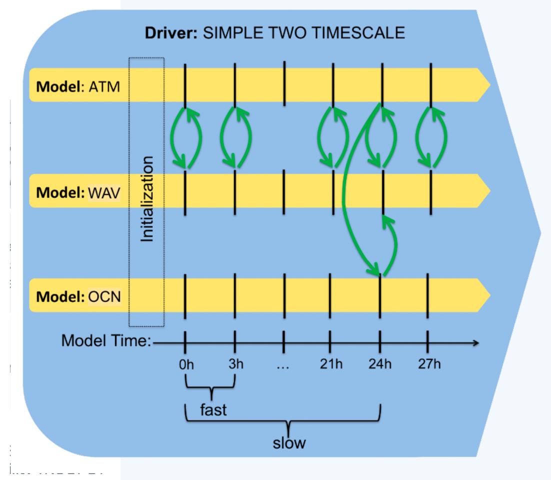
Wave

We leverage the exceptional performance of Sofar's operational wave forecast system (WaveWatch3 assimilating Spotters and altimeter measurements) *Houghton et al. (2022)*



Ocean

We use the Modular Ocean Model (MOM6) developed at GFDL.

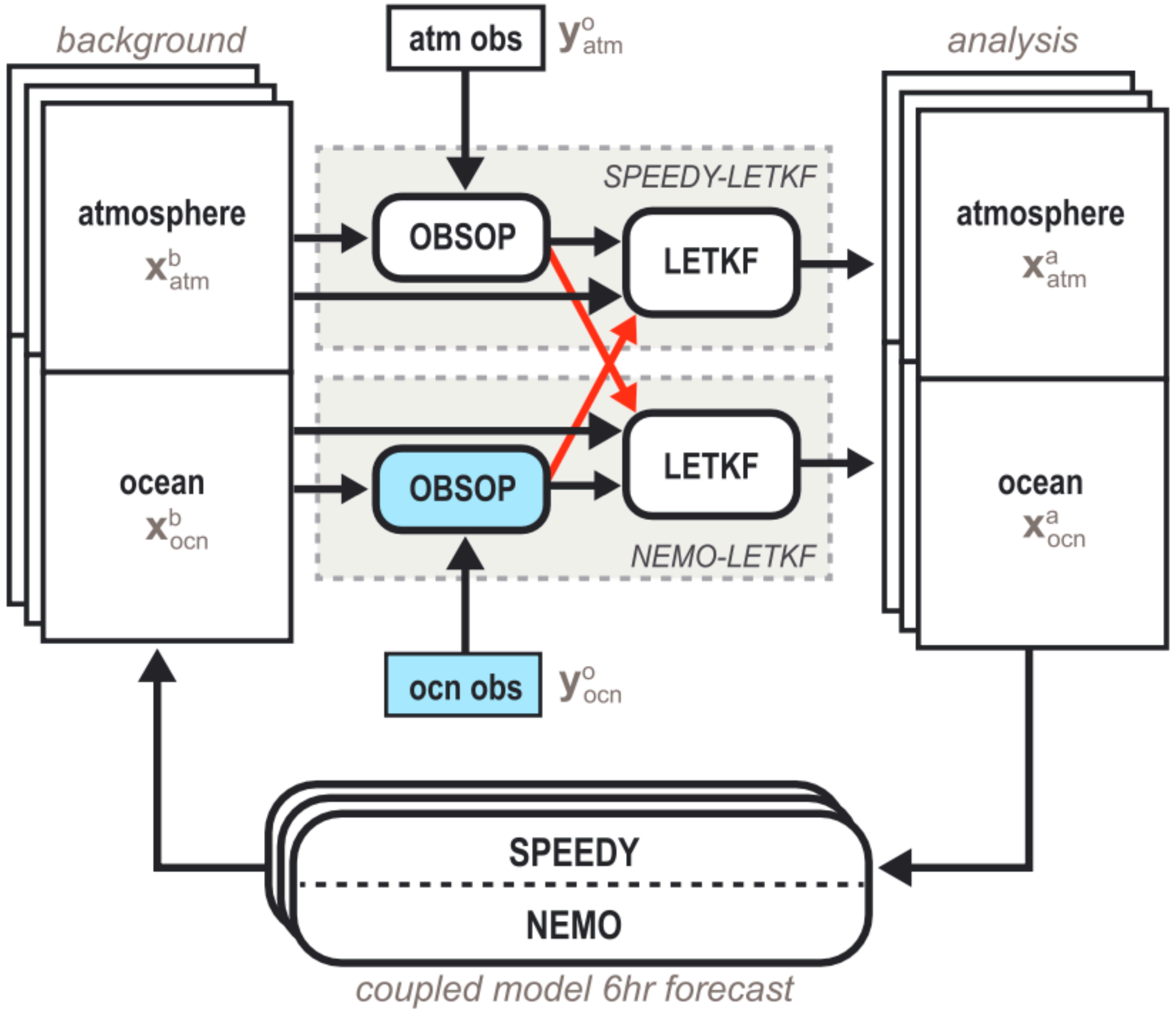


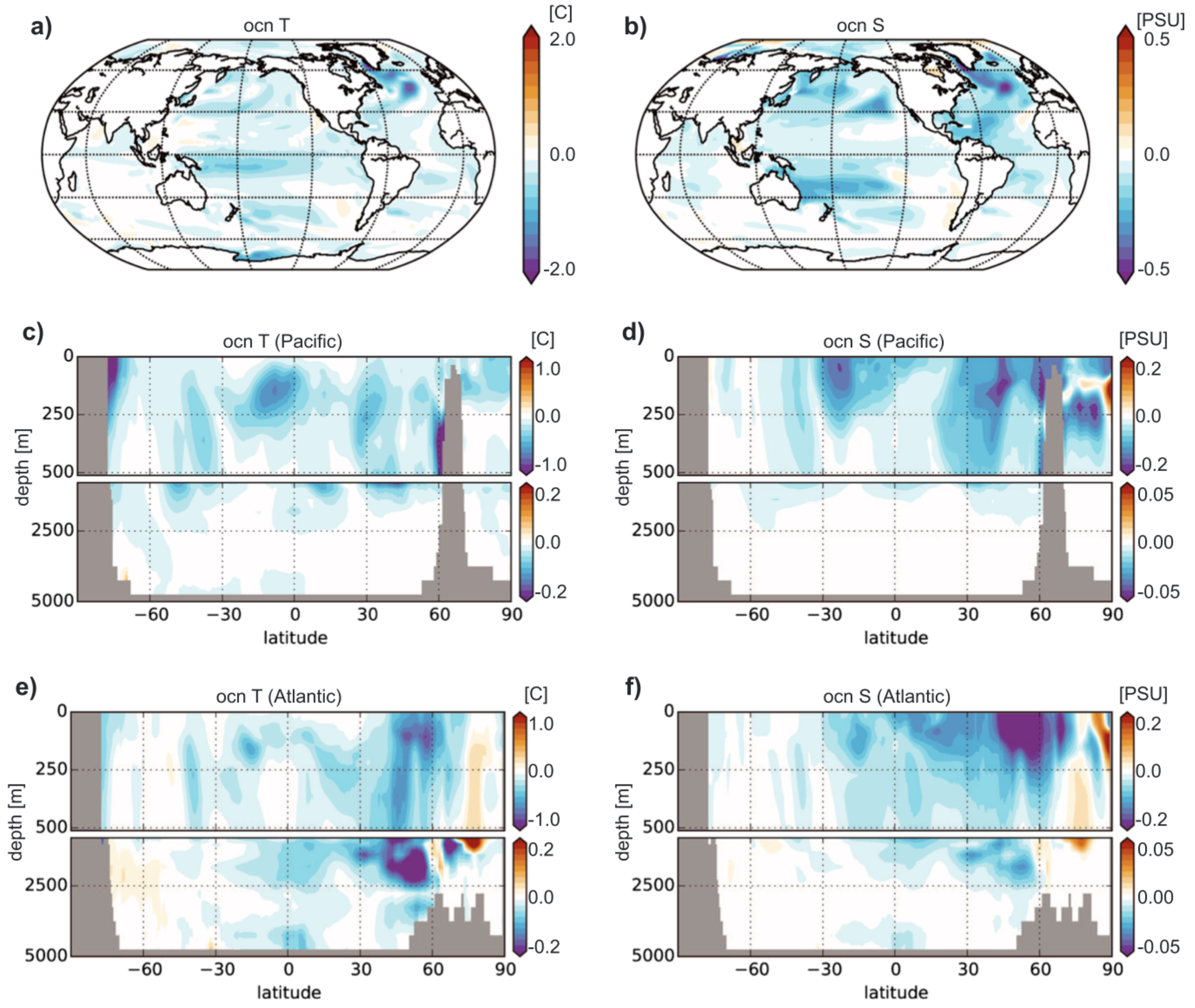
Coupler

We use the Earth System Modeling Framework (ESMF) National Unified Operational Prediction Capability (NUOPC)

