BMKG

SynObs
UN Ocean Decade Project

GOOS | Ocean Observing Co-Design
by The Global Ocean Observing System

Recent Development of The Indonesian Coupled Atmosphere Wave Ocean Model (InaCAWO) through Data Assimilation and Ensemble Forecast System

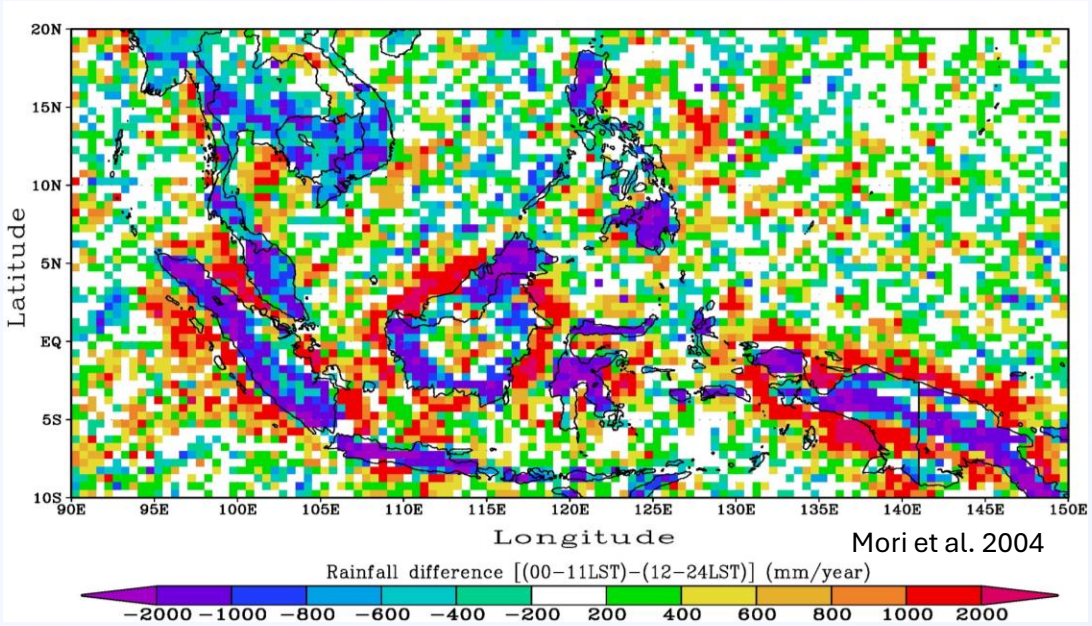
24 – 29 August 2026 | Mutsu, Japan

Dr. Furqon Alfahmi

Marine Meteorological Centre, BMKG

SynObs & Ocean Observing Co-Design, Joint International Workshop

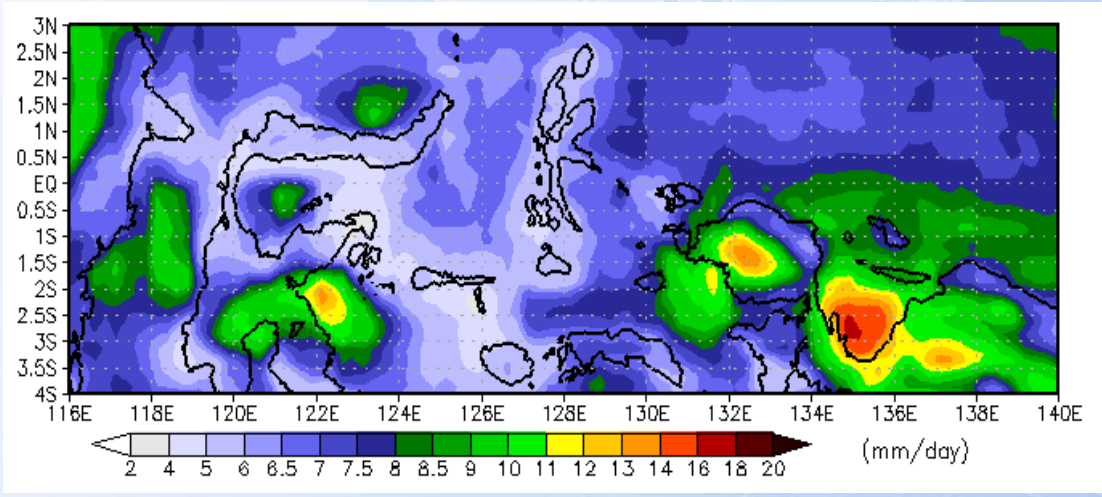
Motivations (Strong Air-Sea Interactions)



Mori et al. 2004

- Rainfall variability across Indonesia is strongly influenced by regional air–sea interaction phenomena, including the monsoon, MJO, IOD, ENSO, tropical cyclones, and variations in the intensity of the Indonesian Throughflow.

- Rainfall patterns across Indonesia (MC) closely follow the coastline, driven by strong diurnal convection generated by the convergence of land-sea breeze circulations along sea-breeze fronts.
- Concave coastlines and small strait widths generate peak rainfall in the ocean at night, while convex coastlines generate peak rainfall on land during the day.



Alfahmi et al. 2019

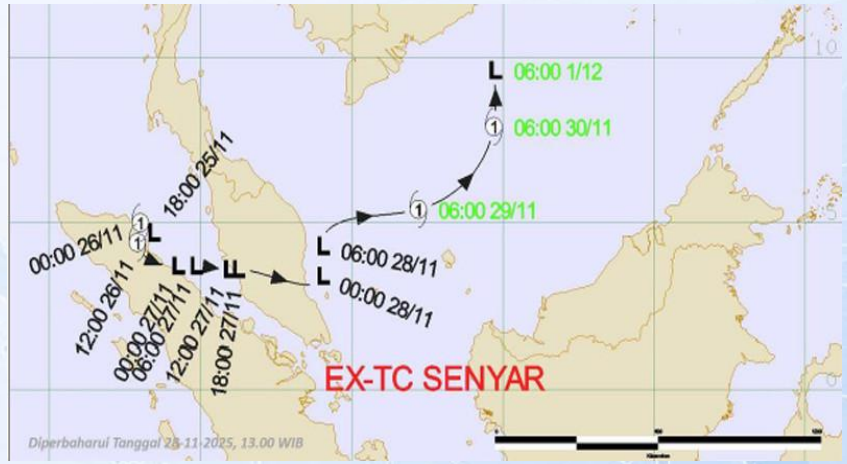
Motivations (Operational need)

- Recently, **Unusual low-latitude tropical cyclones** can develop over or near the Maritime Continent, such as Senyar (2025), Seroja (2021), and Vamei (2001) has strong impact.
- Tropical cyclones **generate multiple hazards at the same time**. Heavy rainfall and strong winds occur in the atmosphere, while high waves and storm surge develop over the ocean, followed by flooding and landslides over land.
- InaCAWO provides an integrated atmosphere–wave–ocean prediction system, allowing these related hazards to be forecast within **one coupled framework**.
- In daily operations, InaCAWO also supports BMKG's routine operational marine services, providing daily forecasts for 673 ports, 383 shipping routes, 42 offshore met-ocean areas, 330 onshore regional areas, and 72 offshore oil and gas rigs.

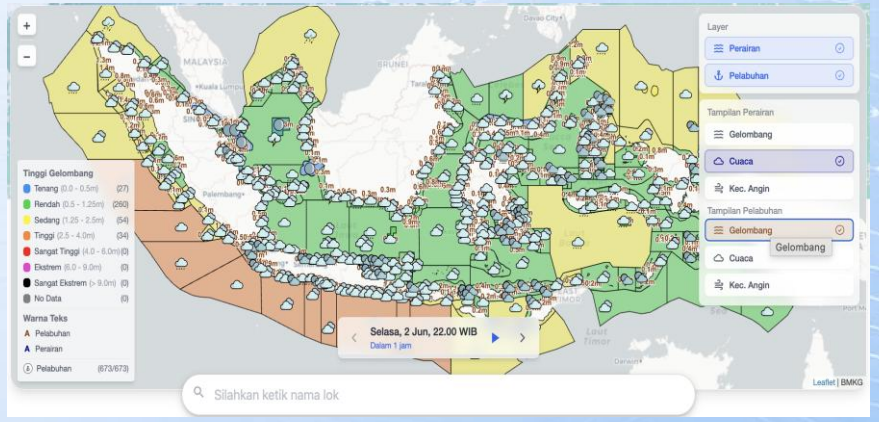
https://met-api.bmkg.go.id/apis/cawo-ocean-3d-raw/1

https://iklim-maritim.dirmar.org/cawo-static/

https://tropicalcyclone.bmkg.go.id/



https://maritim.bmkg.go.id/



Roadmap to improve prediction skills

- **High resolution model** (3 km - Indonesia, 1km – Small Staits , 200 m – Very Local Phenomena (Labuan Bajo)
- **Coupled Model** (InaCAWO – Indonesia Atmosphere Wave Ocean Models)
- **Assimilated with Hf Radar, Argo floats, Drifters, SSH Satellite, SWH Satellite** (In Progress, Target for Operational Implementation: Dec 2026)
- **Ensemble Forecast** (In Progress with 11 members, Target for Operational Implementation: Dec 2026)

2027: Full Evaluation | 2028: Parameter Tuning

Milestone BMKG-OFS

MRI-II
Wave Modeling
1998

Windwave-04
wave modeling
FC : GFS 1 deg.
2004

Windwave-05
wave modeling + Dasboard + Mapping tools
FC : GFS 1 deg.
2006

WavewatchIII WRF
wave modeling
FC : GFS 0.5 deg.+ WRF
2014

FVCOM + Delft3D
wave predictions + dynamical ocean + coastal flood
FC : Hycom, GFS
2016

InaNWP
WRFDA + radar + rason + synop
FC : GFS 1 km
2021

InaCAWOv0 (WRF, ROMS, SWAN)
wave, ocean, atmospheric modeling
FC : ECMWF, MERCATOR
2023

InaCAWOv1 + Assimilation + Ensemble (WRFDA, ROMS+DART, SWAN)
wave, ocean, atmospheric modeling
FC : ECMWF, MERCATOR
2026

