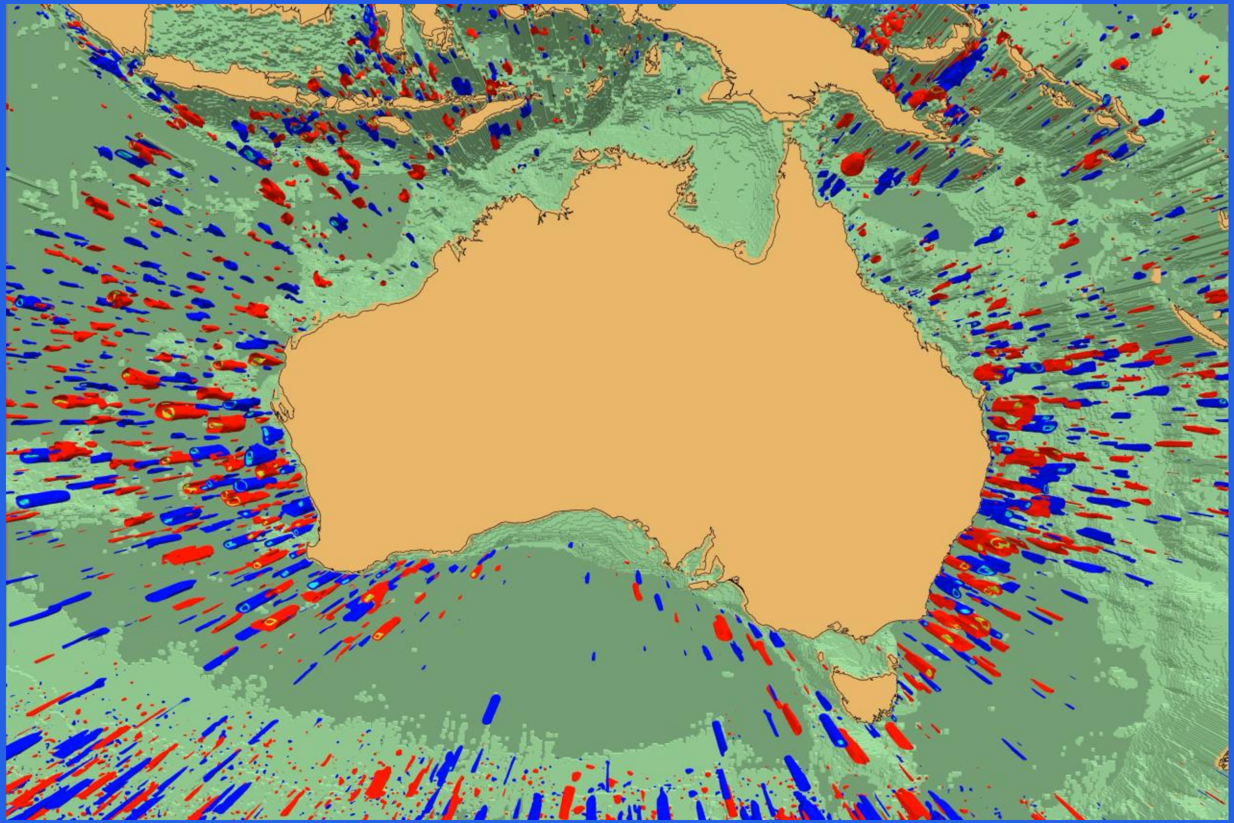
The Bureau of Meteorology

An operational ensemble Kalman Filter global ocean forecasting system OceanMAPSv4

Gary Brassington

Pavel Sakov, Prasanth Divakaran, Saima Aijaz, Mirko Velic, Chris Bladwell, Matt Chamberlain, Xinmei Huang, Roy Thompson, Mikhail Entel, Ahmad Khan



Bluelink Ocean Forecasting

Overview

Bluelink since 2002 – 20+ years of ocean forecasting science

Why Bluelink? Defence and National benefit (Commercial/Public/Research)

In 2019 we faced a design choice

Higher model resolution and 3D DA (preparation for SWOT)

Persist model resolution and implement 4D DA

4D DA – Asynchronous Hybrid-DLETKF

- EnKF vs EnOI benefits
- OceanMAPSv4 performance

Conclusion

OceanMAPSv4.1i

System

Model
OFAM3 (MOM5)
75S-75N, 0-360
0.1° x 0.1°, 51 z*-levels (5m top cell)

Data assimilation
EnKF-C / Hybrid-DLETKF
48 dynamic members
144 low-mode members
FGAT, Restart initialisation

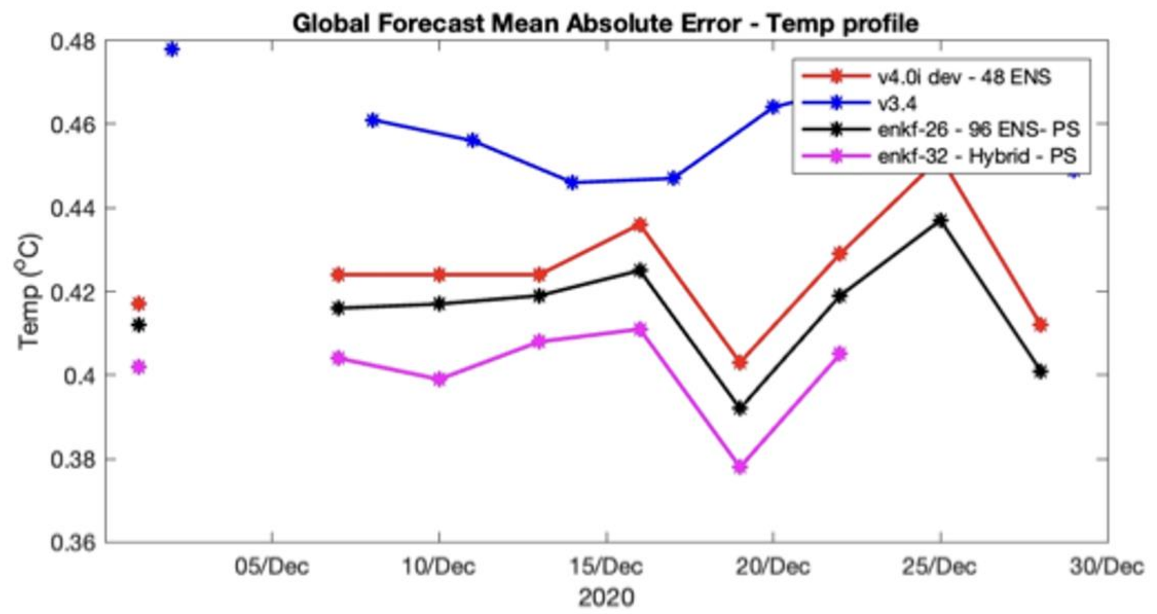
Atmospheric forcing
ACCESS-G4 (APS4)
Bulk formulae

Observations
In situ profiles (GTS, GDAC)
Satellite altimetry (RADS, J3, SARAL, Sentinel-3A, Cryosat-2)
Satellite SST (AMSR2, NAVOCEANO, NPP-VIIRS, NOAA20-VIIRS)

Forecasts
EnKF BRT (-3 day analysis)
EnKF NRT (-2 day analysis)
Daily 7 day forecasts (001, Av. RES)

Impact

Performance
- Reduced forecast innovation
- Reduced latency (-2 days)
- More dynamically balanced increments
- Uniform latency
- Beats persistence
- Reduction in abyssal noise
- Improved separation of eddies
- Sustaining low signal to noise eddies
- Improved skill ocean currents



References
Brassington, G. B., P. Sakov, P. Divakaran, S. Aijaz, J. Sweeney-Van Kinderen, X. Huang and S. Allen, 2023, June. OceanMAPS v4. 0i: a global eddy resolving EnKF ocean forecasting system. In *OCEANS 2023-Limerick* (pp. 1-8). IEEE
Sakov, P., 2014. EnKF-C user guide. *arXiv preprint arXiv:1410.1233*.