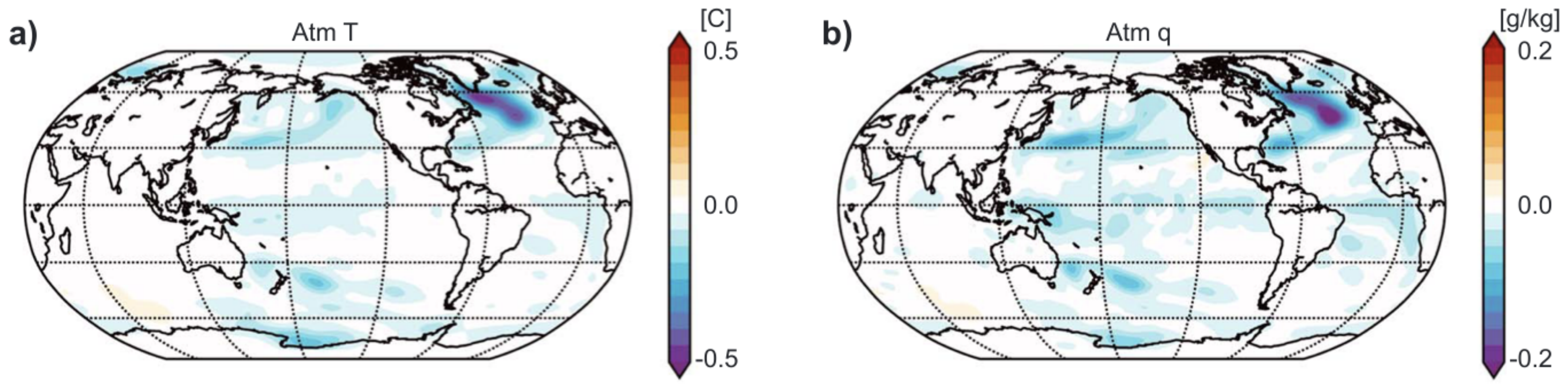
(supported by: NASA, NOAA, DoD, NSF).

Strongly Coupled Data Assimilation

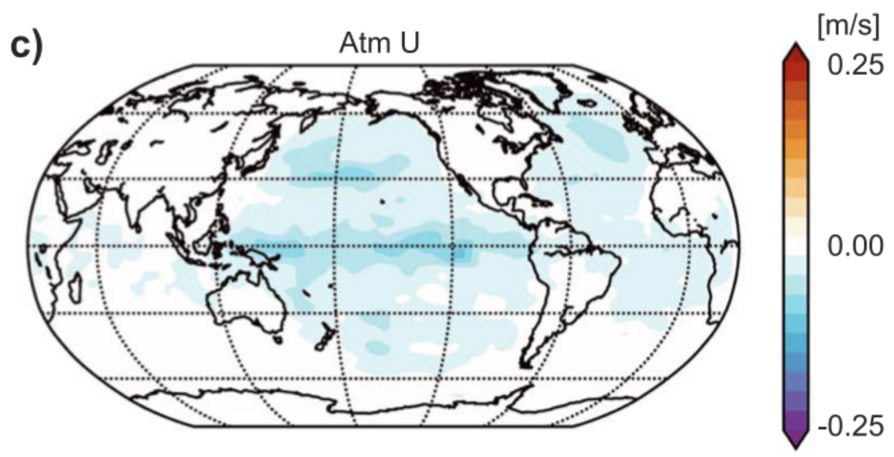




Improvement (blue) in ocean temperature and salinity when *assimilating atmospheric observations into the ocean* for strongly coupled versus weakly coupled DA

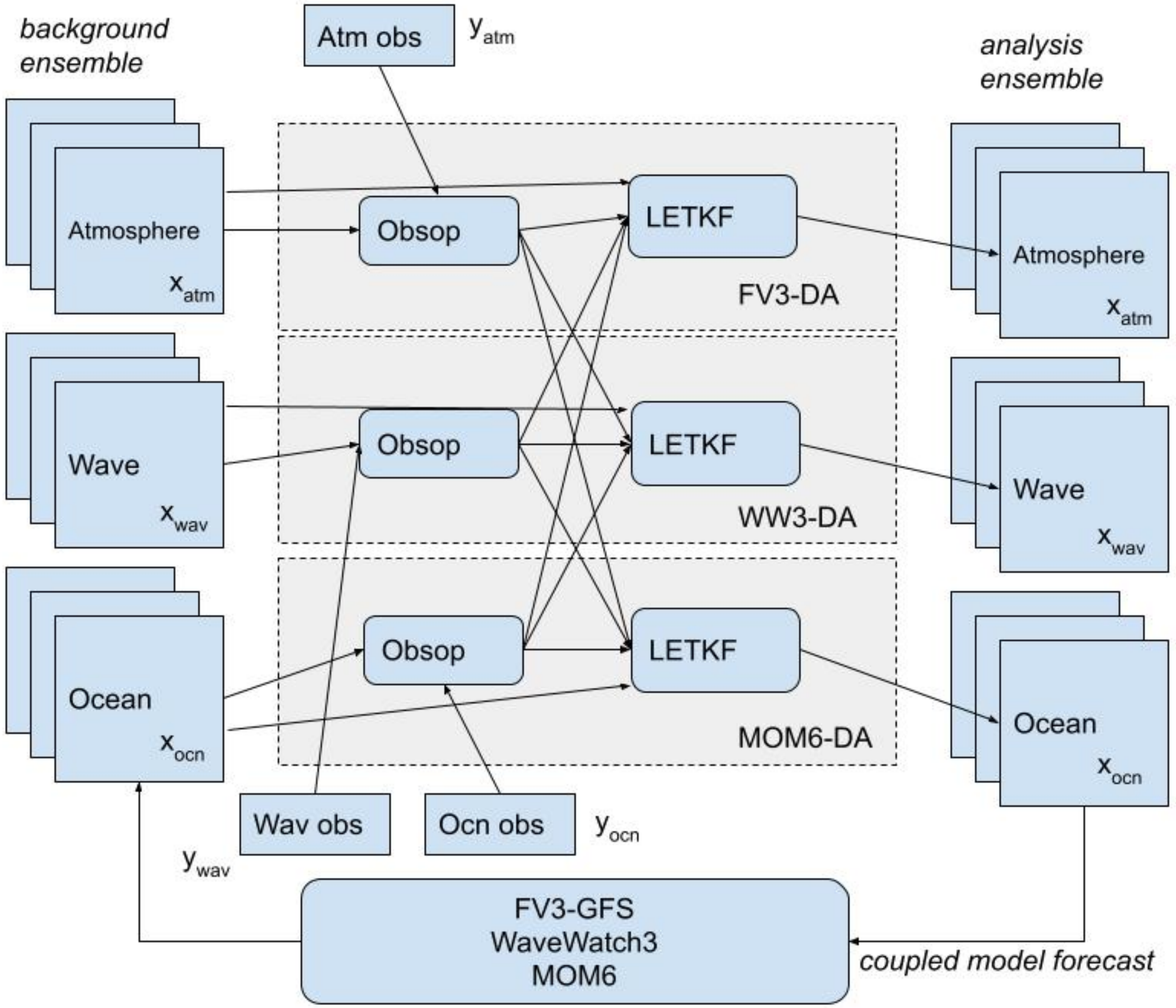


Feedback effects from ocean to atmosphere also improve the surface atmospheric fields