S2S Wave Forecast
wind
FC : CSFV



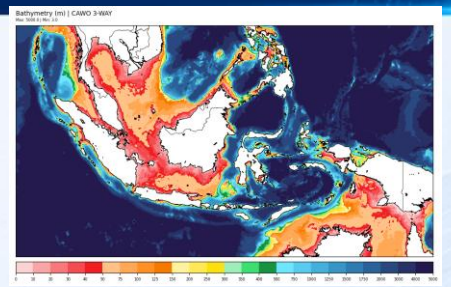
InaCAWO.v1 + NSF NCAR

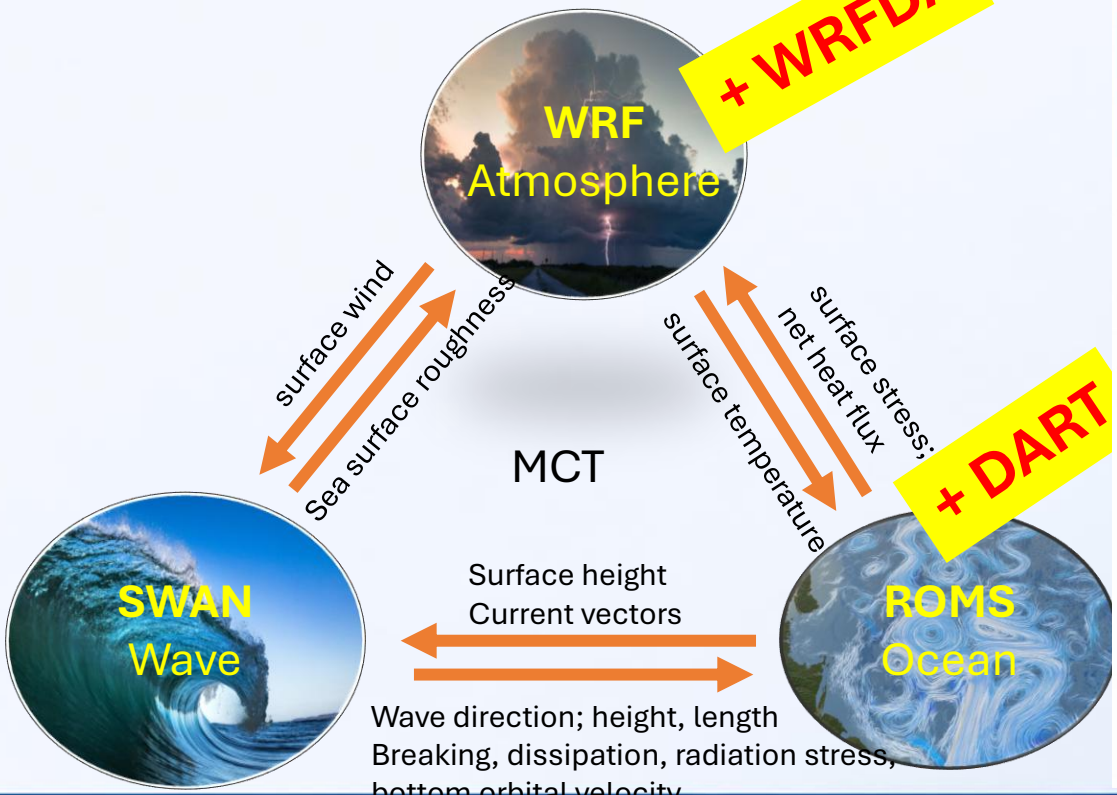
BMKG

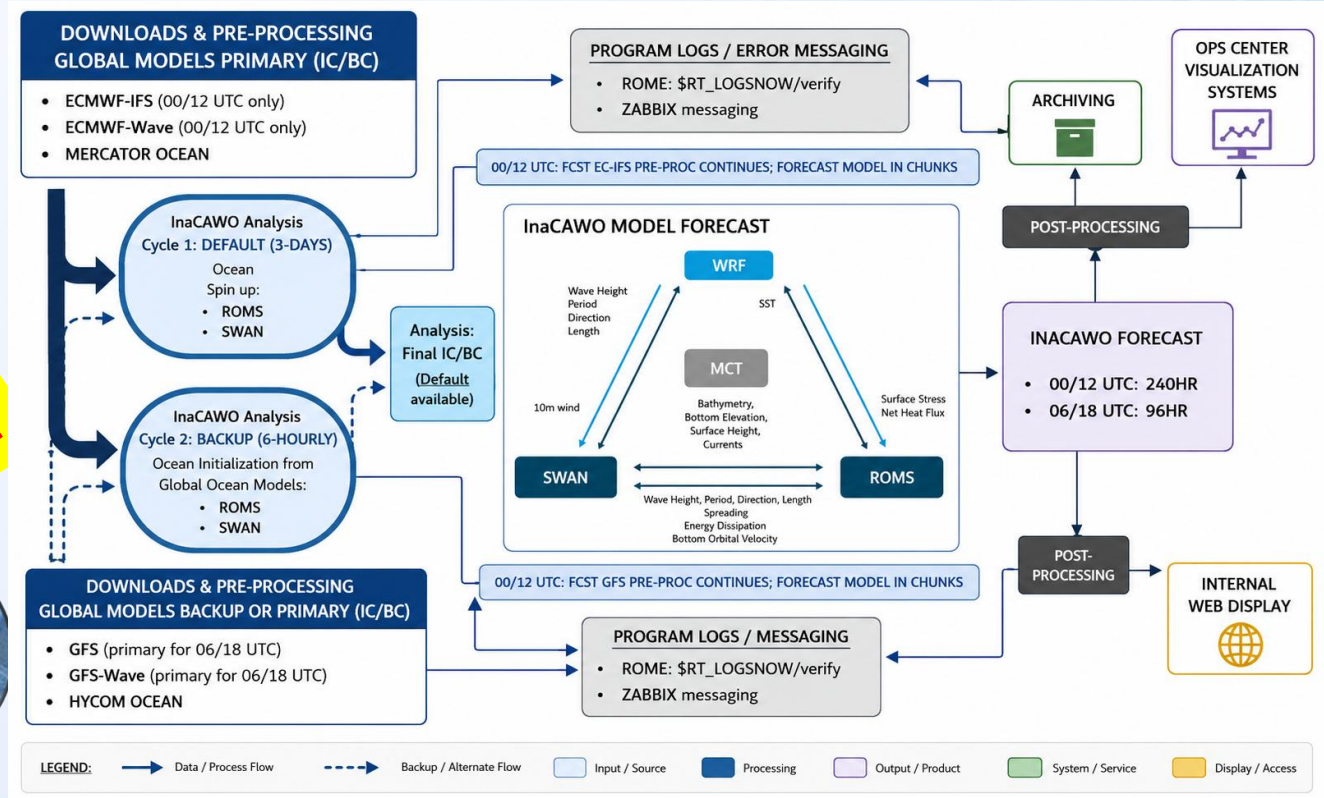
BARON WEATHER

NSF NCAR OPERATED BY UCAR

WRF	2041 x 1131 x 50	15s
ROMS	2036 x 1123 x 70	12s
SWAN	2036 x 1123 x 70	600s
Coupling interval		600s

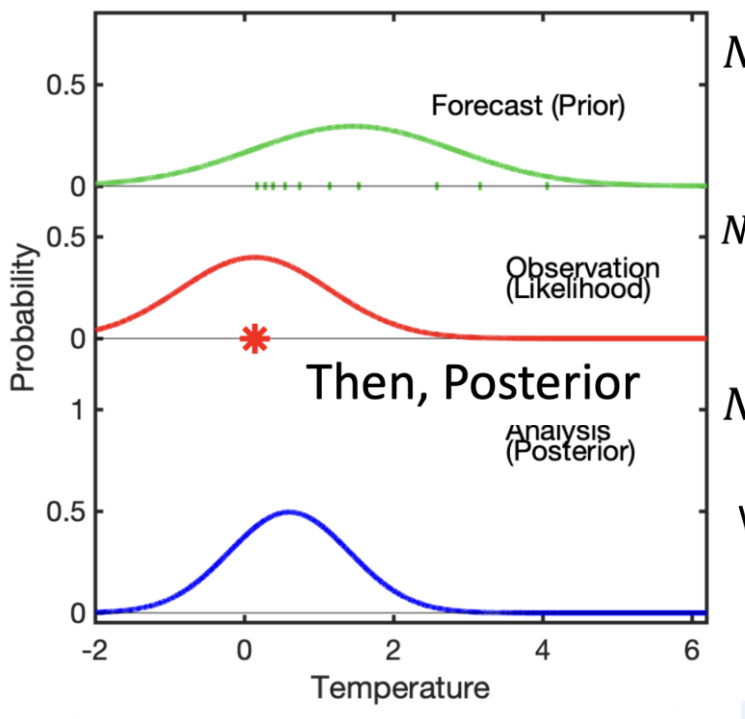






The Data Assimilation Research Testbed (DART)

- an NCAR open-source ensemble data assimilation framework that combines model forecasts and observations to produce improved initial conditions and better forecasts.
- DART takes an **ensemble of model forecasts (prior)**, compares them with observations, then updates the model analysis (posterior) to produce a better estimate of the real atmosphere or ocean.