EnKF-C

The forecast stage of the EnKF involves just propagating each ensemble member:

$$\mathbf{E}_i^f = \mathcal{M}_i(\mathbf{E}_{i-1}^a). \tag{1.13}$$

$$\mathbf{X} = \{\mathbf{E}\} = \{\mathbf{x}, \mathbf{A}\}. \tag{1.9}$$

It is related to the SDAS of the KF (1.8) as follows:

$$\mathbf{x} = \frac{1}{m}\mathbf{E}\,\mathbf{1}, \tag{1.10a}$$

$$\mathbf{P} = \frac{1}{m-1}\mathbf{A}\mathbf{A}^{\mathrm{T}}, \tag{1.10b}$$

$$\mathbf{A} \equiv \mathbf{E} - \mathbf{x}\mathbf{1}^{\mathrm{T}}, \tag{1.10c}$$

Analysis update on the ensemble mean

$$\mathbf{x}_{k+1}^a = \mathbf{x}_{k+1}^f + \mathbf{K}_{k+1}\left[\mathbf{y}_{k+1} - \mathcal{H}_{k+1}(\mathbf{x}_{k+1}^f)\right], \tag{1.6a}$$

where

$$\mathbf{K}_{k+1} \equiv \mathbf{P}_{k+1}^f(\mathbf{H}_{k+1})^{\mathrm{T}}\left[\mathbf{H}_{k+1}\mathbf{P}_{k+1}^f(\mathbf{H}_{k+1})^{\mathrm{T}} + \mathbf{R}_{k+1}\right]^{-1} \tag{1.6c}$$

or equivalently $\mathrm{K} = \mathrm{A}(\mathrm{HA})^T[\mathrm{HA}(\mathrm{HA})^T + \mathrm{R}]^{-1}$

Ensemble anomaly update (model error covariance)

$$\mathbf{A}^a = \mathbf{T}_L\,\mathbf{A}^f, \tag{1.15}$$

where

$$\mathbf{T}_L = \mathbf{I} - \frac{1}{2}\mathbf{K}\mathbf{H}. \tag{1.30}$$

$$\mathbf{E}^a = \mathbf{x}^a\mathbf{1}^T + \mathbf{A}^a \tag{1.11a}$$

Hunt, B. R., E. J. Kostelich and I. Szunyogh, 2007: Efficient data assimilation for spatiotemporal chaos: A local ensemble transform filter. *Physica D*, 230, 112-126.
Sakov, P. and P. R. Oke, 2008: A deterministic formulation of the ensemble Kalman filter: an alternative to ensemble square root filters, *Tellus*, 60A, 361-371
Sakov, P., 2014. EnKF-C user guide. *arXiv preprint arXiv:1410.1233*.

Forecast error covariance

$$\mathbf{P}^f = \frac{1}{n-1}\mathbf{A}\mathbf{A}^T$$

where

$$\mathbf{A} = \alpha\left[a_1', a_2', \ldots, a_n'\right]$$

$$a_i = \overline{T}_i^{month} - \overline{T}_i^{clim}$$ Stationary

$$a_i(t) = T_i(t) - \overline{T}(t)$$ Dynamic

Observation error covariance

$$\mathbf{R} = \sigma_{obs}^2\mathbf{I} + \sigma_{rep}^2\mathbf{I}$$

Real-time observations

- Satellite altimetry (RADS)
- Satellite SST (VIIRS, AMSR2)
- In situ profiles (Argo, CTD, XBT)

Oke, P.R. and Sakov, P., 2008. Representation error of oceanic observations for data assimilation. Journal of Atmospheric and Oceanic Technology, 25(6), pp.1004-1017.

Hybrid implementation

$$\mathbf{P}^f = \alpha\mathbf{P}^{dyn} + \gamma\mathbf{P}^{stat}$$ $$\alpha = 1.03 \qquad \gamma = 0.25$$

$$\mathbf{P}^{dyn} = A^{dyn}(A^{dyn})^T / (m^{dyn} - 1)$$ $$m^{dyn} = 48$$

$$\mathbf{P}^{stat} = A^{stat}(A^{stat})^T / (m^{stat} - 1)$$ $$m^{stat} = 144$$

Chamberlain, M. A., P. R. Oke, G. B. Brassington, P. Sandery, P. Divakaran, R. A. S. and Fiedler, 2021: Multiscale data assimilation in the Bluelink ocean reanalysis (BRAN). Ocean Modelling, 166, p.101849.

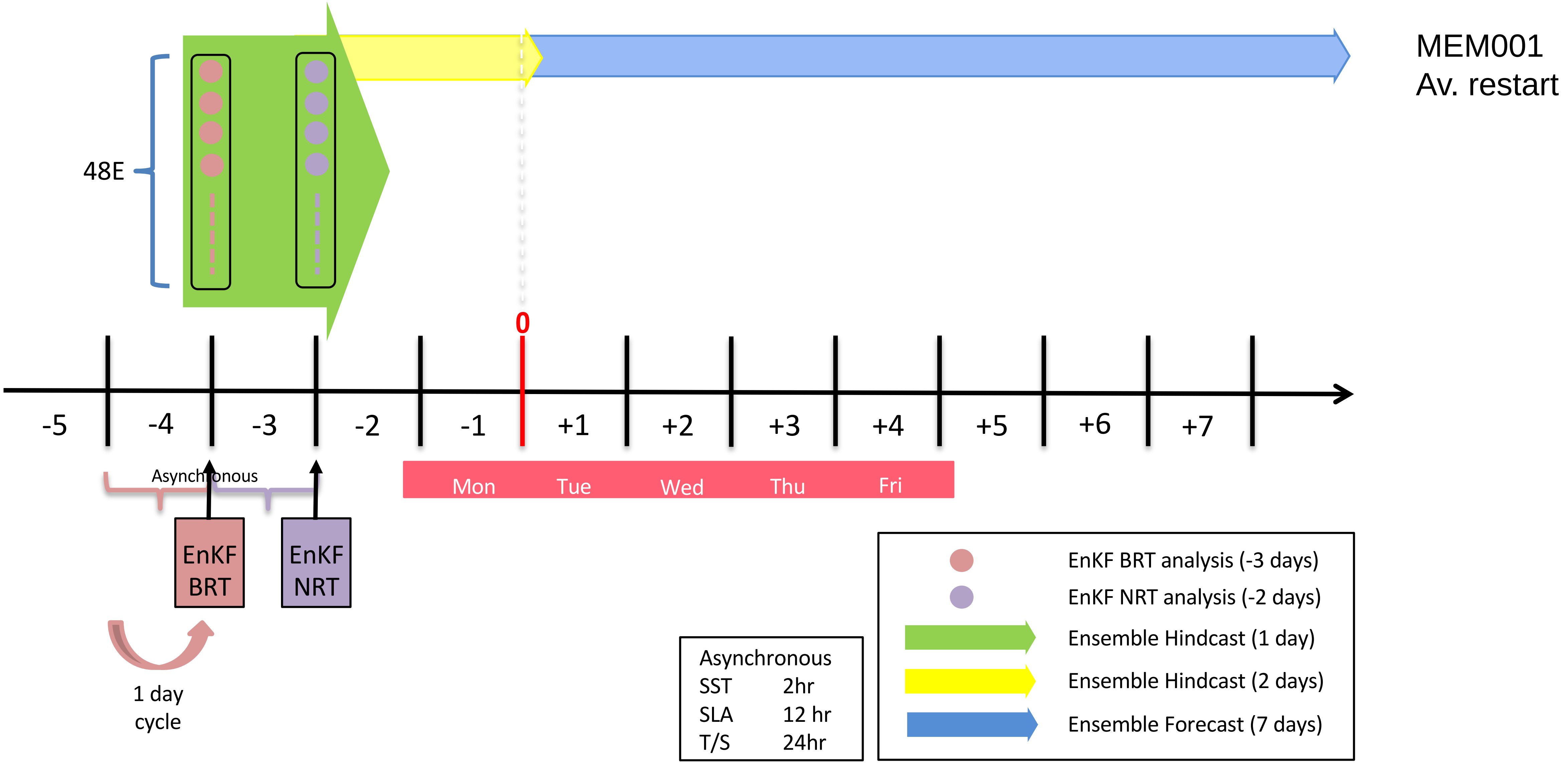
Asynchronous data assimilation

[SLA, SST, T, S] = [12h, 6h, 24h, 24h] averaging bin sizes exploit satellite/2D

Sakov, P., Evensen, G. and Bertino, L., 2010. Asynchronous data assimilation with the EnKF. Tellus A: Dynamic Meteorology and Oceanography, 62(1), pp.24-29.