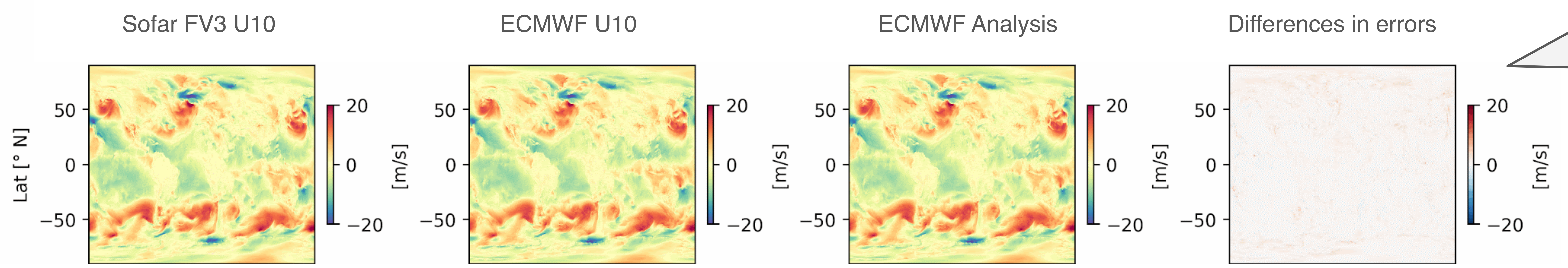
Sluka, T. C., **S. G. Penny**, E. Kalnay, and T. Miyoshi (2016), Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation, Geophys. Res. Lett., 43, 752–759, doi:10.1002/2015GL067238.

Strongly Coupled Data Assimilation

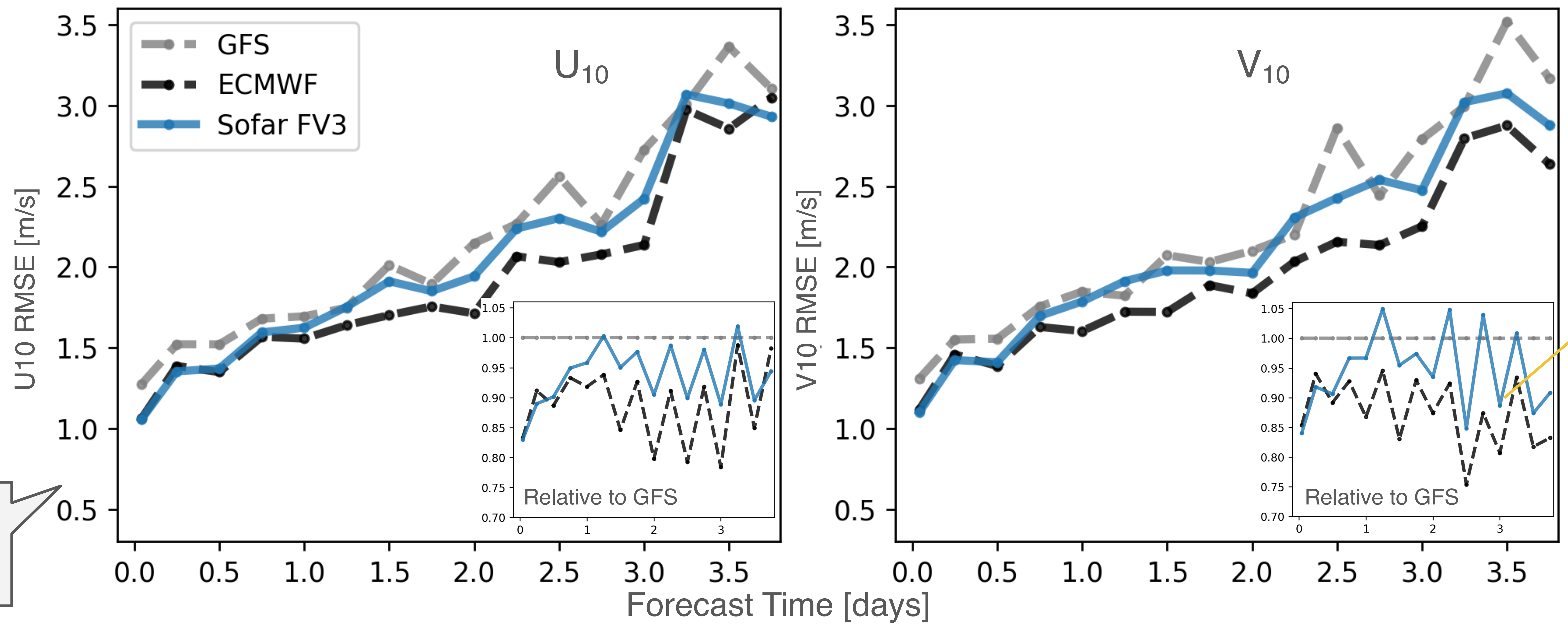


Sofar FV3 Atmosphere Implementation

13 km resolution GFDL FV3-SHiELD system with reduced vertical levels (<⅓ the cost), ECMWF initial conditions, no additional DA or tuning yet -



As evaluated against ECMWF analysis fields. Blue where Sofar FV3 is closer to the analysis than ECMWF.