$Normal(T_p, \sigma_p^2)$

$Normal(T_O, \sigma_O^2)$

$Normal(T_u, \sigma_u^2)$

With $\sigma_u^2 = (\sigma_p^{-2} + \sigma_O^{-2})^{-1}$ and

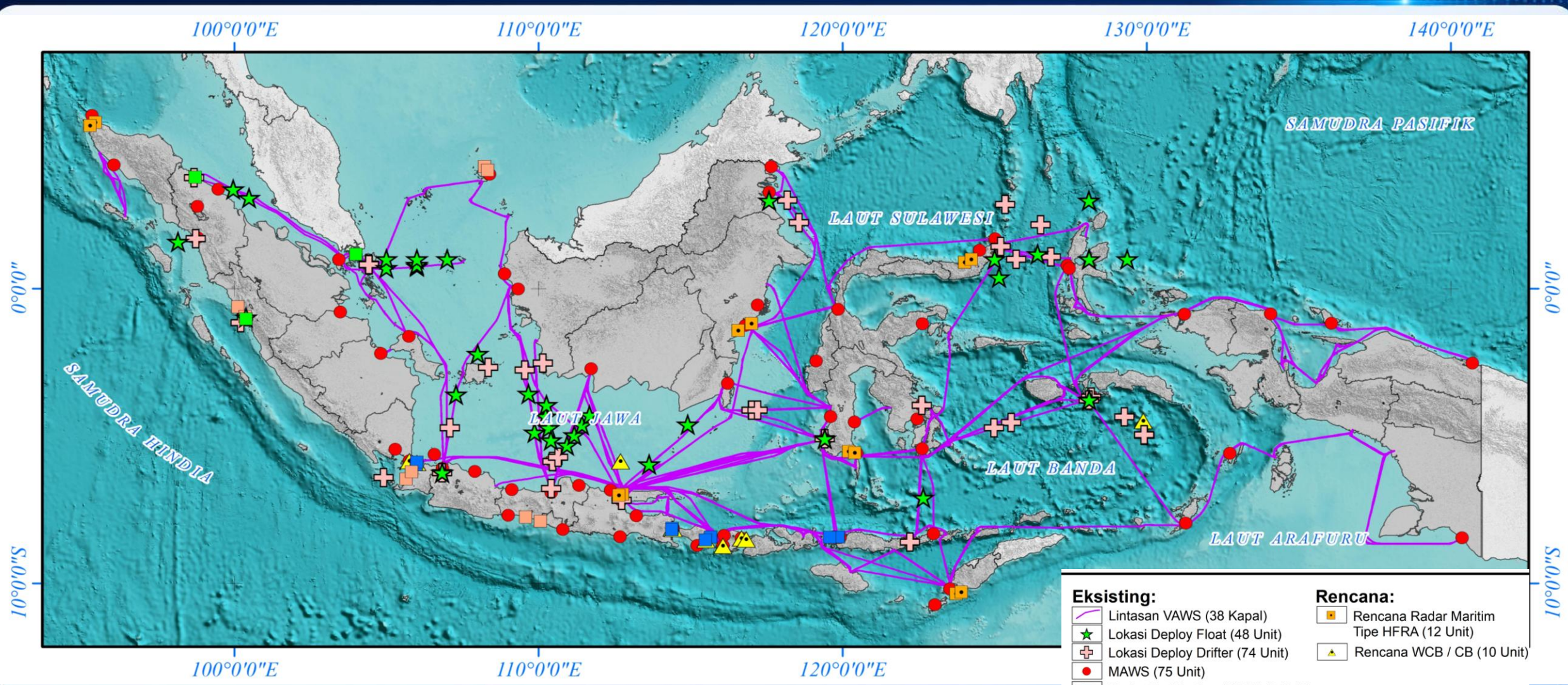
$T_u = \sigma_u^2(\sigma_p^{-2}T_p + \sigma_O^{-2}T_O)$

Posterior ∝ likelihood × prior

More DART tutorial

BMKG | InaCAWO OCEAN FORECAST SYSTEM

Ocean Observation Real-Time (2022 - 2026)



Assimilation Test

Available Ocean Observations:

1. **SVP:** Drifters – Surface Velocity Program – 3 drifter
   a. SST
   b. Surface currents (U, V)
2. **ARVOR:** Floats – in-situ profiles of T and S – 2 arvor
3. **HF Radar:** High Frequency radar – 1 HF radar
   a. Surface ocean currents (U, V)
   b. Radial velocities (Vr)
4. **Satellite SST:** Copernicus Marine Environment Monitoring Service (CMEMS) Level-3S blended SST
5. **Satellite SSH:** CMEMS Level-3 Near-Real-Time along-track SSH

SVP Drifter

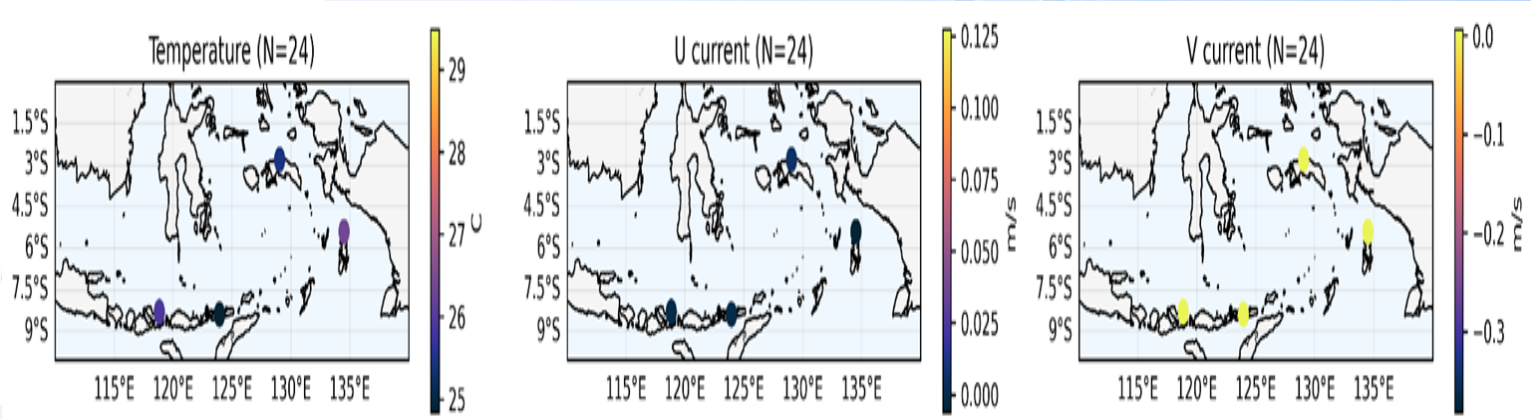
Convert to Sequence File `./svp_to_obs`

```
 obs_sequence
obs_type_definitions
           3
          17 DRIFTER_U_CURRENT_COMPONENT
          18 DRIFTER_V_CURRENT_COMPONENT
          20 DRIFTER_TEMPERATURE
  num_co                  1  num_qc                  1
  num_obs:           72  max_num_obs:           72
observation
QC
  first:            1  last:           72
 OBS            1
   27.1100000000000
  0.000000000000000E+000
          -1           2          -1
obdef
loc3d
     2.347596998297021       -0.9406626536548642E-01     0.000000000000000      -1
kind
          20
 36000     155141
  4.000000000000001E-002
 OBS            2
  0.000000000000000E+000
  0.000000000000000E+000
          1           3          -1
obdef
loc3d
     2.347596998297021       -0.940662653654864 2E-01     0.0
kind
          17
 36000     155141
  1.000000000000000E-002
```

types

varians

- Converter will write 72 observations
- Types: 3
- The observation error standard deviations, :
  - 0.2 C for SST
  - 0.1 m/s for U, V



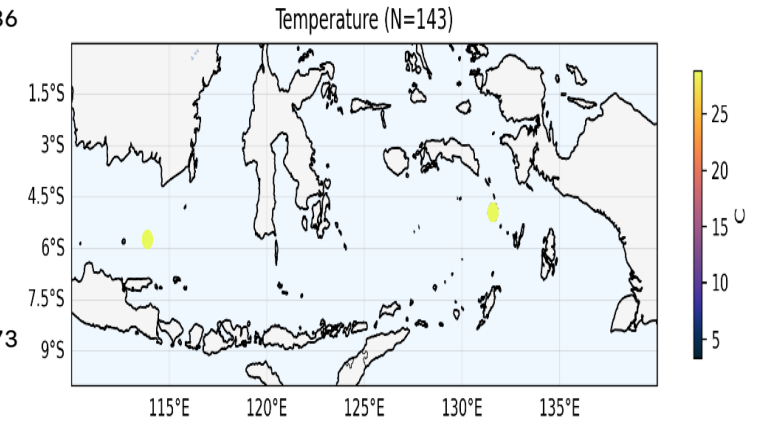
Profiling Floats (ARVOR)

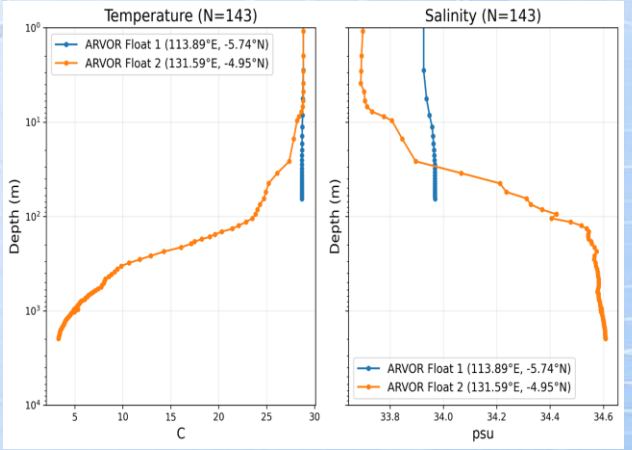
Convert to Sequence File `./arvor_to_obs`

```
 obs_sequence
obs_type_definitions
           2
          15 FLOAT_SALINITY
          16 FLOAT_TEMPERATURE
  num_copies:            1  num_qc:            1
  num_obs:             286  max_num_obs:          286
observation
QC
  first:               9  last:             127
 OBS            1
   4.95800000000003
  0.000000000000000E+000
         286          120           -1
obdef
loc3d
     2.296735485900028       -0.8630798595216292E-01     1030.475486
kind
          16
 14450     155142
  4.000000000000000E-004
 OBS            2
   4.78100000000001
  0.000000000000000E+000
         120          121           -1
obdef
loc3d
     2.296735485900028       -0.8630798595216292E-01     1030.079673
kind
          16
 57650     155142
  4.000000000000000E-004
```

varians

- SST will be converted K -> C
- Converter will write 286 observations
- Profiling floats are highly accurate. ARVOR CTDs are precise; obs error defaults:
  - 0.02 C for T
  - 0.02 psu for S