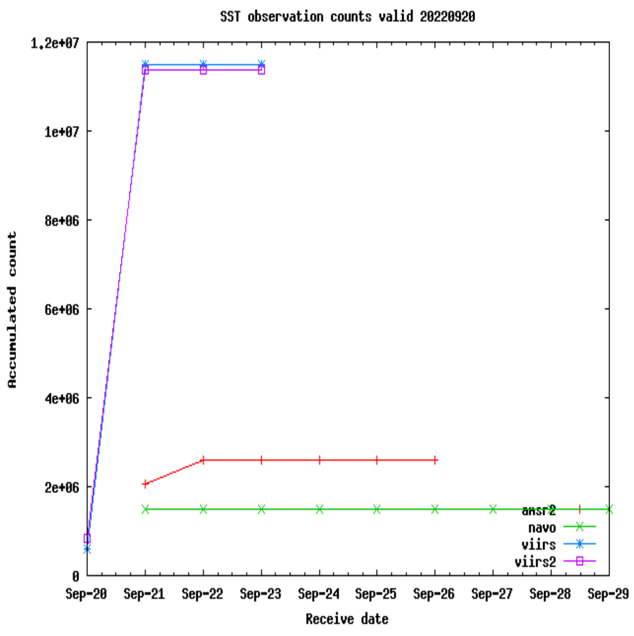
Localisation

[SLA, SST, T, S] = [175, 150, 450, 450] km

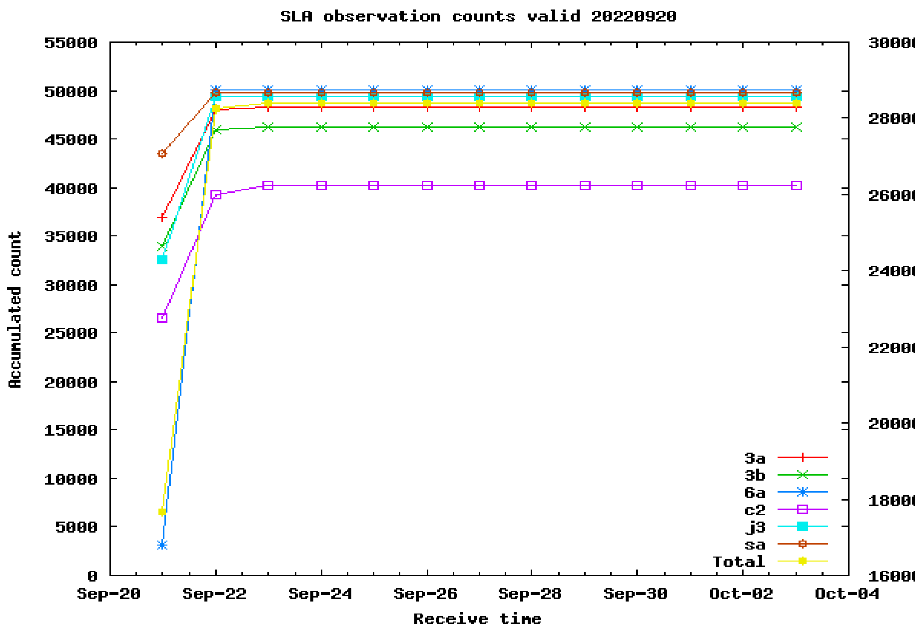


MEM001
Av. restart
48E
0
-5
-4
-3
-2
-1
+1
+2
+3
+4
+5
+6
+7
Asynchronous
Mon
Tue
Wed
Thu
Fri
EnKF BRT
EnKF NRT
1 day cycle
Asynchronous
SST 2hr
SLA 12 hr
T/S 24hr
EnKF BRT analysis (-3 days)
EnKF NRT analysis (-2 days)
Ensemble Hindcast (1 day)
Ensemble Hindcast (2 days)
Ensemble Forecast (7 days)

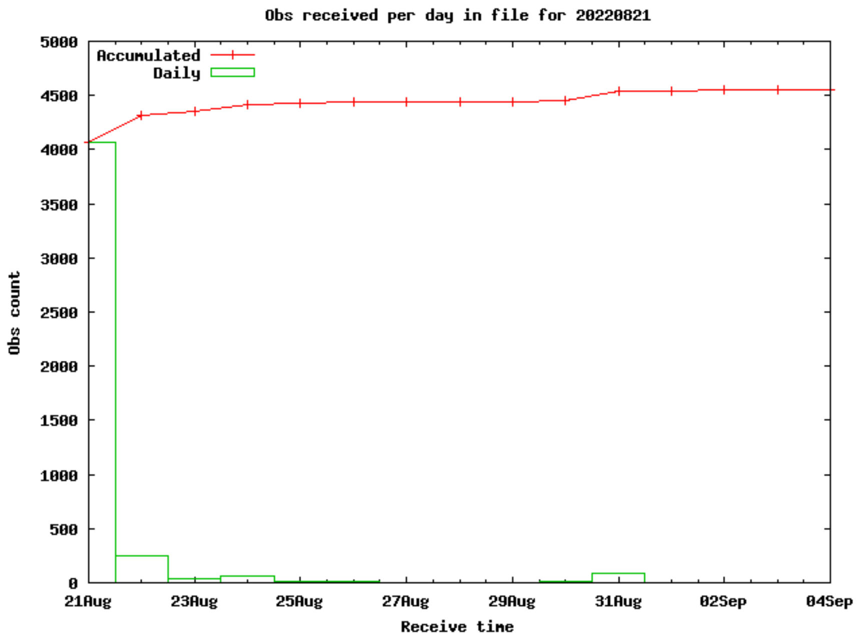
Realtime observation latency



-1 day -2 day -3 day



-1 day -2 day -3 day



-1 day -2 day -3 day

Satellite SST	Low latency/Good coverage	-3 days – persistent analysis cycle
Satellite altimetry	Medium latency/Medium coverage	-2 days – intermediate analysis to introduce available obs
Profiles	Medium latency/Sparse coverage	-1 days – imbalanced obs not tested

The Bureau of Meteorology

EnKF vs EnOI

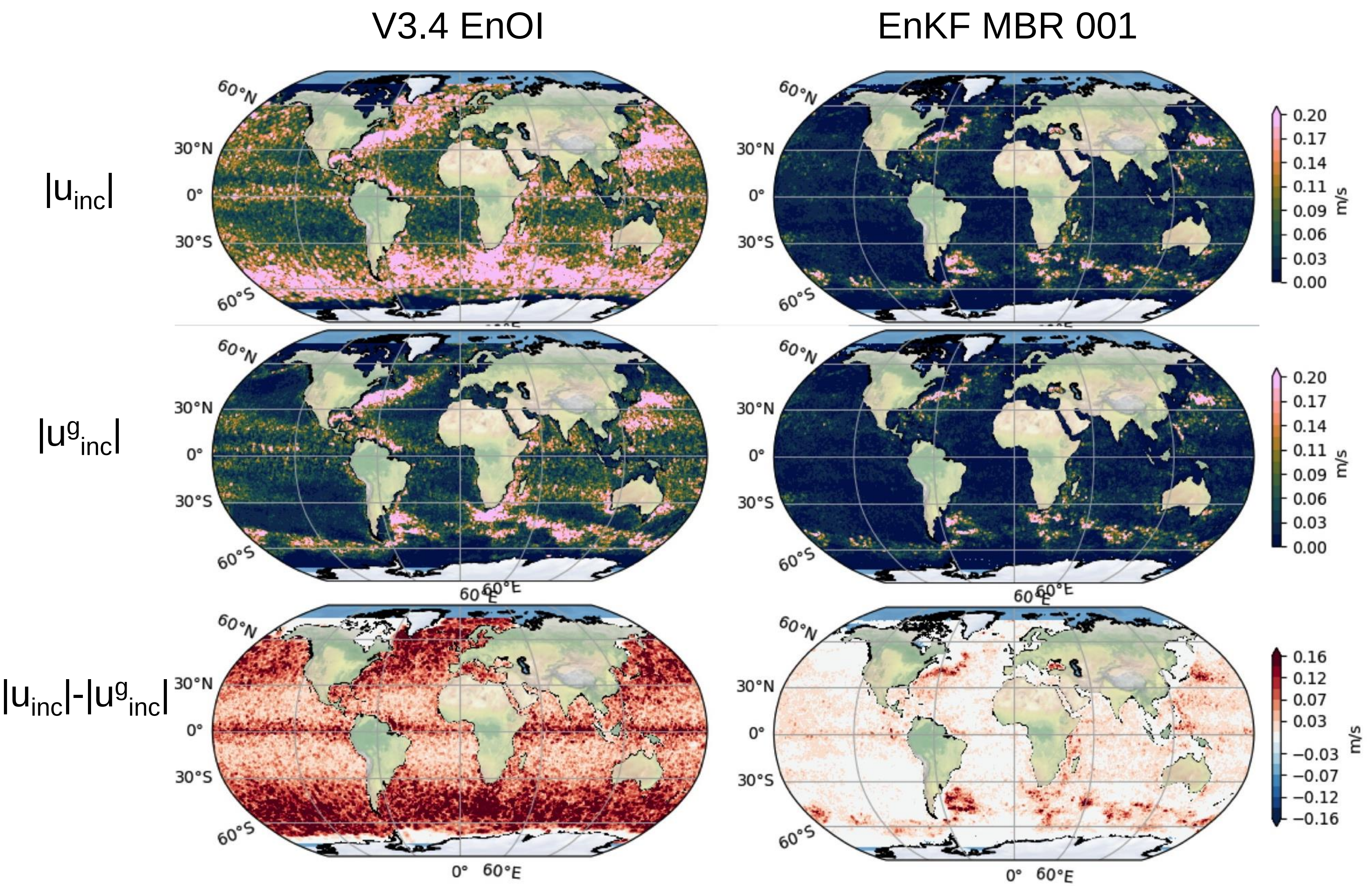
Geostrophic increments

$$u^g_{inc}(z) = \frac{g}{f\rho_0}\frac{\partial}{\partial y}\int_{-H}^{z}\Delta\rho_{inc}dz$$

$$v^g_{inc}(z) = -\frac{g}{f\rho_0}\frac{\partial}{\partial x}\int_{-H}^{z}\Delta\rho_{inc}dz$$

How consistent are the density increments with geostrophic increments?

How much ageostrophic increment remains?