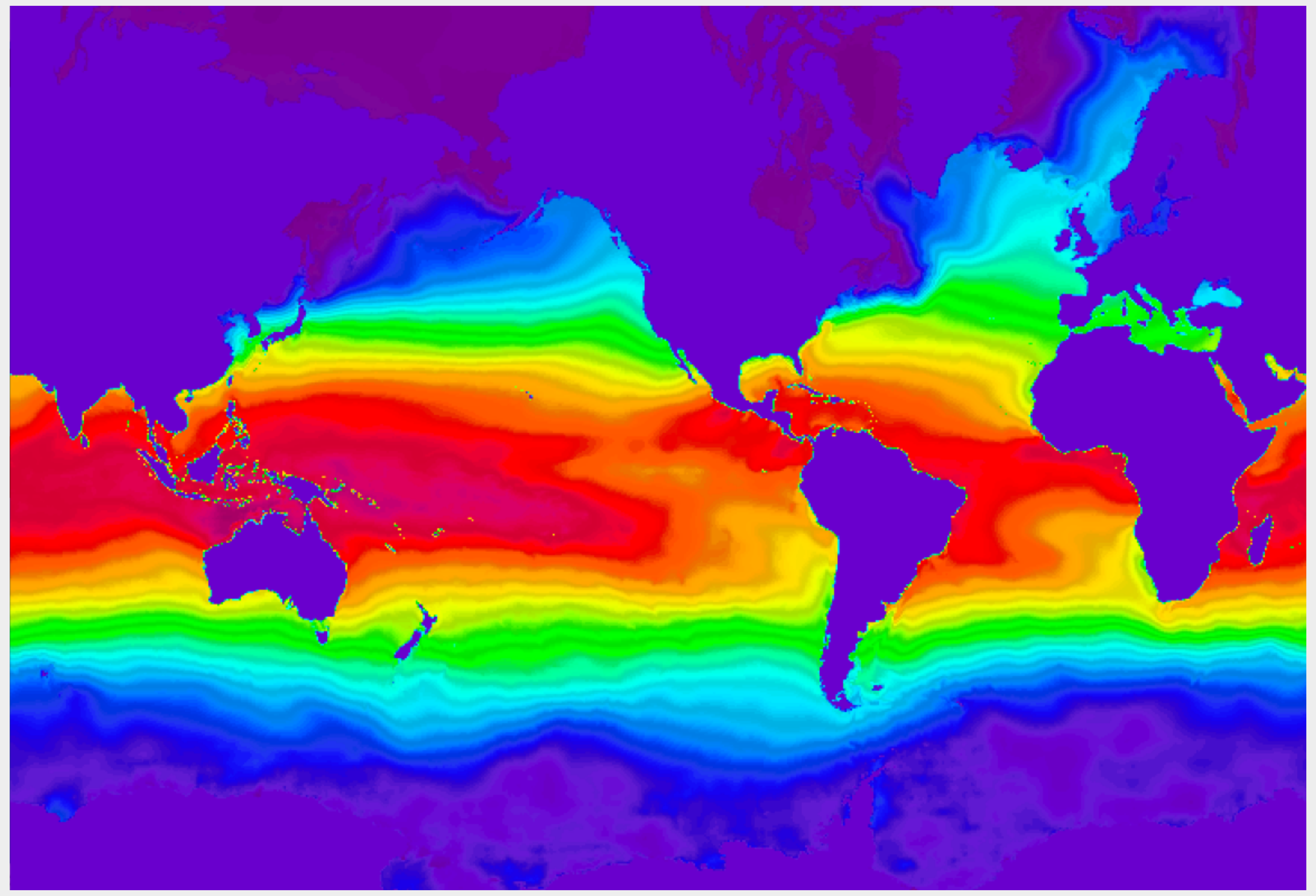


Compared to METOP-B,C scatterometer observations

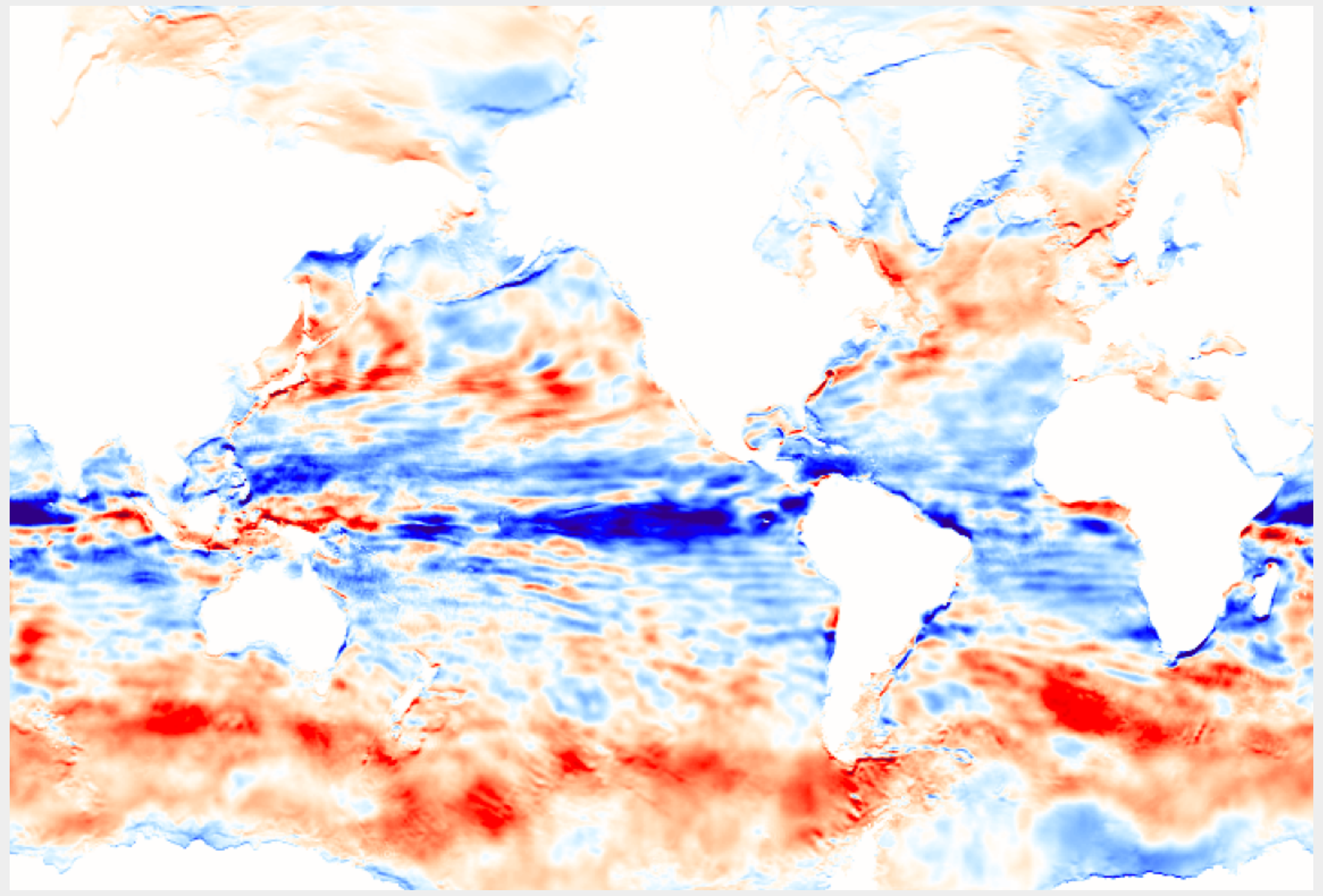
Up to ~10% improvement over operational GFS

Ocean model implementation

Early testing running GFDL's Modular Ocean Model (MOM6) at ¼-degree on AWS cloud infrastructure (left), ultimately targeting 1/12-degree (right)



Sea surface temperature (SST)



Zonal currents (U)

Targeting 1/12-degree:

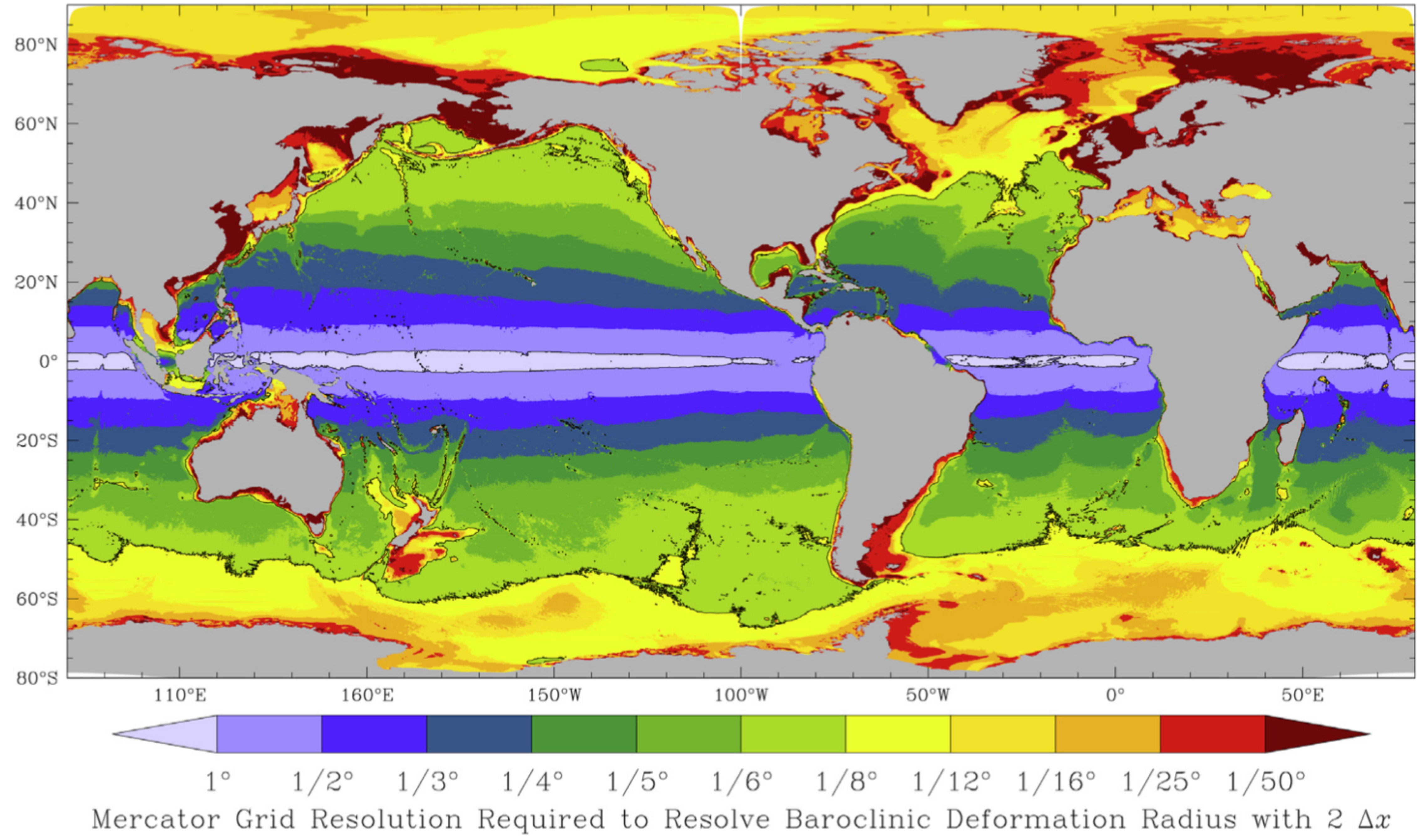
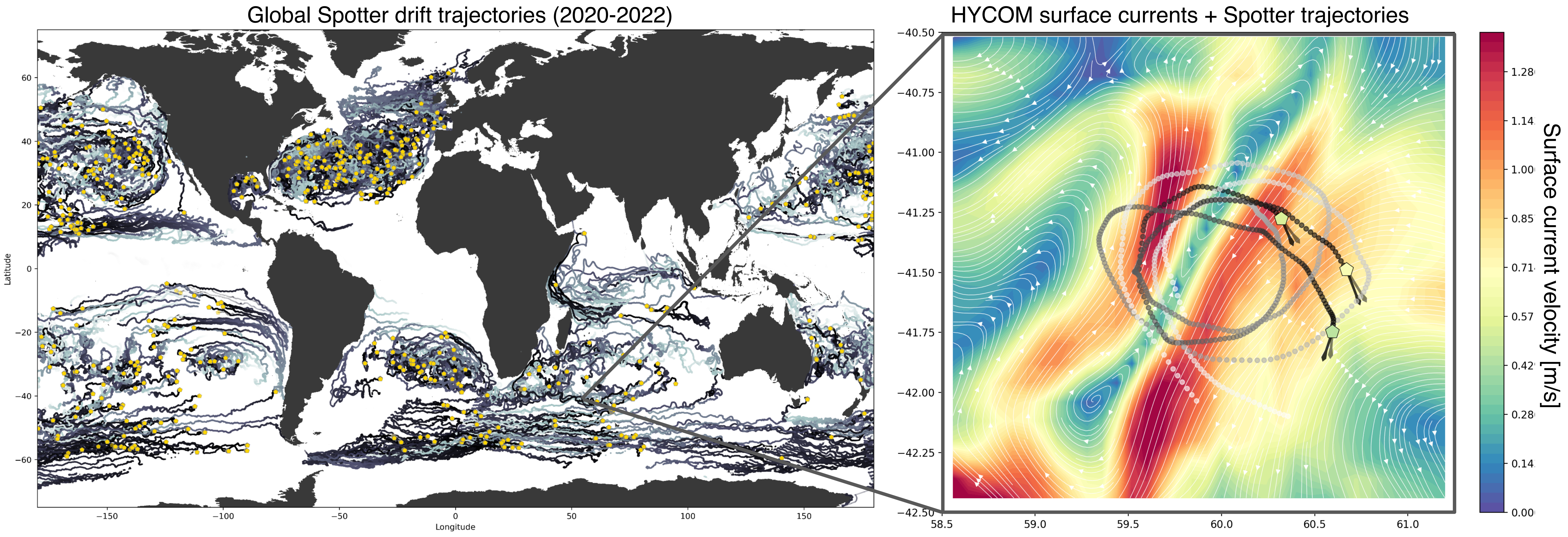