HF Radar

The converter supports two data families: `./hf_to_obs`

- Totals (vector currents): gridded U, V
  - Observation errors are provided with the incoming data
- Radials (single-site line-of-sight currents): curvilinear grids with bearing angle & range

$$Vr = Ucos(\phi) + Vsin(\phi)$$

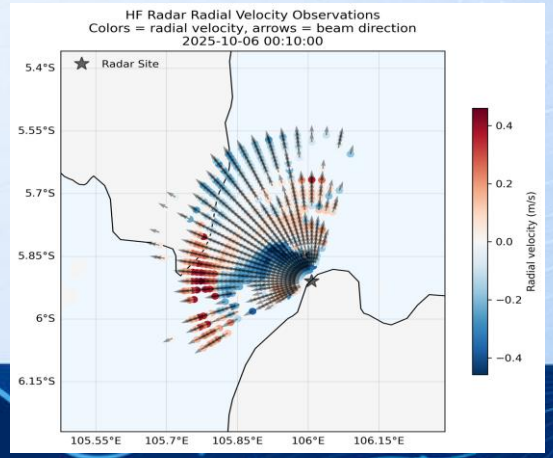
  - Observation errors are range dependent (mimic degradation)

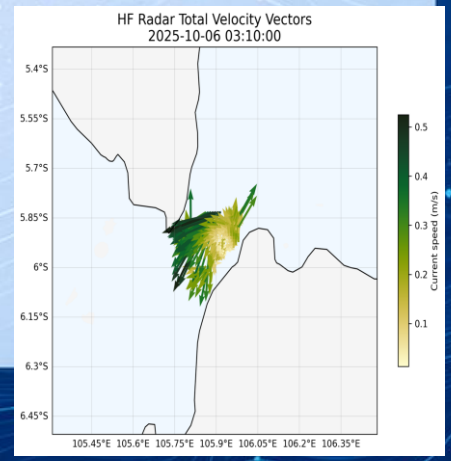
$$\sigma(r) = \sigma_0 \left(1 + \alpha \frac{r}{r_{max}}\right), \quad \sigma_0 = 0.15\ \mathrm{m/s}, \quad \alpha \approx 1$$

- All errors are eventually clamped: 0.001 – 0.4 m/s
- QC filter – 0 < flag < 1024
- Velocities are converted to m/s
- Converter will write 6,471 observations

```
 obs_sequence
obs_type definitions
          3
         61 HFRADAR_U_CURRENT_COMPONENT
         62 HFRADAR_V_CURRENT_COMPONENT
         63 HFRADAR_RADIAL_VELOCITY
  num_c                                1
  num_obs:          6471  max_num_obs:          6471
observation
QC
  first:            1  last:         6471
 OBS            1
  3.405999898910522E-002
  0.000000000000000E+000
          -1           2          -1
obdef
loc3d
     1.849769674874062       -0.1033755157457358        0.000000000000000     -1
kind
          63
HFRADAR
InsID
        1361
angle
   240.000000000000
            1
   600      155141
  2.600160803059251E-002
```

varians

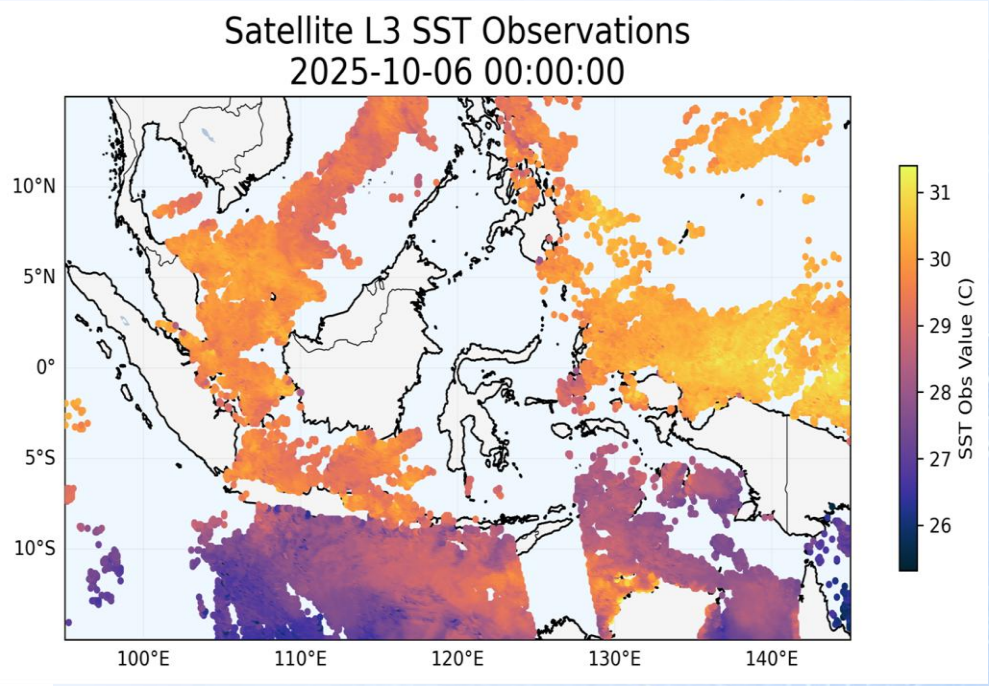




CMEMS SST L3S

Convert to Sequence File `./cmems_sst_to_obs`

```
 obs_sequence
obs_type definitions
          1
          53 SATELLITE_BLENDED_SST
  num_copies:            1  num_qc:            1
  num_obs:       109906  max_num_obs:       109906
observation
QC
  first:        36639  last:       109906
 OBS            1
   26.5200134277344
  0.000000000000000E+000
       81828           2          -1
obdef
loc3d
     1.828232391464060       -0.2609267198442009         0.000000000000000     -1
kind
          53
     0     155141
  8.352100261831286E-002
 OBS            2
   26.7000061035156
  0.000000000000000E+000
           1           3          -1
obdef
loc3d
     1.831722996704827       -0.2609267198442009         0.000000000000000     -1
kind
          53
     0     155141
  6.200099899077416E-002
```



- The incoming SST data is converted from K -> C
- Observation errors come in with the raw data. The converter caps them at 0.05 C

CMEMS SSH L3 NRT

Convert to Sequence File `./cmems_ssh_to_obs`

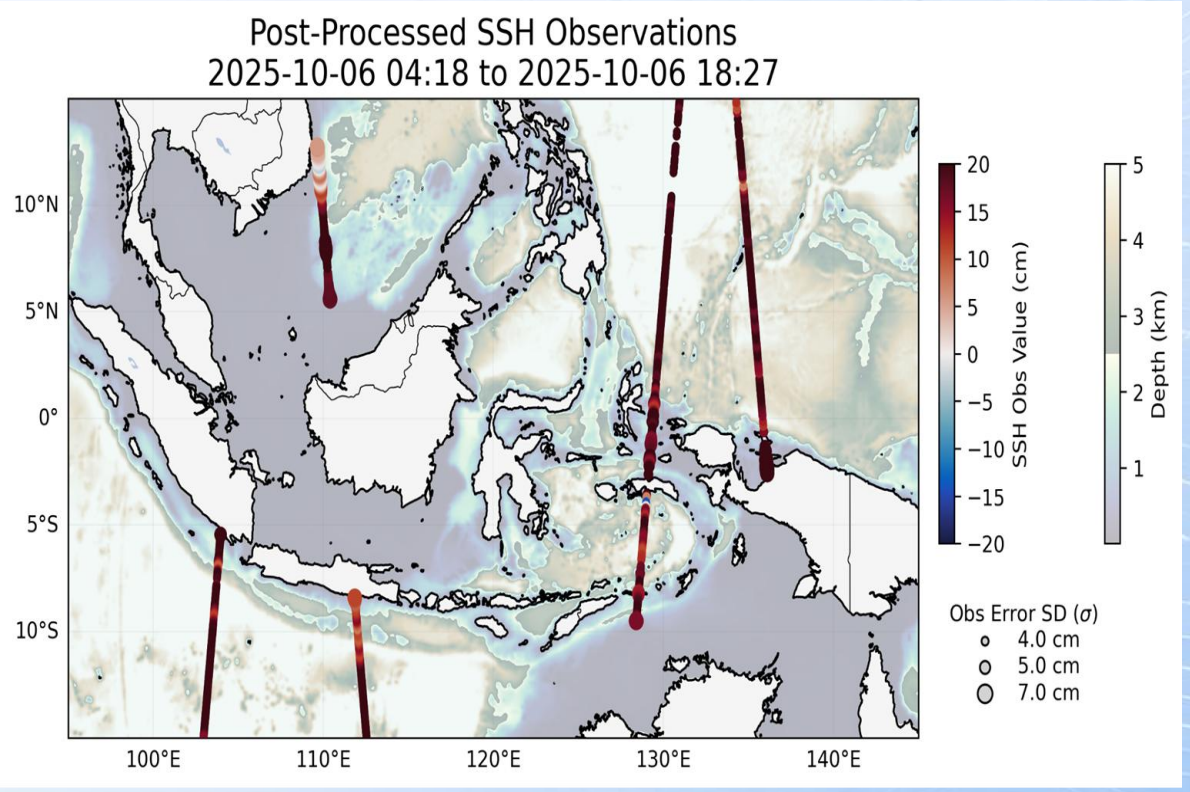
Observation Errors: This CMEMS data product does not provide estimate of the obs errors. A post-processing script within the DART repo can be used to:

- Remove observations located in shallow-water regions, and
- Apply depth-dependent observation error model

$$\sigma = \sigma_{min} + (\sigma_{max} - \sigma_{min}) \exp\left(-\frac{h}{h_0}\right),$$