*$\Delta\rho_{inc} = \rho(T+Tinc, S+Sinc) - \rho(T,S)$,
-H is the depth of the water column

Pseudo steric sea level

$$\eta_{inc}^{steric} = -\frac{1}{\rho_0}\int_{-H}^{\eta} \Delta\rho_{inc}\, dz$$

$$\Delta\eta_{inc} = \eta_{inc} - \eta_{inc}^{steric}$$

How consistent are the density increments with pseudo steric sea level?

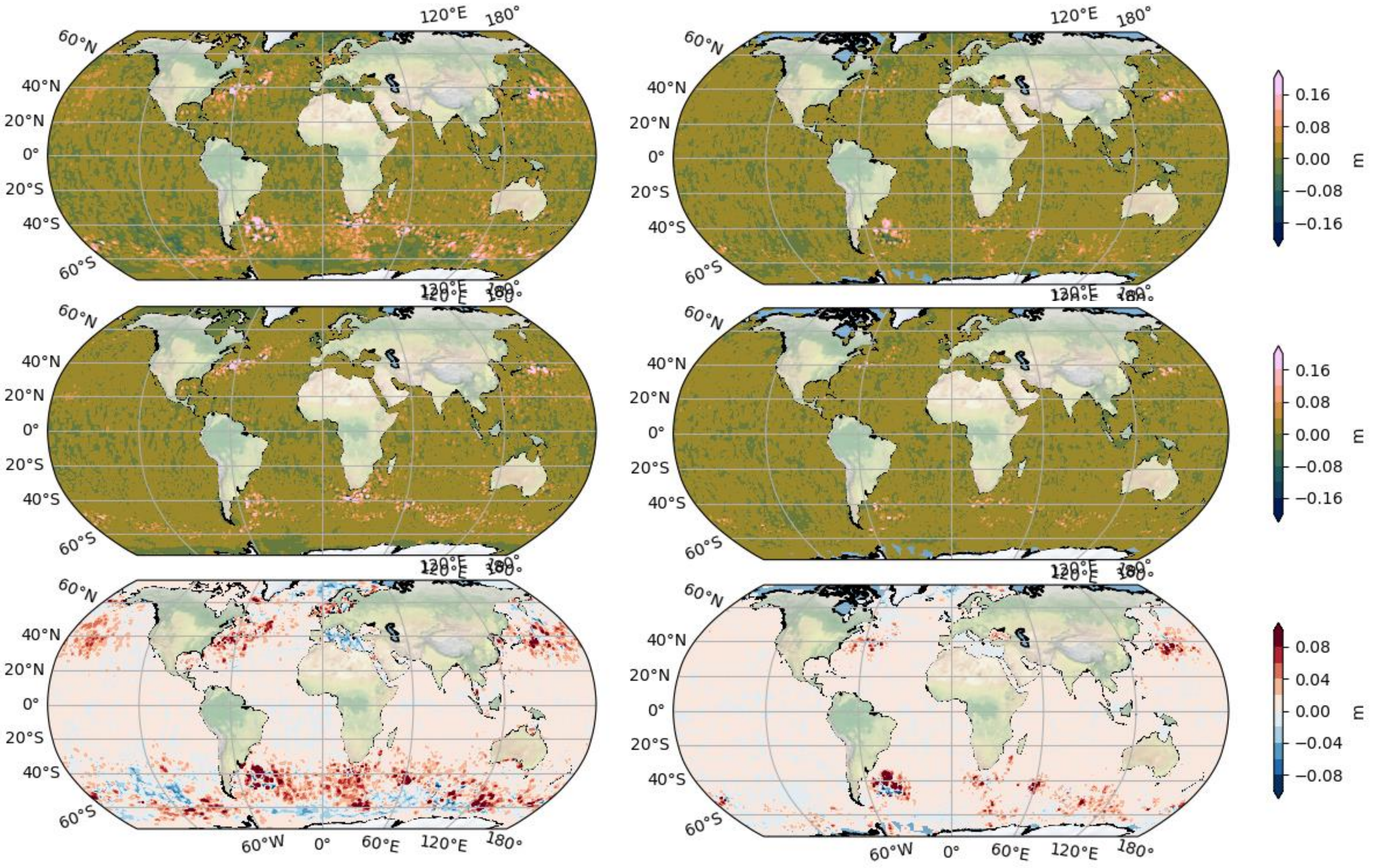
How much sea level increment contributed to the shallow water equation?

V3.4 EnOI | EnKF MBR 001

Total $\boldsymbol{\eta}_{\mathrm{inc}}$

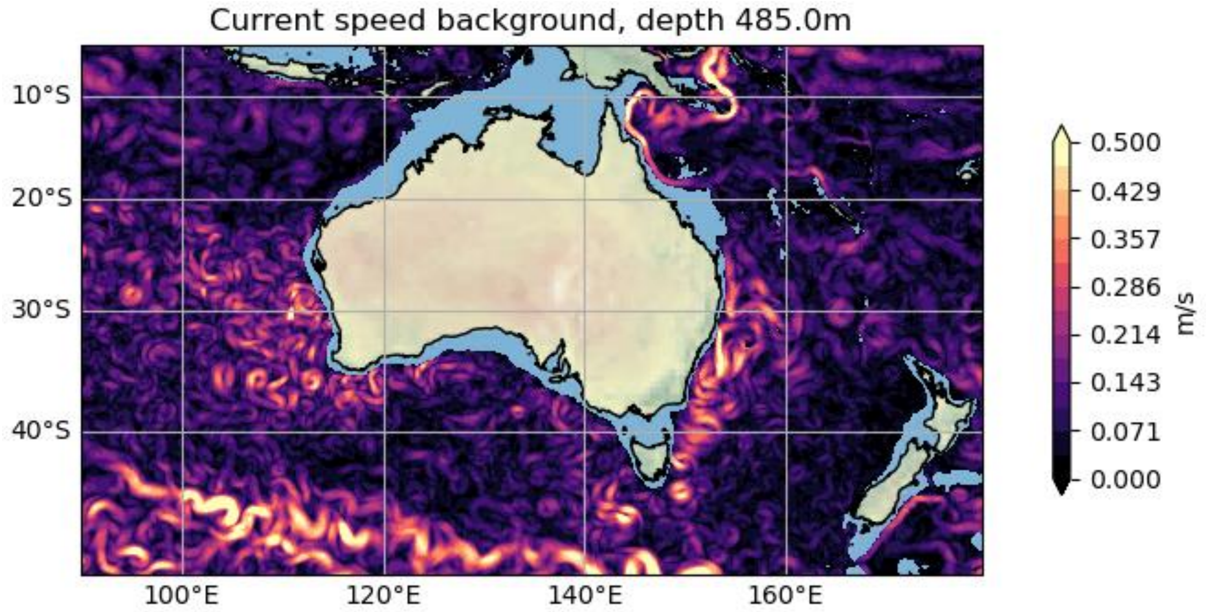
Pseudo steric η_{inc}^{steric}

Difference $\boldsymbol{\Delta\eta}_{\mathrm{inc}}$



29 April 2021

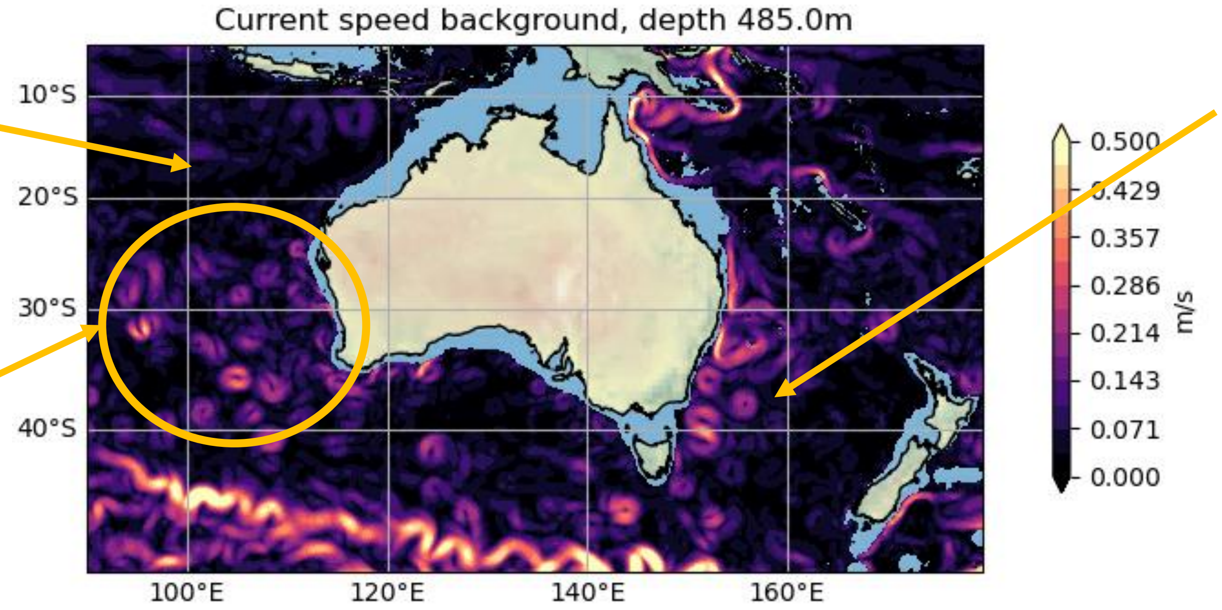
OceanMAPSv3.4
(EnOI)