Fig. 1. The horizontal resolution needed to resolve the first baroclinic deformation radius with two grid points, based on a 1/8° model on a Mercator grid (Adcroft et al., 2010) on Jan. 1 after one year of spinup from climatology. (In the deep ocean the seasonal cycle of the deformation radius is weak, but it can be strong on continental shelves.) This model uses a bipolar Arctic cap north of 65°N. The solid line shows the contour where the deformation radius is resolved with two grid points at 1° and 1/8° resolutions.

Hallberg (2013)

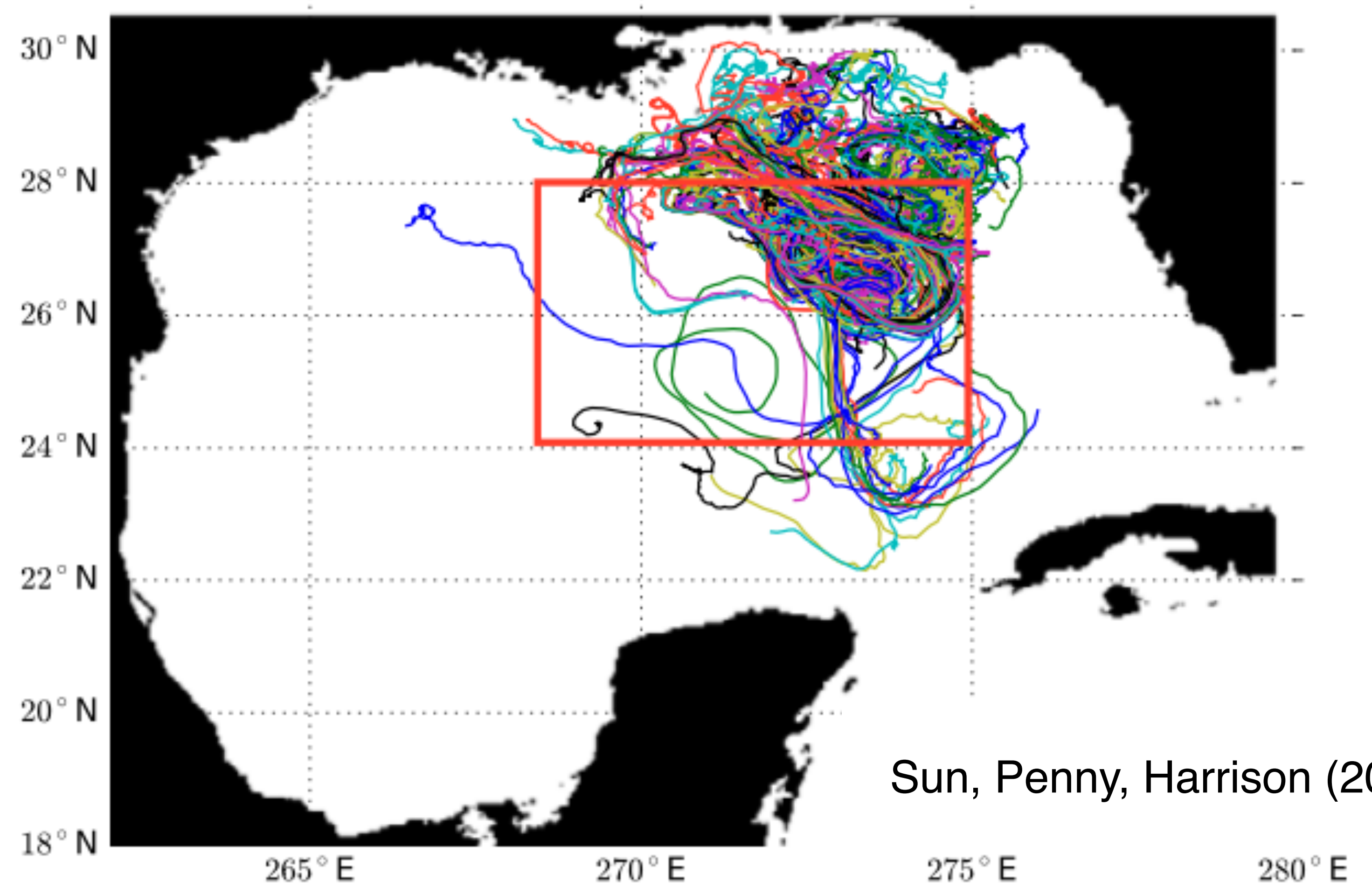
Currently setting up 1/12º configuration from Wallcraft & Chassignet