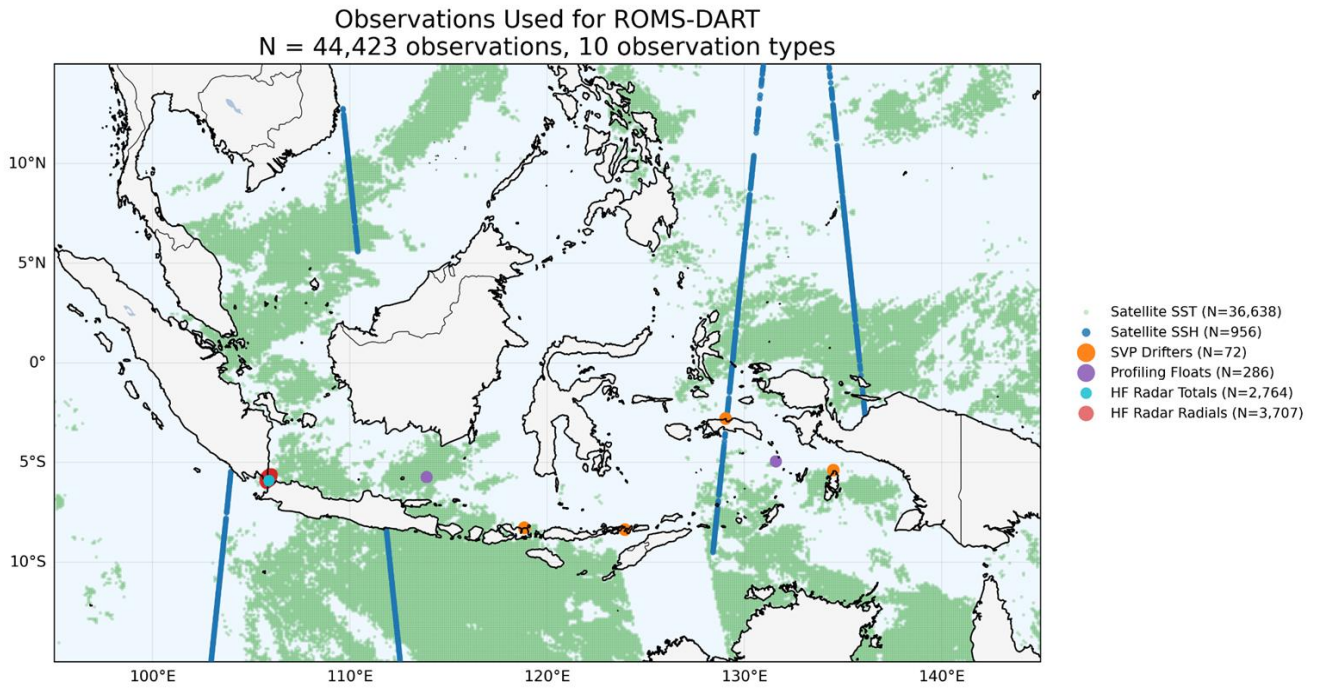
h_0 : transition depth scale

- Converter will write a lot of data (~1k)
- VERT: 0.0 (surface)
- Obs error Var: 0.016 m (0.04*0.04)
- Types: 1 SATELLITE_SSH



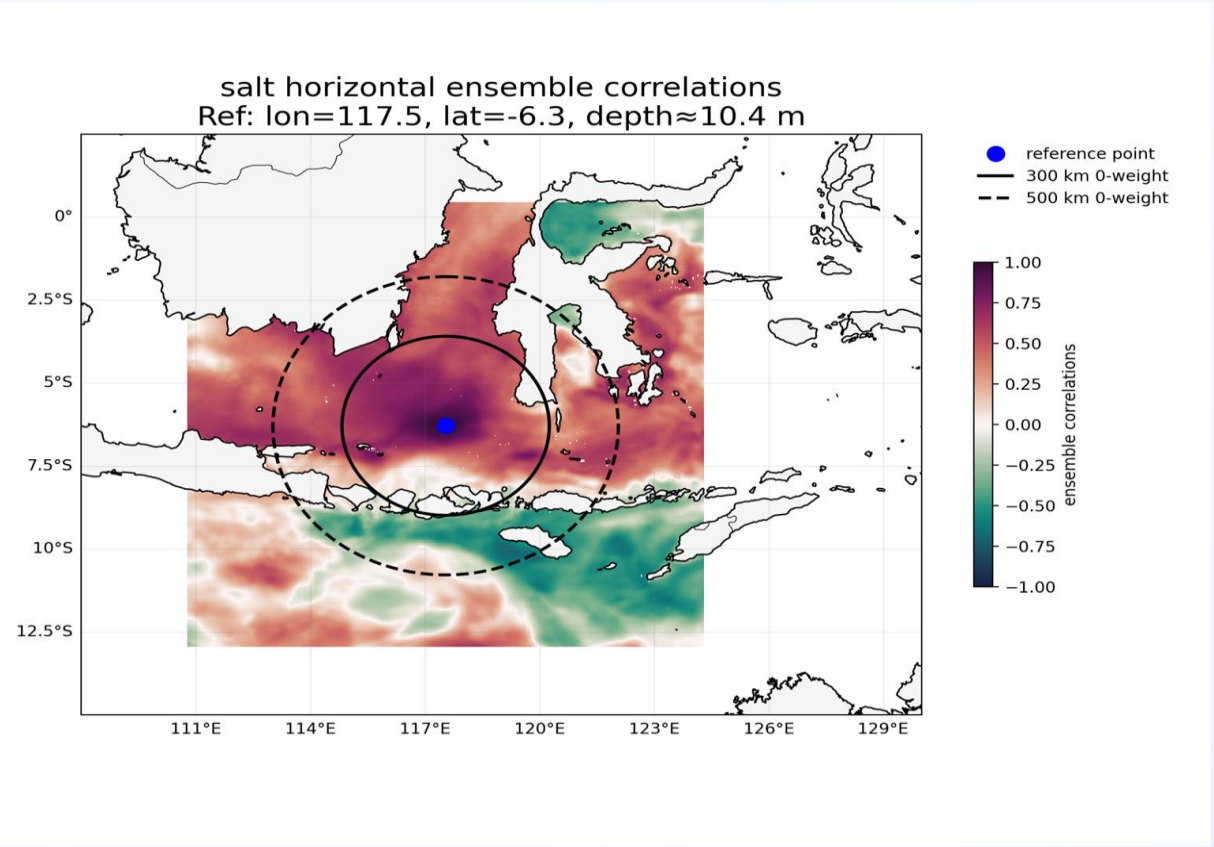
Merging all Observations

- Run the program: ./obs_sequence_tool
- Inspect the output messages
- 10 Types
- Total of 44,423 obs

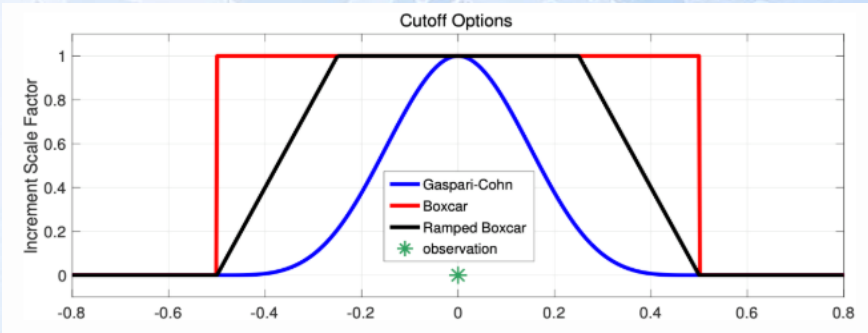



```
Processing sequence file
../../../../models/ROMS_rutgers/work/obs_seq_all.out
   Data Metadata: observation
     QC Metadata: QC
  First obs time: day=155137, sec=7250
   Gregorian day: 2025 Oct 02 02:00:50
   Last obs time: day=155145, sec=57650
   Gregorian day: 2025 Oct 10 16:00:50
   Number of obs processed  :                  44423
   ------------------------------------------------
                      FLOAT_SALINITY      143 obs
                 FLOAT_TEMPERATURE        143 obs
       DRIFTER_U_CURRENT_COMPONENT         24 obs
       DRIFTER_V_CURRENT_COMPONENT         24 obs
                 DRIFTER_TEMPERATURE       24 obs
             SATELLITE_BLENDED_SST      36638 obs
                      SATELLITE_SSH        956 obs
       HFRADAR_U_CURRENT_COMPONENT       1382 obs
       HFRADAR_V_CURRENT_COMPONENT       1382 obs
           HFRADAR_RADIAL_VELOCITY       3707 obs
```

Localization



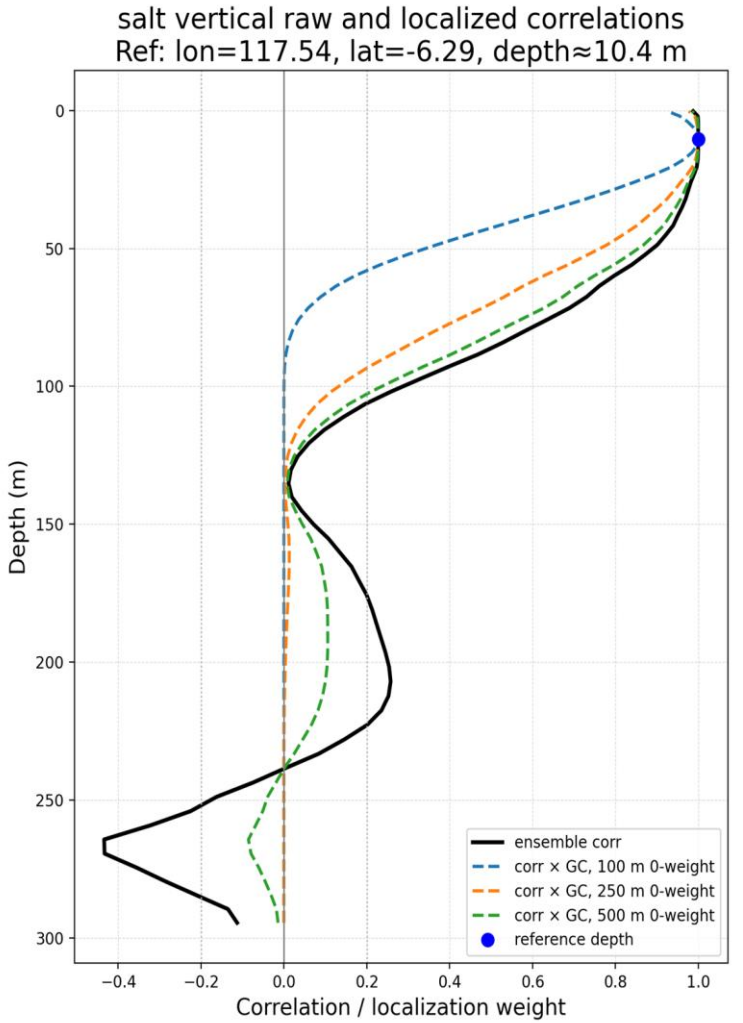
- Controls how far an observation can correct the model. The correction is strongest near the observation and becomes weaker with distance
- Impossible for one point observation in Java Sea have impact to indian ocean
- Gaspari-Cohn function