Realistic passive regions

OceanMAPSv4.0i
(EnKF)

Clearly defined eddies that are observed

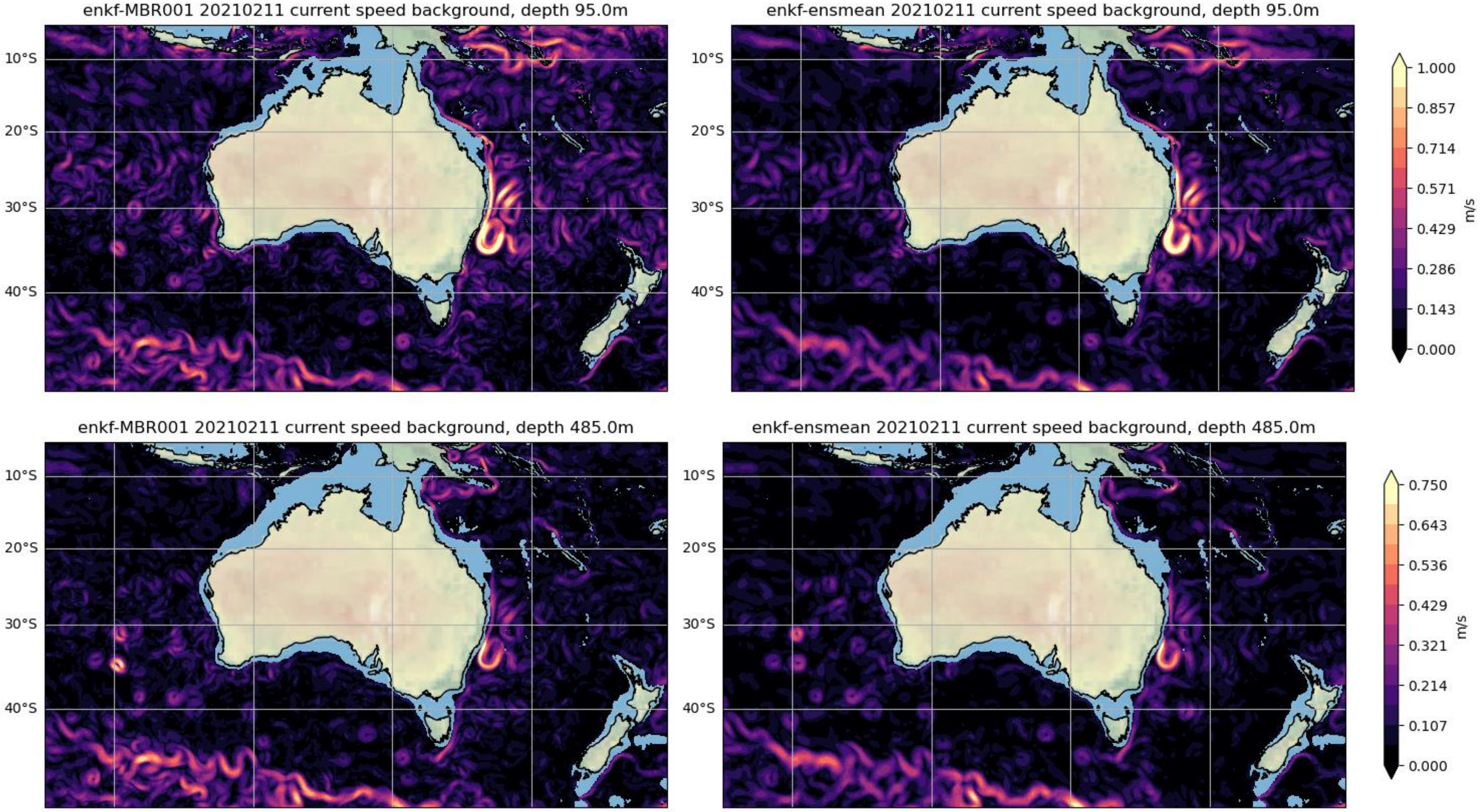


Clear separation of eddies

3-day hindcast
Ocean current speed
485 m
25 JULY 2020

95m

485m

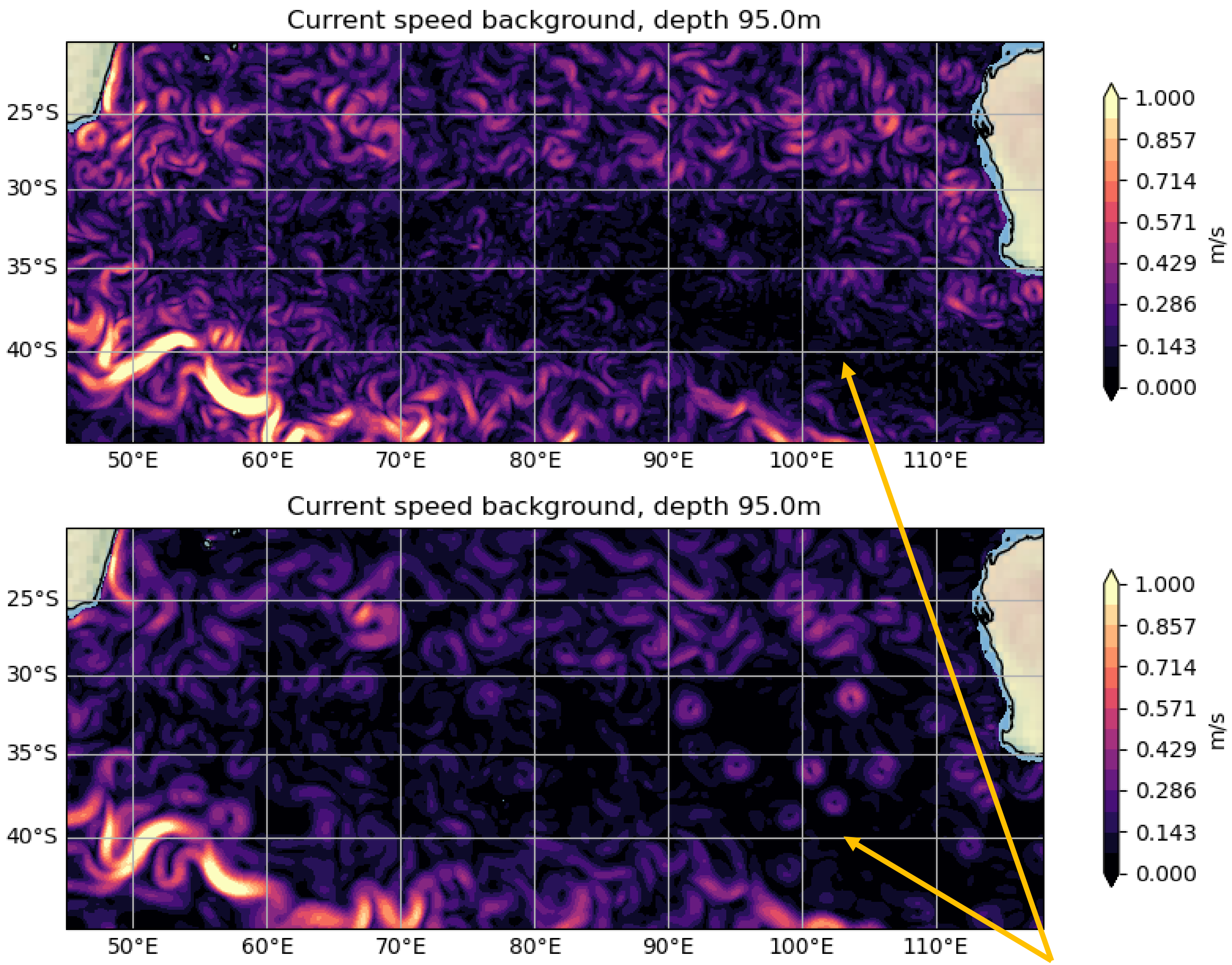


MEM001

ENSMEAN

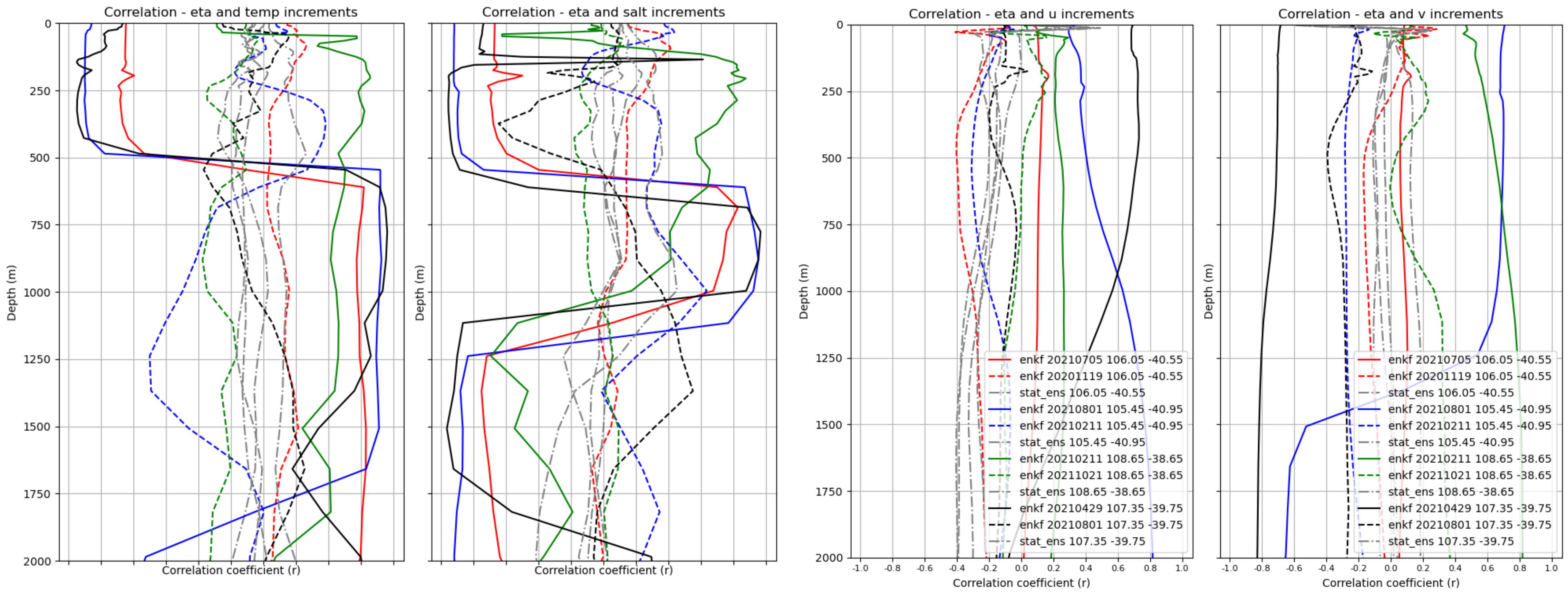
EnOI

EnKF



EnOI dissipates low signal to noise eddies

CORRELATION COEFFICIENTS in the presence/absence of eddies



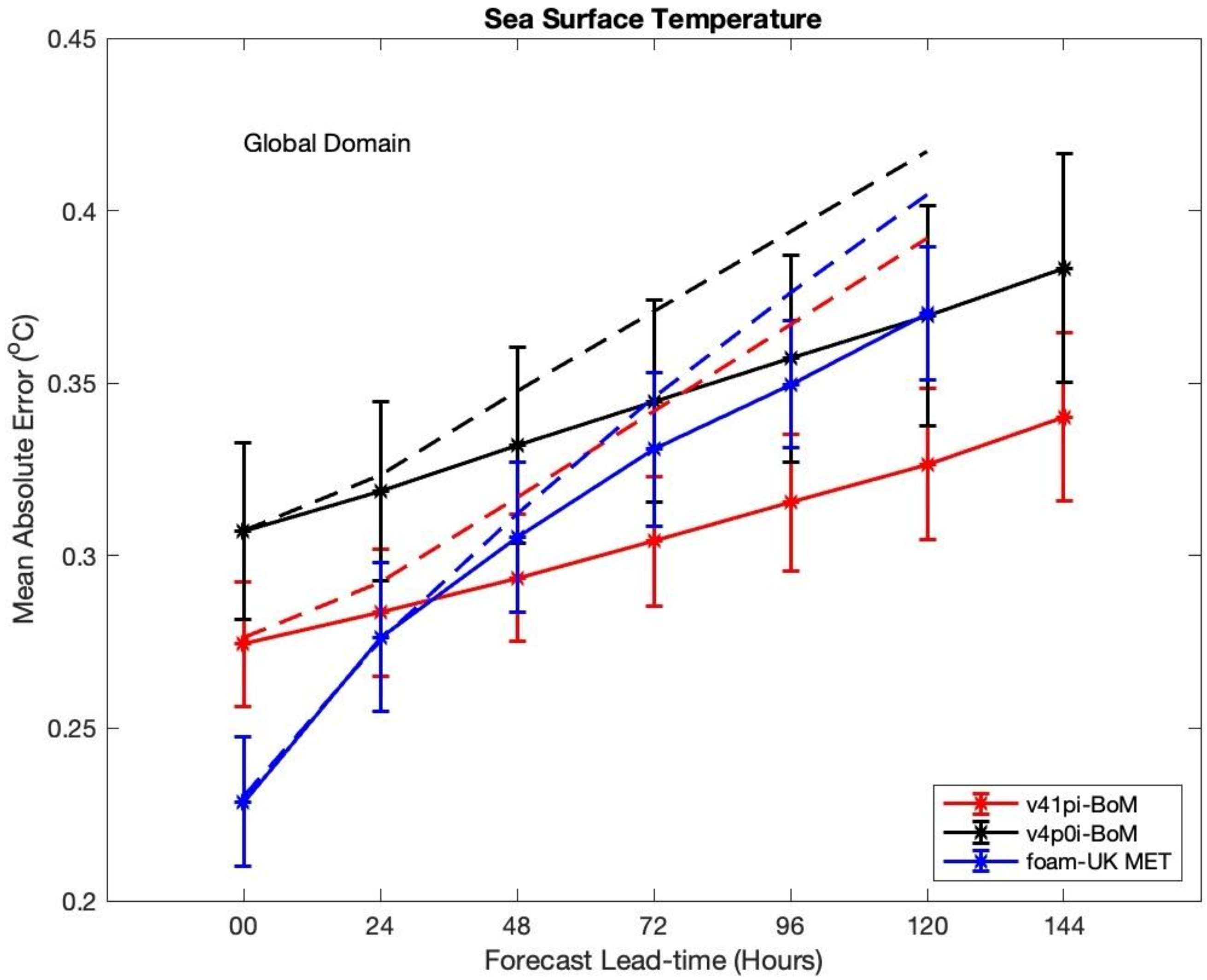
- Four eddies from SE Indian Ocean eddy graveyard.
- Identified through SLA signature in EnKF ensmean.
- All are cold-core eddies.