Assimilating drifter trajectories

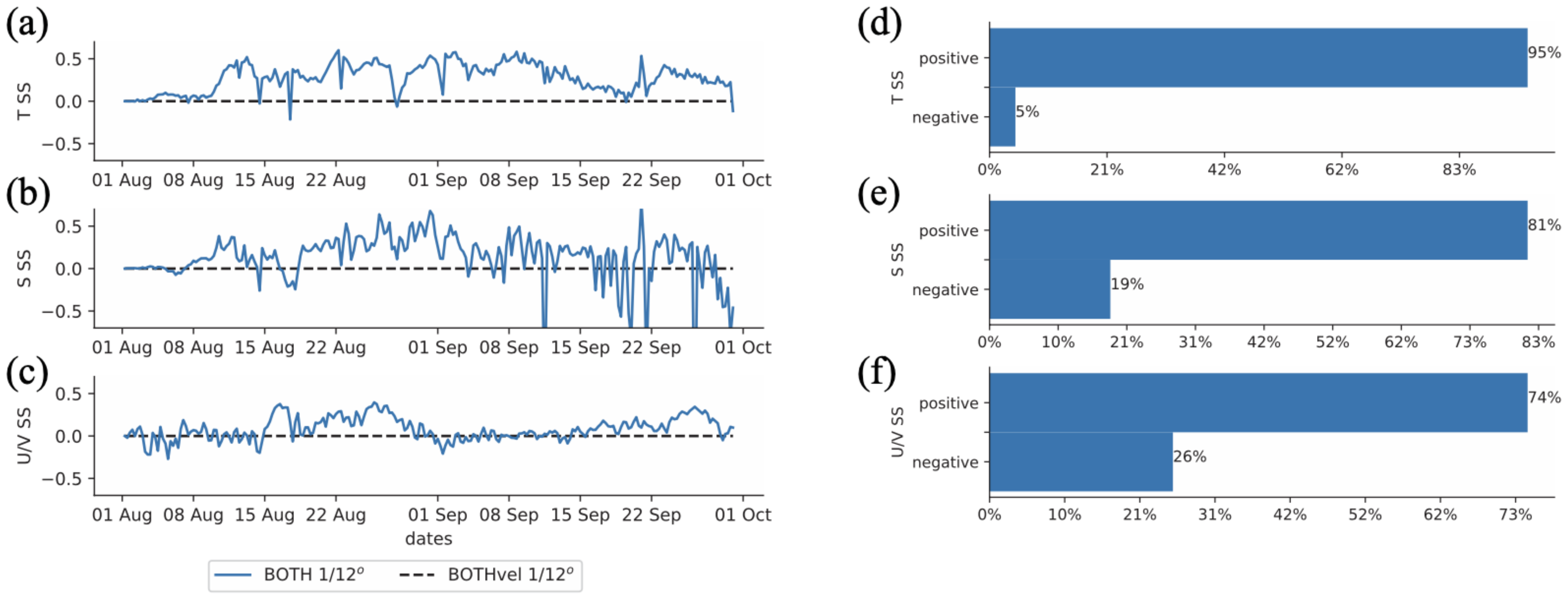


Left: A map of global Spotter buoy drift trajectories from January 2020 to June 2022, colored by time (light to dark). Last location of Spotters is indicated by yellow pentagon, where every Spotter (over 600) reports a surface drift estimate hourly. Right: A comparison of 9 days of drift locations from three Spotters in the Southern Ocean to the HYCOM surface current estimates on the 9th day. Light vector indicates the raw drift trajectory, dark vector indicates the wind-corrected drift estimate. **Assimilation of wind-adjusted drift from the comprehensive global Spotter network can anchor surface currents more accurately in space and time.**