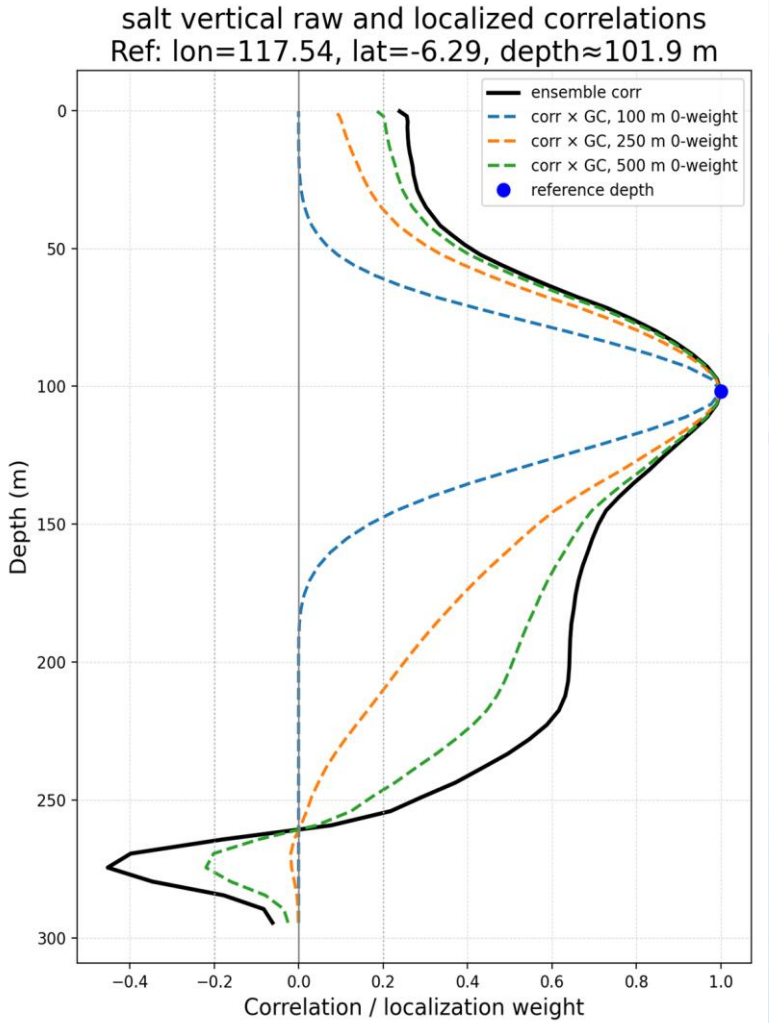


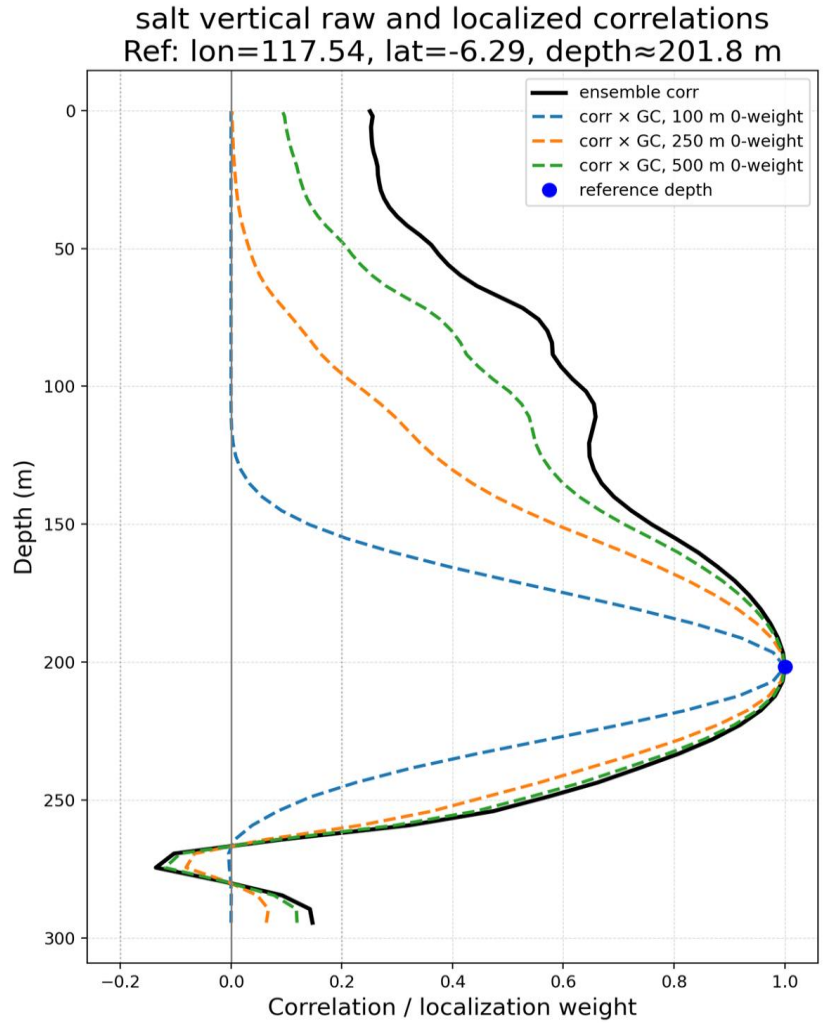
- (*input.nml*) For an effective localization radius of 300 km, set the cutoff to 0.0236
  - 2(0.0236)(6371) ~ 300 km

- 300 km seems appropriate
- A larger 500 km radius could potentially include areas with noisy correlations

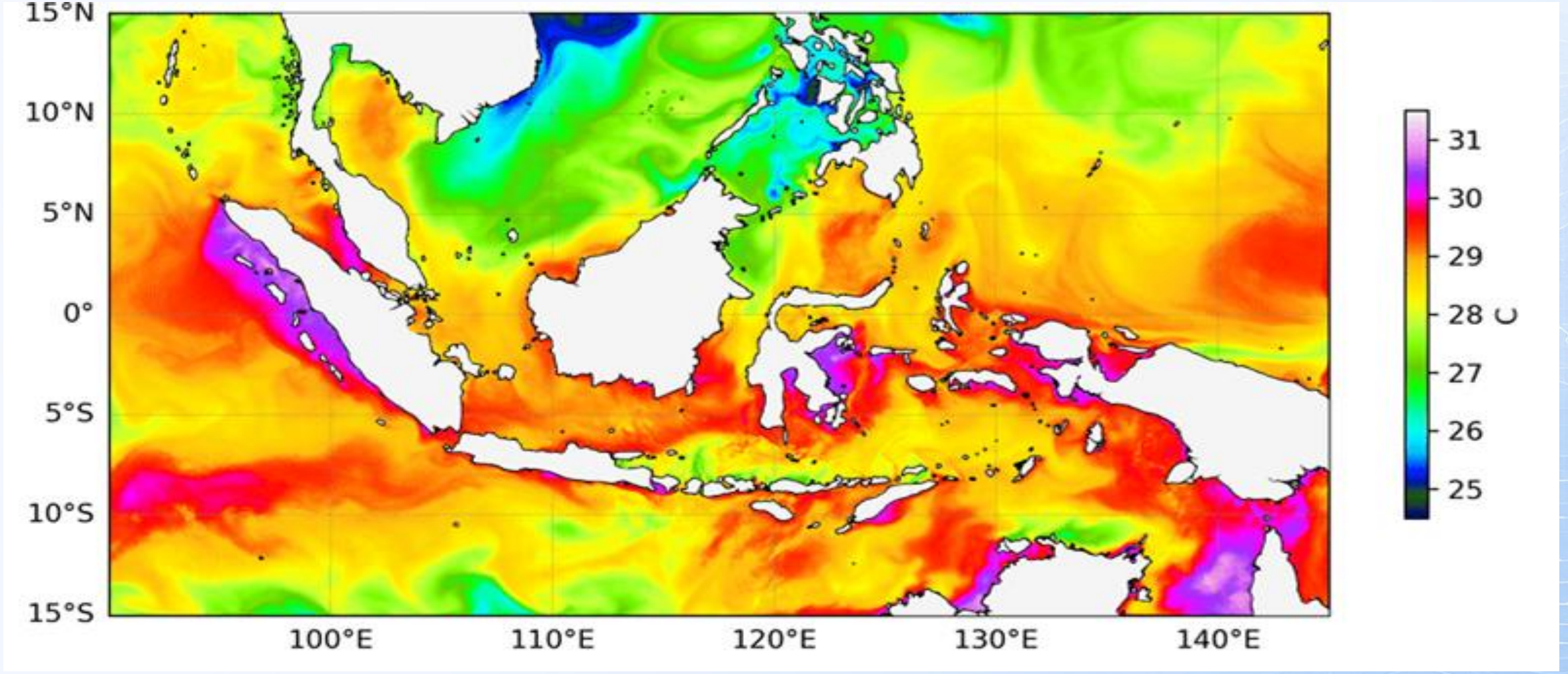
Vertical Localization



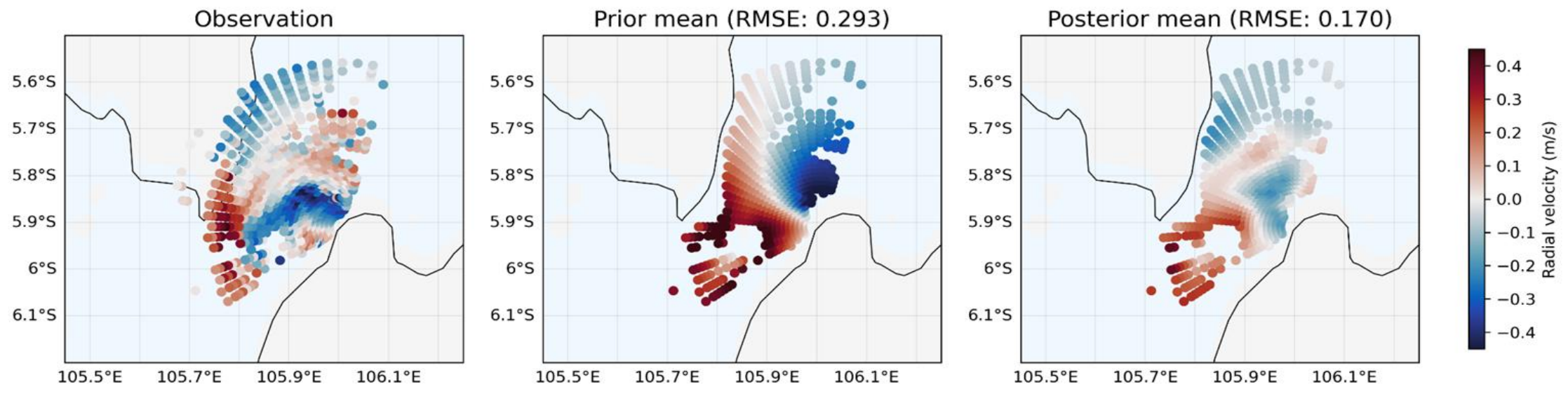




ROMS Ensemble (80 Members)



Impact of HF Radars



The prior model : the general **dipole structure of the surface current,** with **positive radial velocities in the western sector and negative velocities toward the east**.