Solid lines are correlations for EnKF ensemble increments when eddy is present
Dashed lines are correlations for EnKF ensemble increments at same location on a different day (no eddy)
Grey lines are correlations for EnOI stationary ensemble members at the same location.

The Bureau of Meteorology

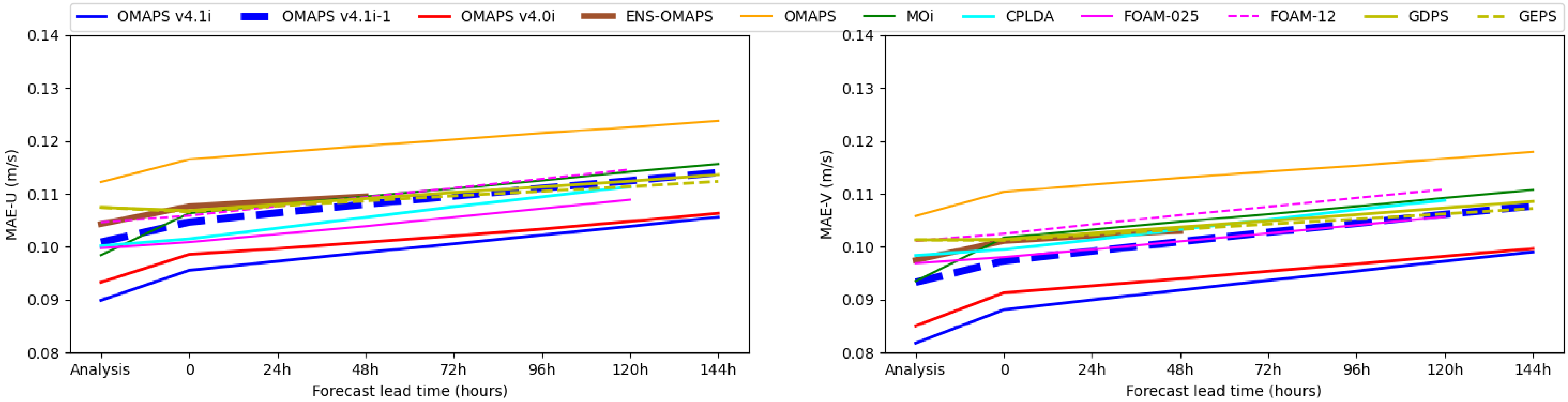
OceanMAPSv4.1i

CLASS4 SST


Sea Surface Temperature
Global Domain
Mean Absolute Error (°C)
0.45
0.4
0.35
0.3
0.25
0.2
00
24
48
72
96
120
144
Forecast Lead-time (Hours)
v41pi-BoM
v4p0i-BoM
foam-UK MET

Currents verification & intercomparison against global drifters (GDP)