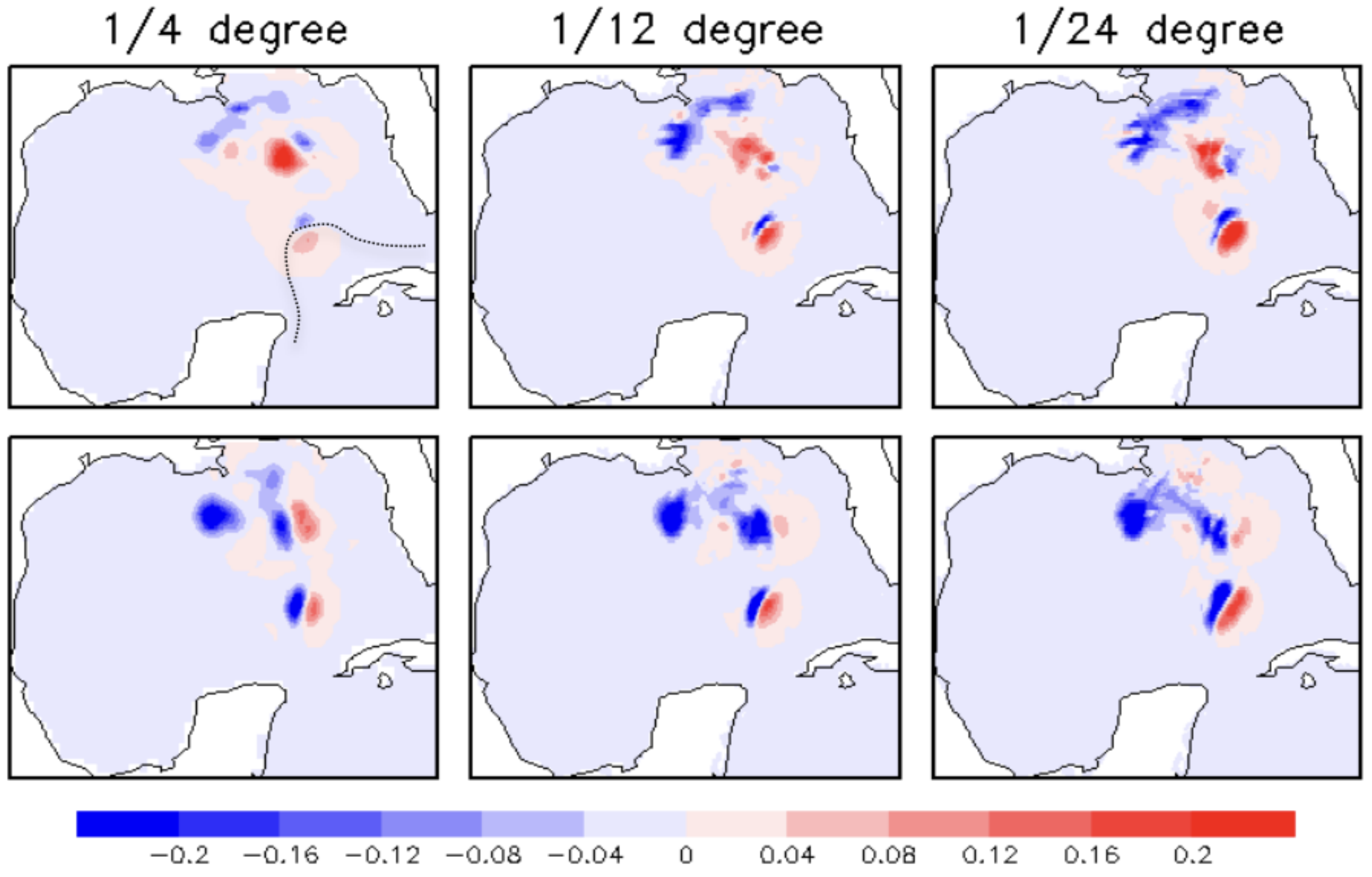
Assimilating drifter trajectories



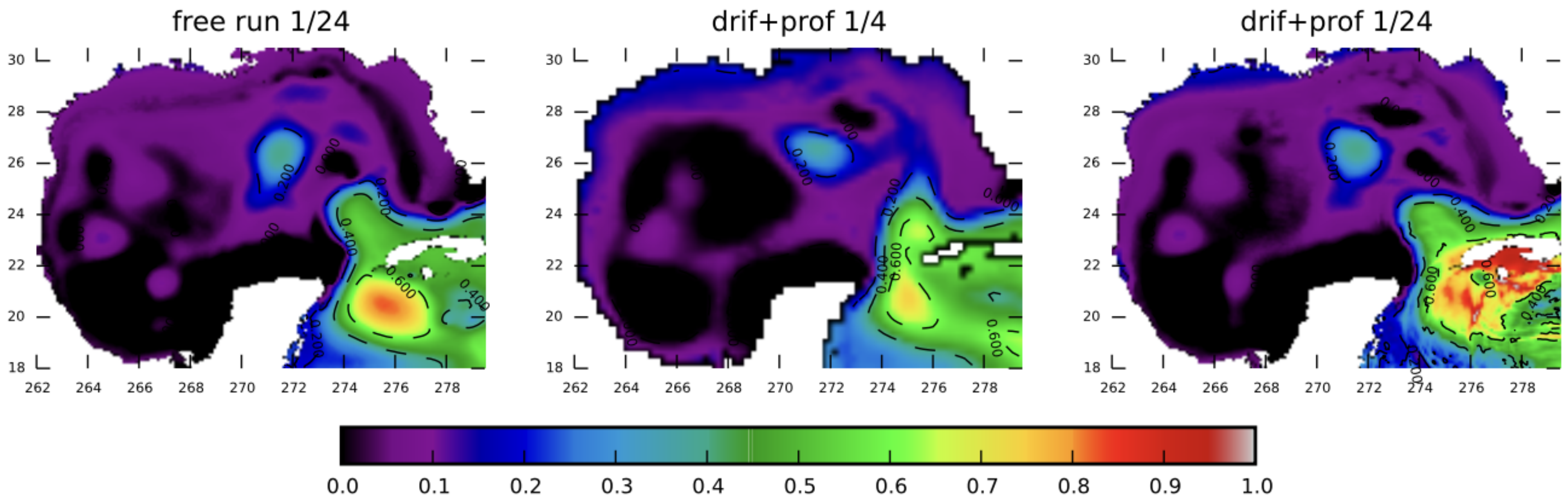
Sun, Penny, Harrison (2022)



Improvements in skill score assimilating Lagrangian tracks versus derived Eulerian velocities



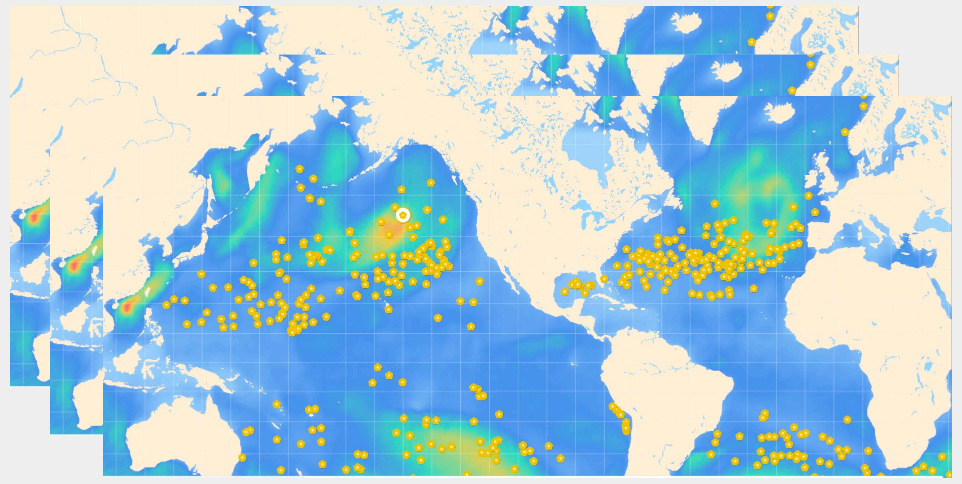
Analysis increments at the end of the first DA cycle in zonal (first row; m/s) and meridional velocity (second row; m/s) at depth level z=1m. The dashed line in the first subplot shows the rough profile of Loop Current as a reference.



SSH (m) for: (a) a free model run using ocean model of 1/24°horizontal resolution; (b) assimilation of both drifter positions and *in situ* observations at 1/4° resolution; and (c) as in ‘b’ but with a 1/24° resolution, shown at the end of the 8th DA cycle. Drifter positions are provided by Grand Lagrangian Deployment (~300 drifters) and *in situ* measurements by World Ocean Database 18.

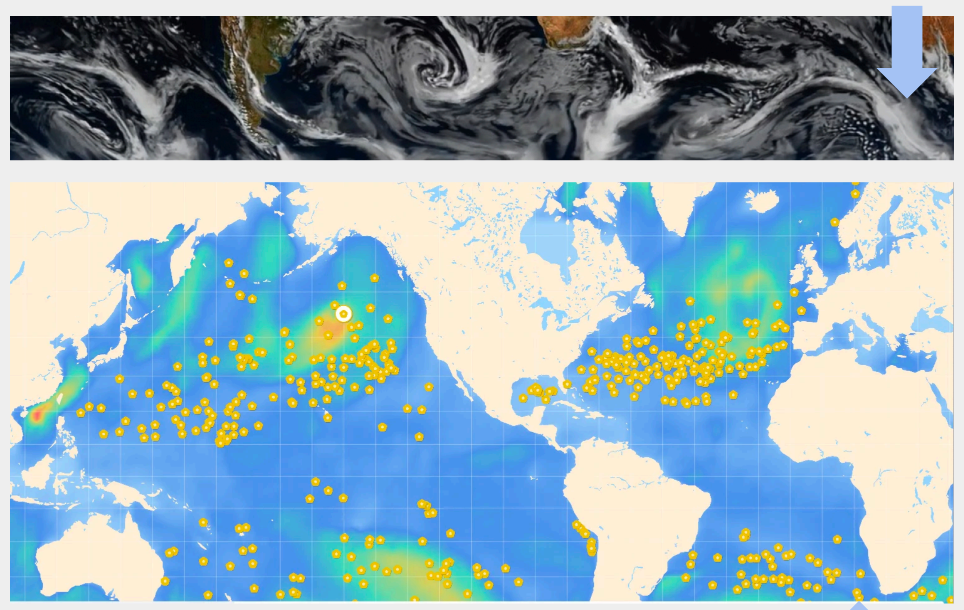
R&D forecast system roadmap (2023)

Wave-only forecasts



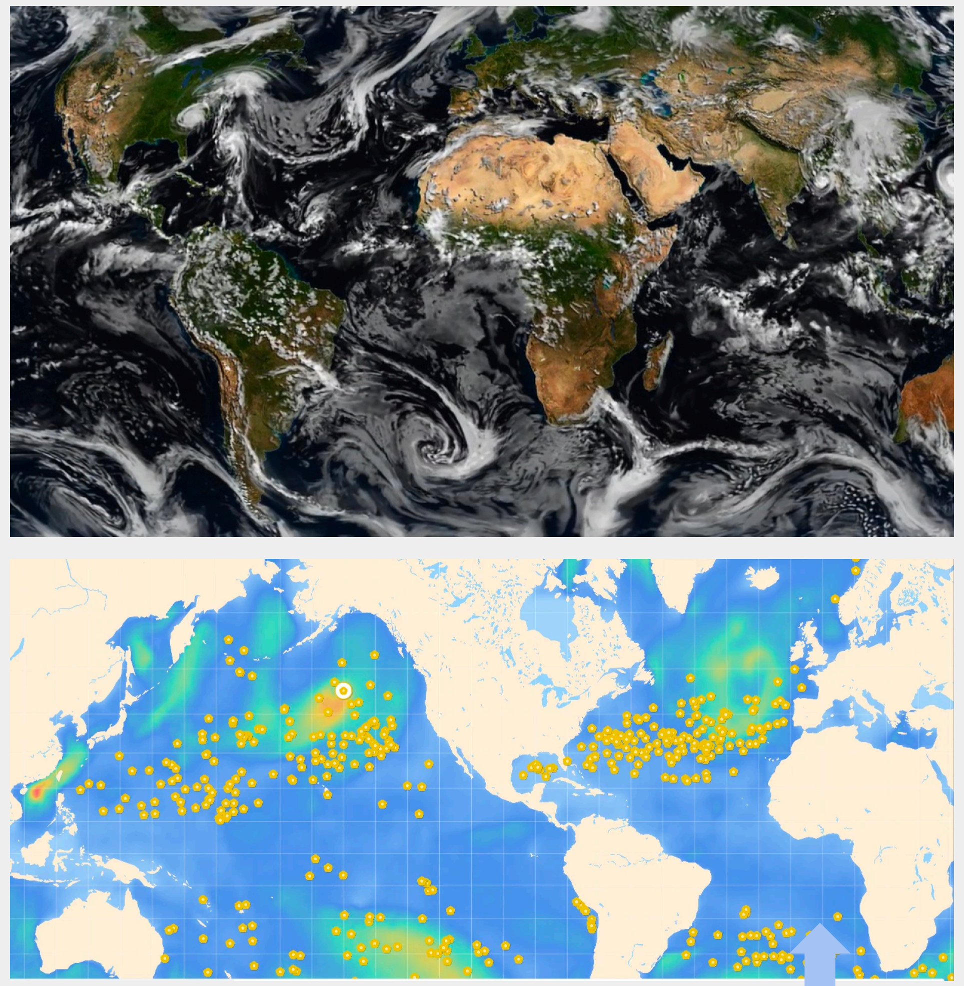
Expand to an **ensemble-based** DA and modeling capability (LETKF).