Overestimated, and the spatial pattern is **much smoother** than the observations

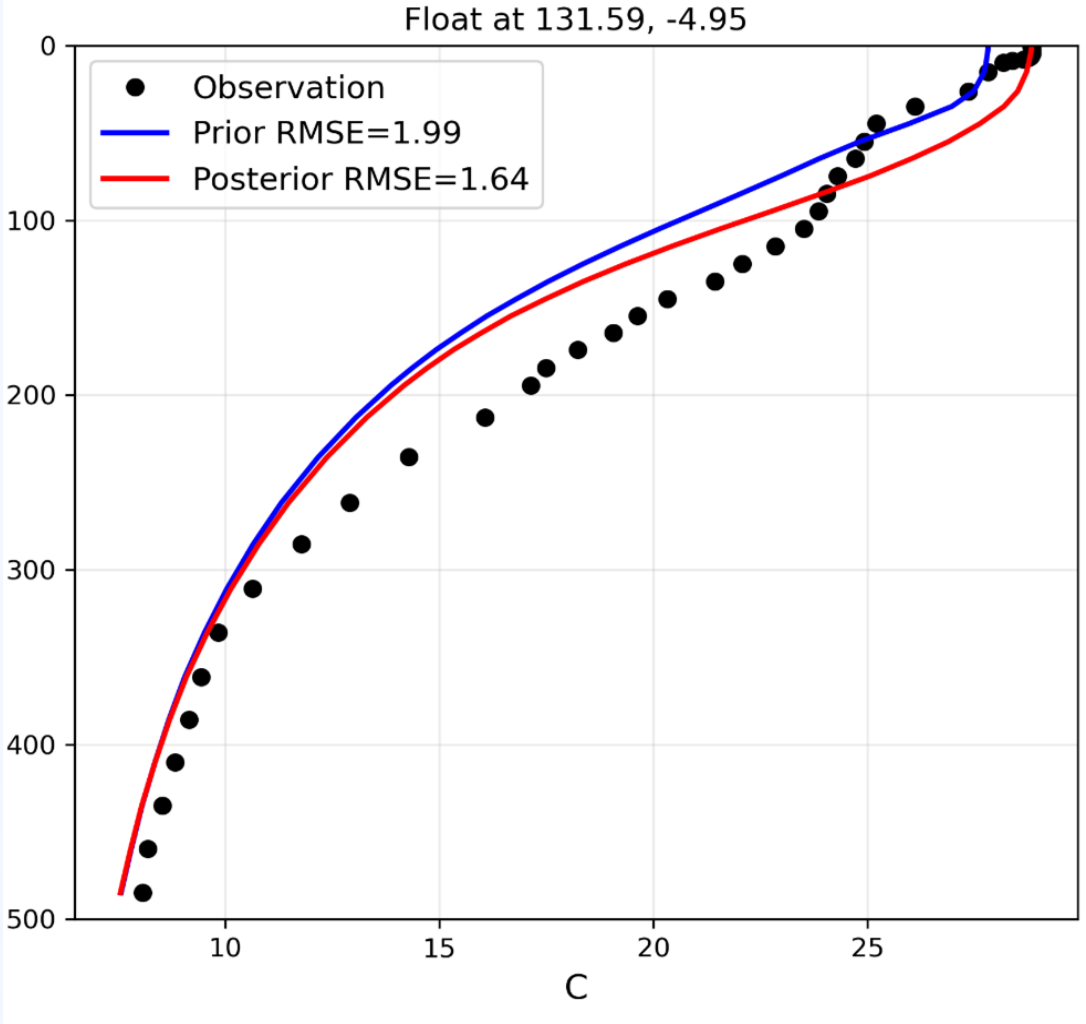
This results in a prior RMSE of **0.293 meters per second**

Posterior model : **clear adjustment** in both the magnitude and spatial distribution of the surface currents

The excessively **strong positive and negative velocities are reduced**, and the **transition between the two current regimes becomes more consistent with the observations**

The RMSE decreases from **0.293 to 0.170 meters per second**, corresponding to an error reduction of about **42 percent**.

Impact of Argo Floats



Both the prior and posterior **can reproduce this general pattern.**

Near the surface, the temperature is around **28 C**, and then it decreases quickly through the thermocline. At around **500 meters**, the temperature is about **8 degrees Celsius**

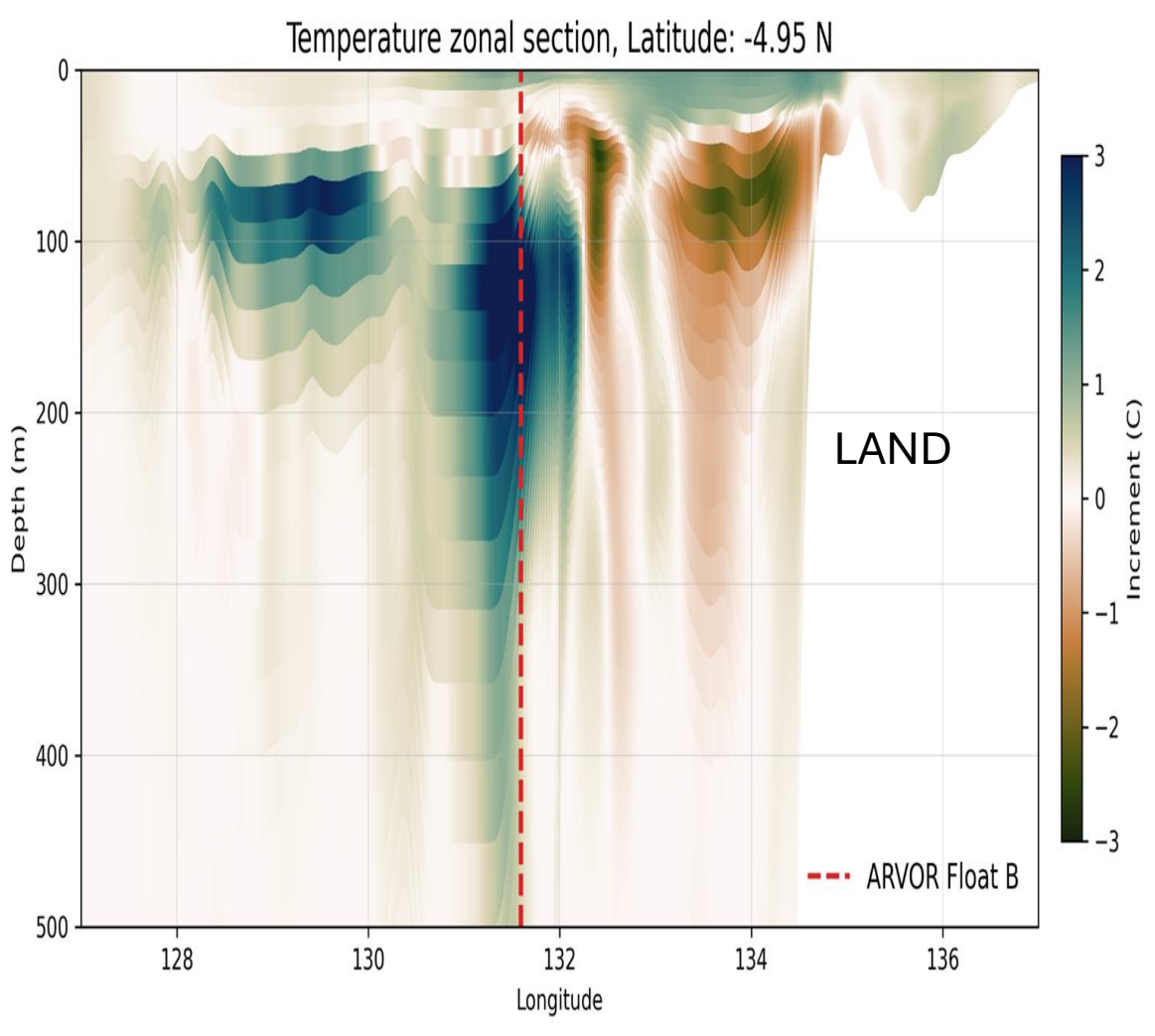
However, the prior is too cold, especially between around **100 and 300 meters**.