Global forecast error growth



Zonal **Meridional**

Aijaz et al. (2023), Ocean Modelling

Conclusion

Transition to Hybrid-DLETKF was successfully implemented in 2022, (Brassington et al., 2023)
- Updated to OceanMAPSv4.1i (1-day cycle)

Broad range of positive impacts
- Improved dynamical balance on increments
- Realistic separation of mesoscale eddies
- Adaptive to high variability/high tendency mesoscale dynamics
- Continuity of eddy propagation
- Constraining low signal to noise eddies
- Improved accuracy of state variables and ocean currents

NRT(-3)/BRT(-2) analysis design maximises observation coverage / minimise latency

Deterministic forecast from average restart initial conditions
- Improves forecast accuracy with minimal impact on mesoscale eddies

The Bureau of Meteorology

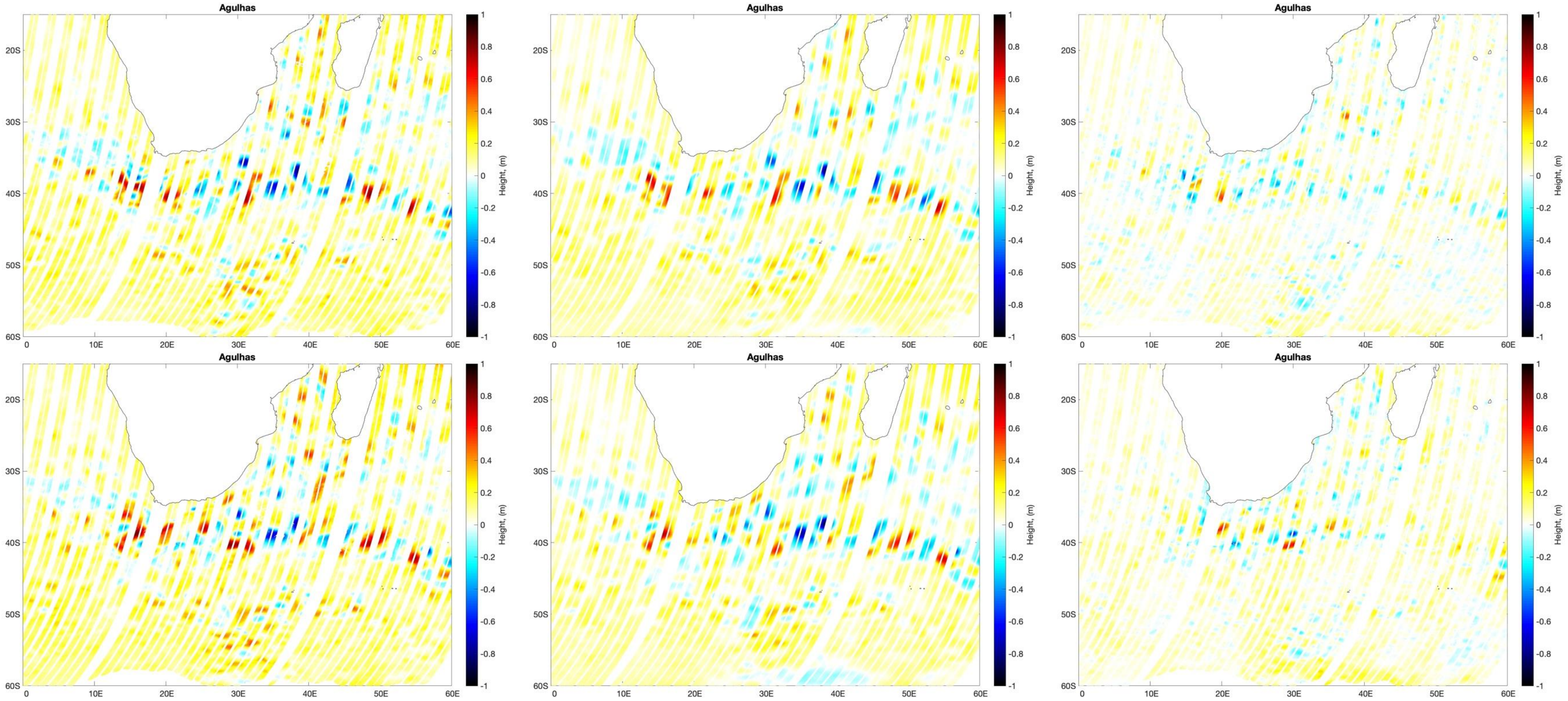
Thank you

Gary Brassington
gary.brassington@bom.gov.au

Independent verification - SWOT

Cycle 005, Sub1, Asc.

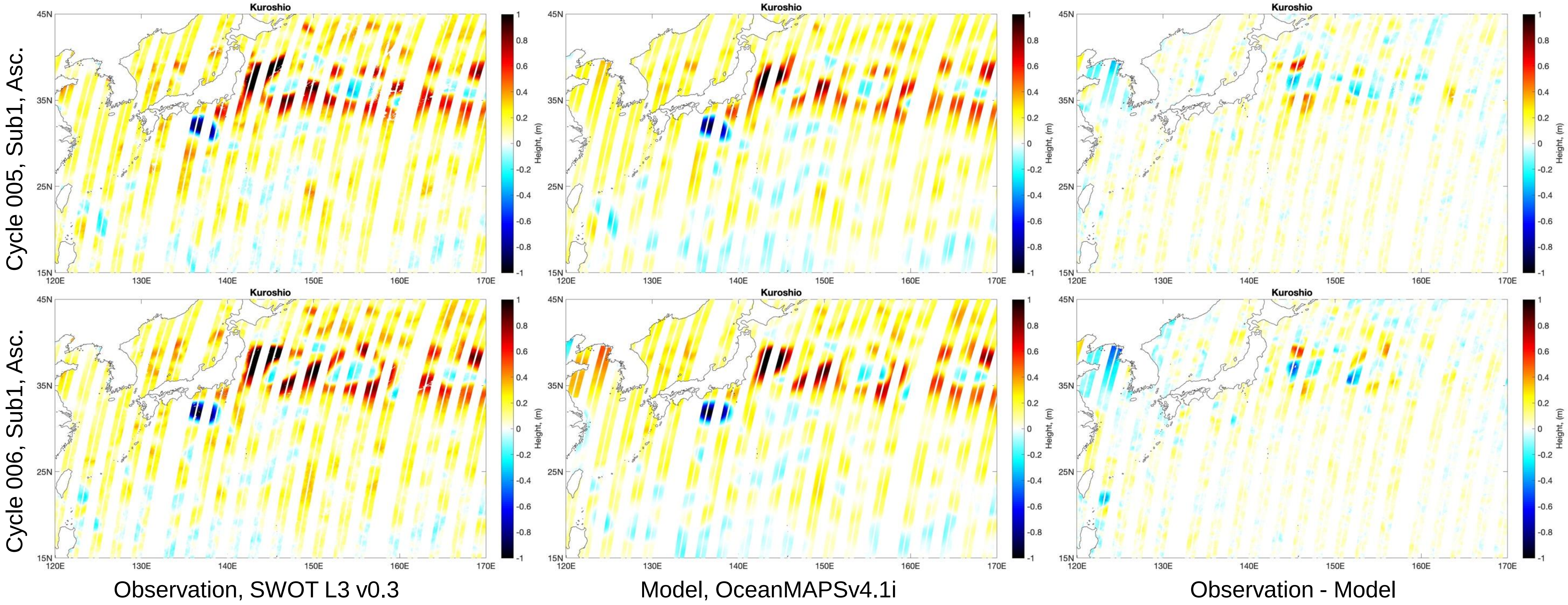
Cycle 006, Sub1, Asc.