1-way coupled wave-atmos DA

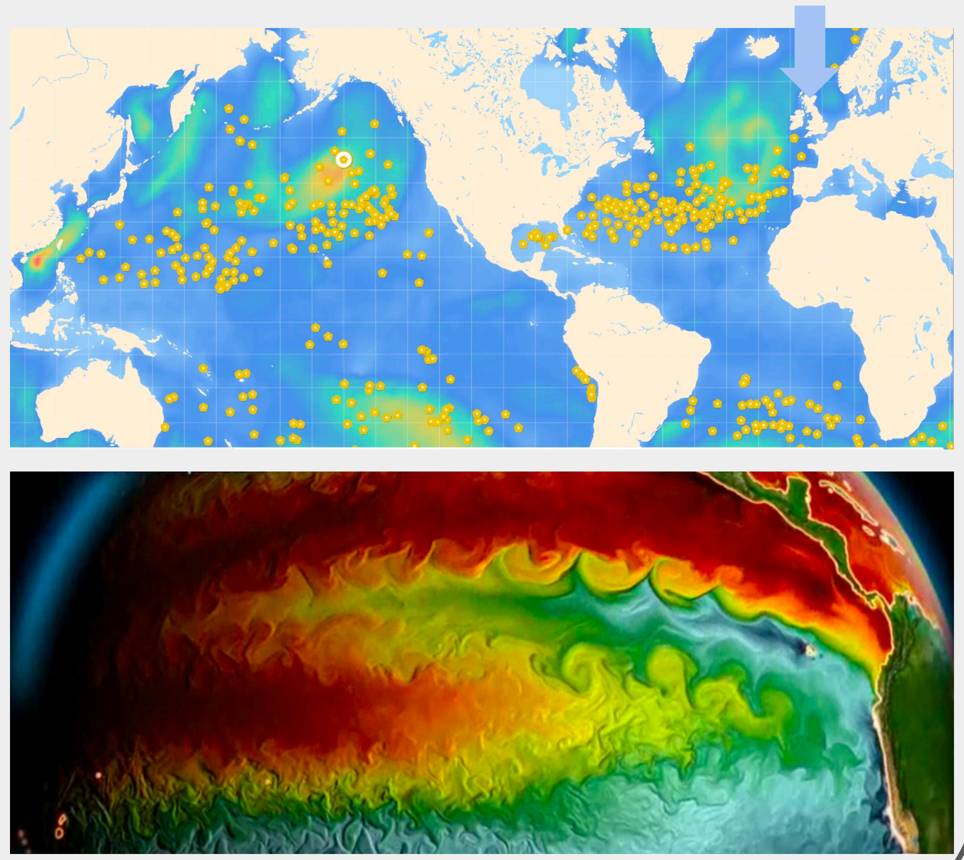


Use ensemble information to allow atmospheric observations (Spotter winds, surface pressure, scatterometer winds) to inform ocean surface wave analysis.

Coupled wave-atmos modeling/DA

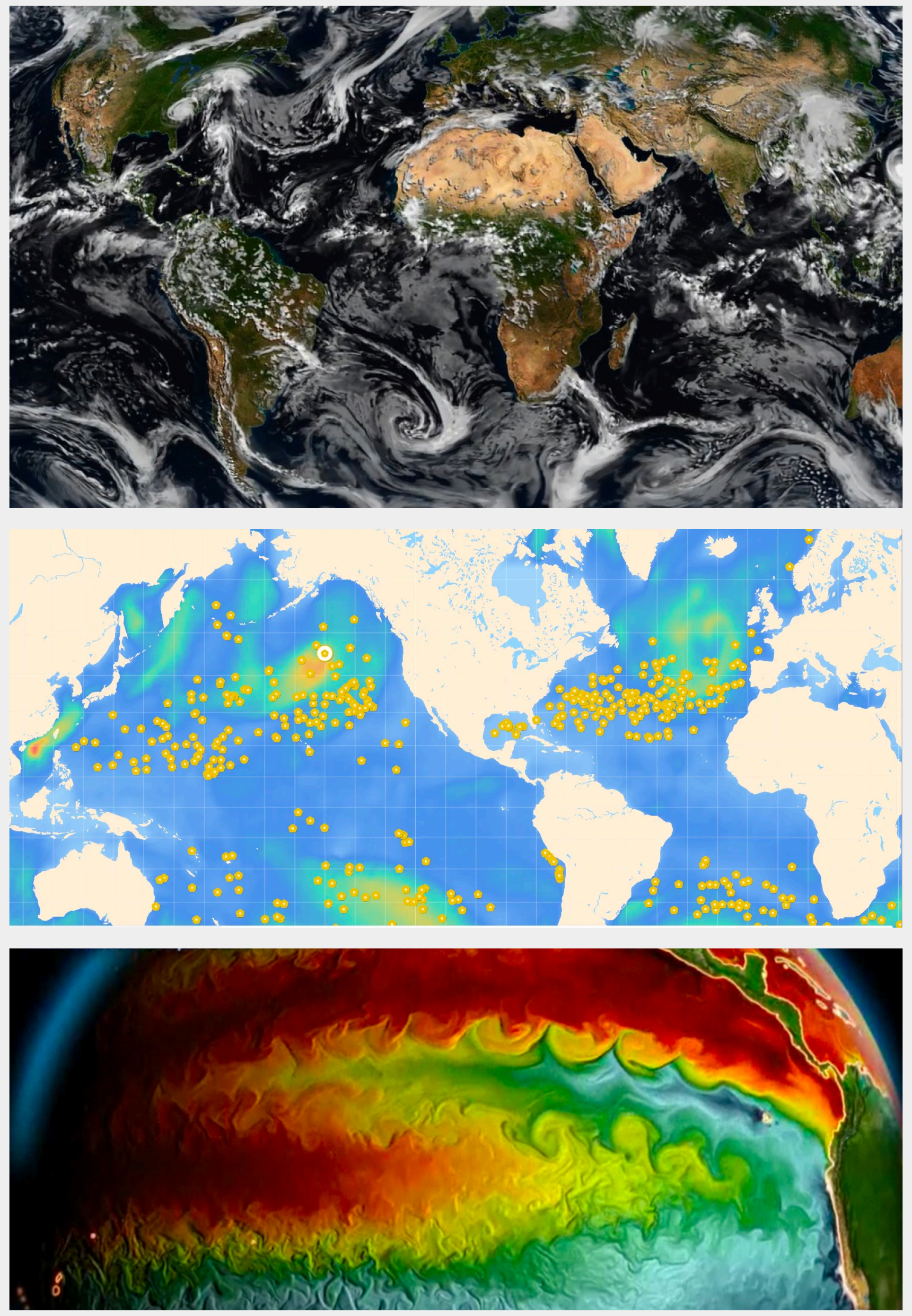


Coupled wave-ocean modeling / DA



"Forecast on Demand"

Coupled ocean-wave-atm forecast system (model, obs, DA)



Focus:

(1) *high accuracy at the air-sea interface*

(2) minimize cost

(3) flexible production

Conclusion

Coupled air-wave-sea interactions impact climate simulations

Waves produce non-local ocean mixing and affect heat and momentum fluxes between the ocean and atmosphere.

Global in situ observations help to constrain estimation of the air-sea interface

The Sofar Spotter network, combined with Argo, moored buoys, and satellite measurements helps to constrain state estimation and modeling at the air-sea interface.

Coupled Data Assimilation and Modeling amplify the benefit of these observations for forecasting and model development

Using these observations to initialize forecasts allows us to calibrate the wave, atmosphere, and ocean models to improve forecast skill.

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