After assimilation, **the posterior becomes warmer and moves closer to the observations**

The RMSE decreases from **1.99 to 1.64 degrees Celsius**, which is about an **18 % improvement**

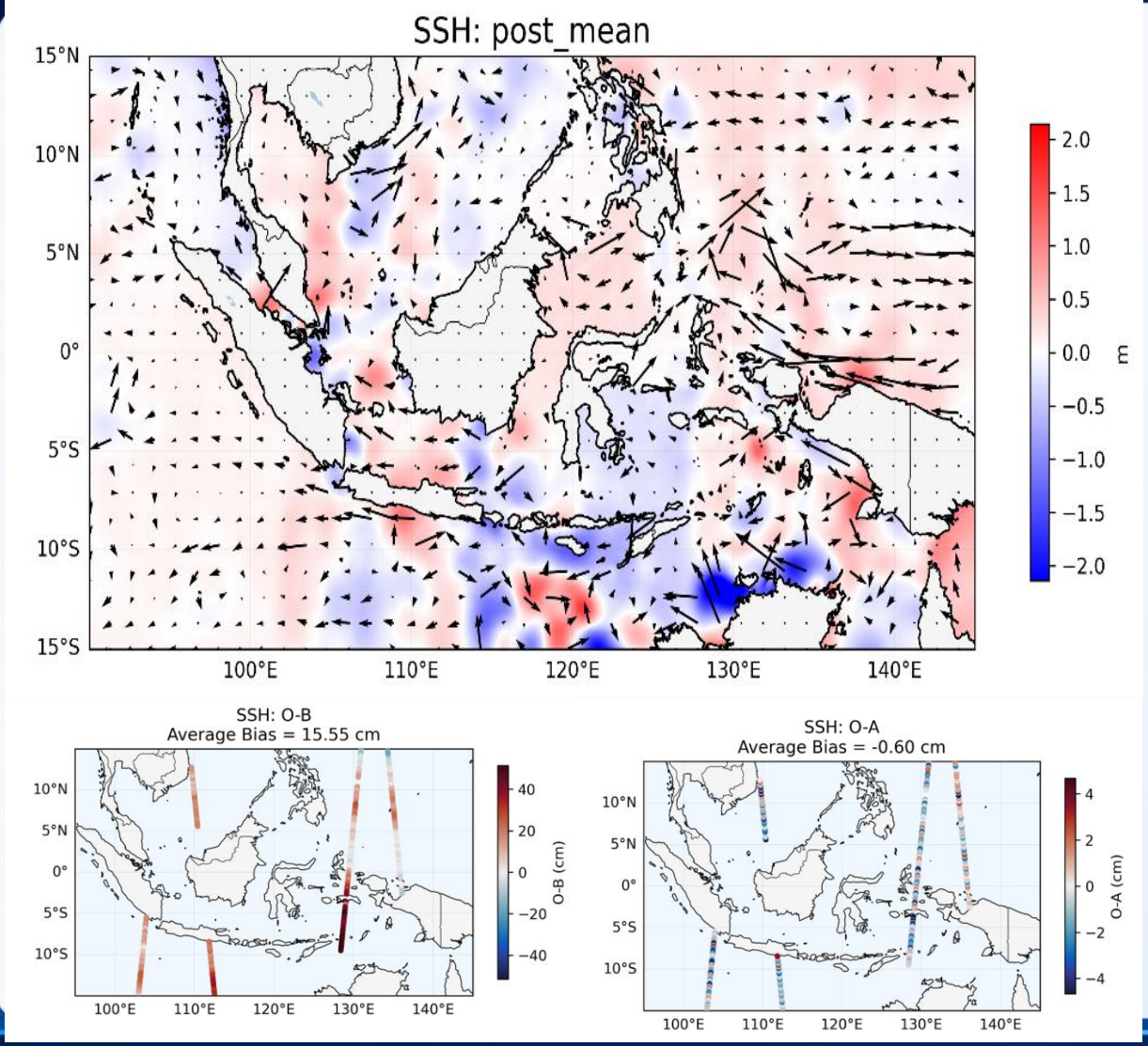
Assimilation improves the deep-ocean temperature profile and reduces the cold bias in the thermocline, although some errors still remain

Evaluate Vertical Impact



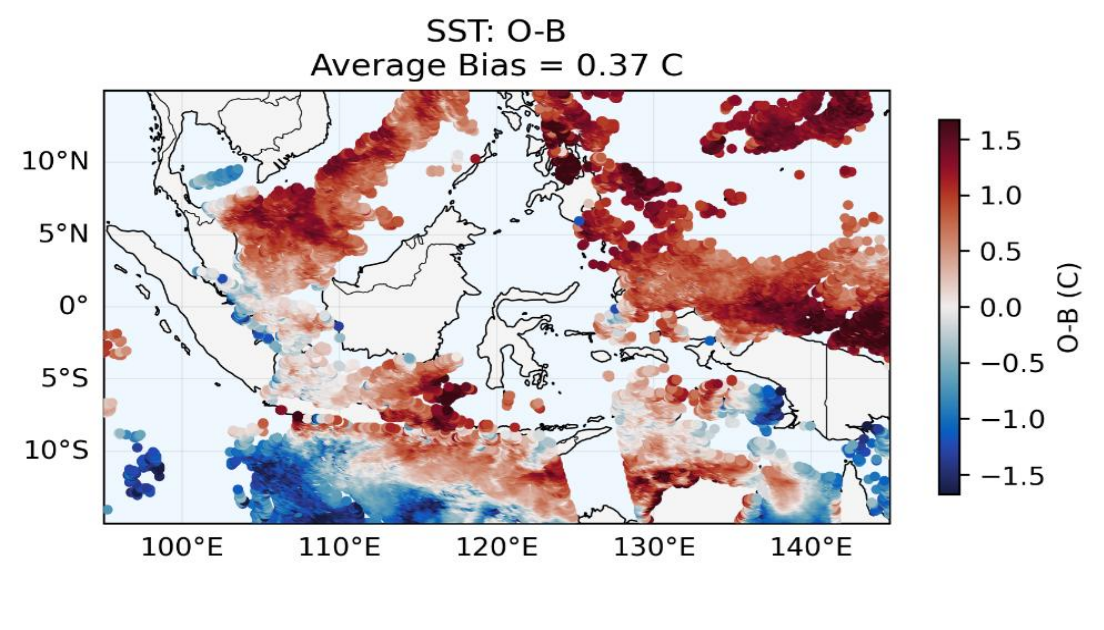
- The strongest correction appears near the float, especially around the thermocline. the posterior becomes around **2 to 3 C warmer** than the prior.
- The effect can extend down to almost **500 meters**
- DART spread the information from the observation through the water column using the ensemble covariance
- **One profiling-float observation can influence not only the observation point, but also the surrounding area and deeper ocean layers**

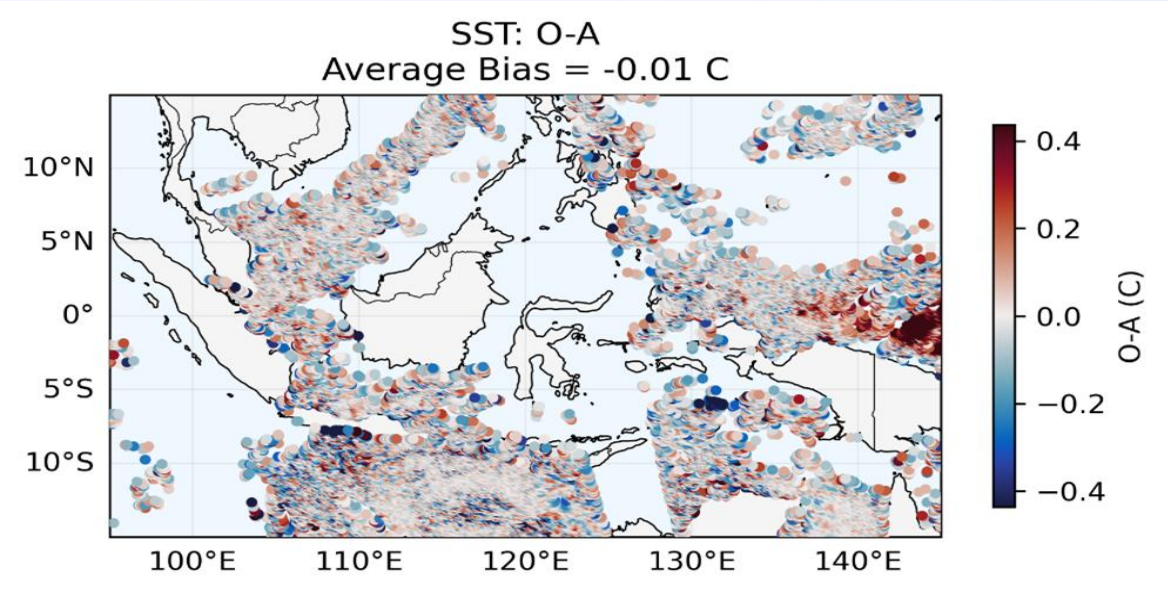
Evaluate the SSH impact



- Strong SSH variation across the Indonesian seas, with both positive and negative values
- Where the SSH changes more strongly, we can also see stronger currents, especially **south of Java and Nusa Tenggara, and in parts of eastern Indonesia**
- These high and low SSH patterns may be related to **eddies, fronts, and regional circulation**
- The assimilation successfully reduced the SSH bias until ~96%, from 15.55 cm to −0.6 cm
- SSH assimilation is especially powerful because correcting sea level also modifies the pressure gradients that control the ocean circulation

Evaluate the SST impact





- Prior SST shows a mean cold bias of +0.37°C in O–B space.
- After assimilation, the mean bias decreases to −0.01°C.
- SST assimilation reduces the mean bias by ~97% and brings the posterior much closer to observations.

Conclusions

- **InaCAWO integrates atmosphere, wave, and ocean models** to better represent the strong air–sea interaction over the Indonesian Maritime Continent.
- **DART successfully combines ROMS ensemble forecasts with multiple ocean observations**, including HF Radar, drifters, Argo floats, satellite SST, and SSH.
- **HF Radar assimilation significantly improves surface currents**, reducing RMSE from **0.293 to 0.170 m/s**, or about **42%**.
- **Argo float assimilation improves the subsurface temperature structure**, especially around the thermocline, with RMSE reduced from **1.99°C to 1.64°C** at the deep-ocean location.
- **Satellite assimilation strongly reduces model bias**: SST bias decreases from **+0.37°C to −0.01°C (~97%)**, while SSH bias decreases from **+15.55 cm to −0.60 cm (~96%)**.
- Overall, the first results show that **data assimilation can bring ROMS closer to the observed ocean state**, although further evaluation, localization tuning, and independent forecast verification are still needed before full operational implementation


Thank You