Observation, SWOT L3 v0.3

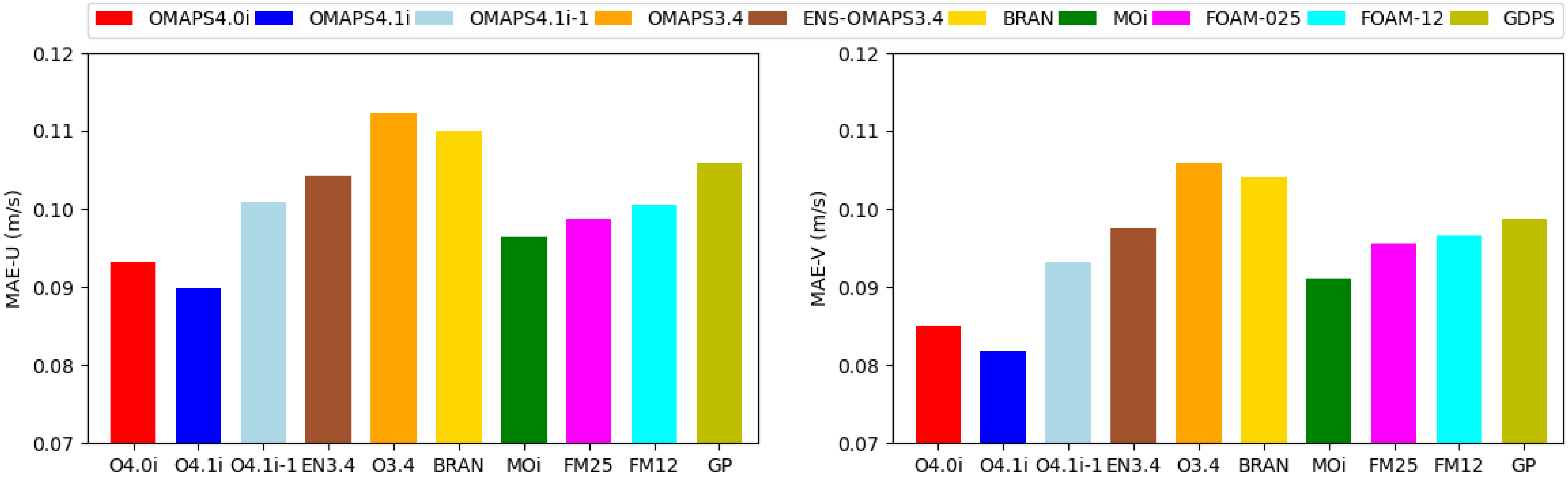
Model, OceanMAPSv4.1i

Obs - Model


Cycle 005, Sub1, Asc.
Cycle 006, Sub1, Asc.
Kuroshio
45N
35N
25N
15N
120E
130E
140E
150E
160E
170E
Height, (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Observation, SWOT L3 v0.3
Model, OceanMAPSv4.1i
Observation - Model

Currents verification & intercomparison against global drifters (GDP)

Global Analysis

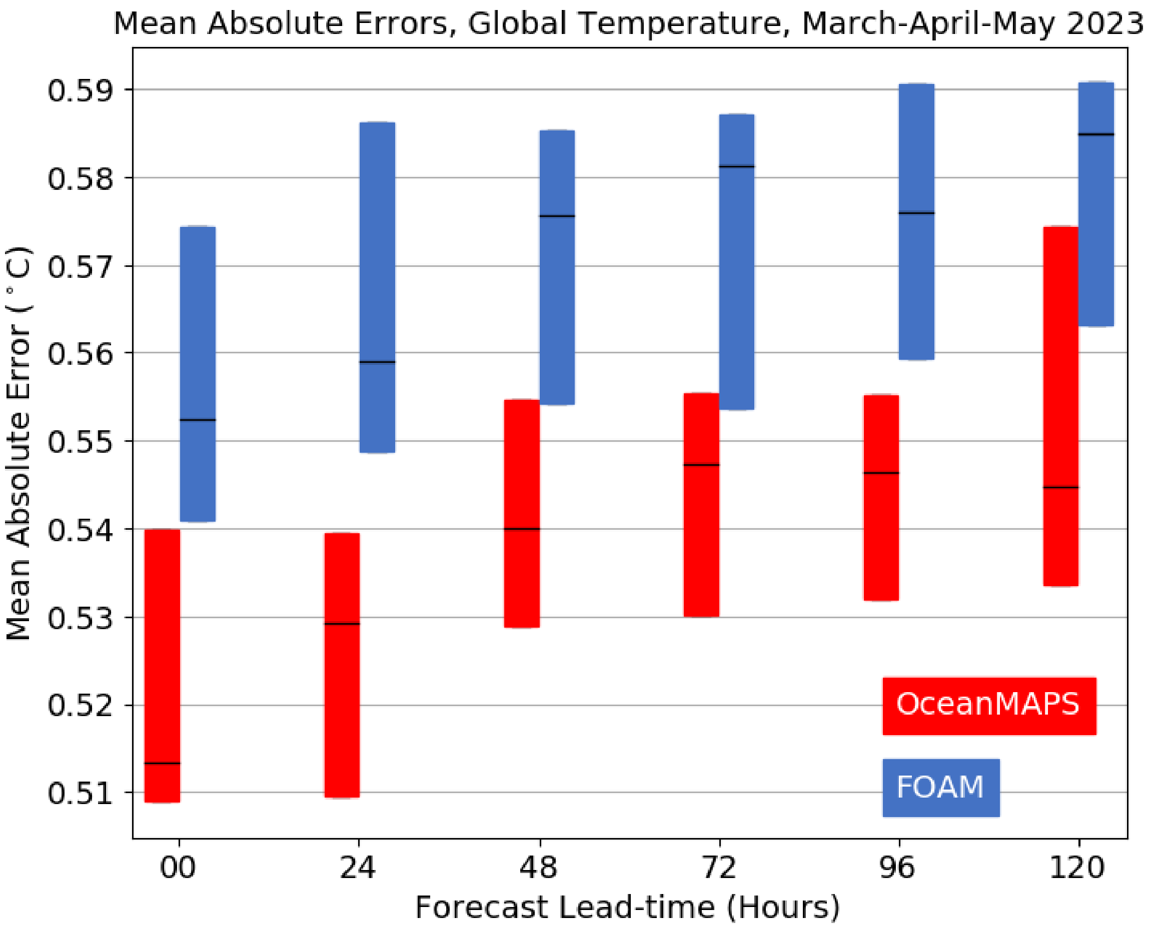


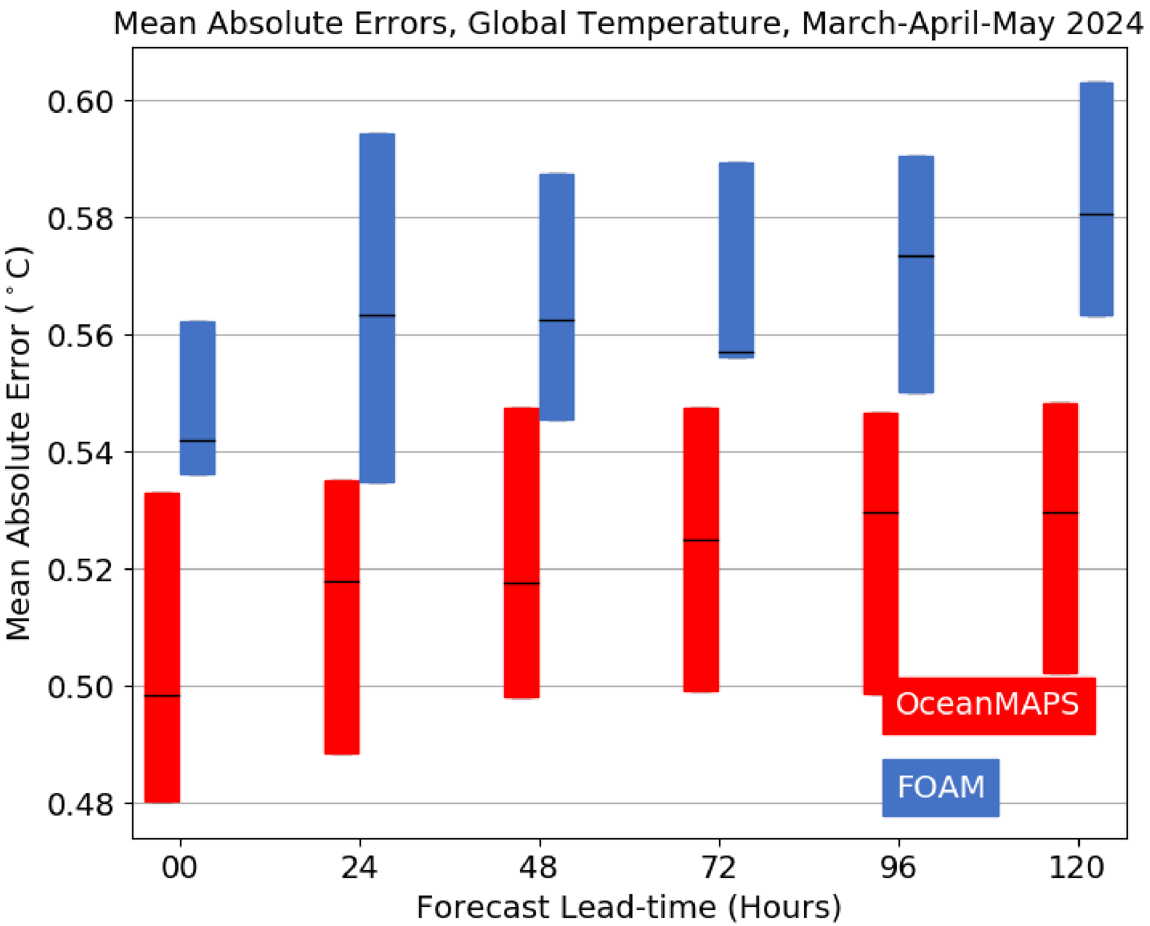
Zonal **Meridional**

OMAPS 4.0i, 4.1i, 4.1i-MEM1: 1JAN2024 – 30JUN2024 (182 days)
MOi,FOAM-025, FOAM-12, GDPS: 1JAN2022 – 10MAR2023 (432 days)
OMAPS3.4, ENS-OMAPS3.4: 20MAY2021 – 19MAY2022 (364 days)

Australia: OMAPS3.4/4.0i/4.1i, ENS-OMAPS3.4, BRAN
France: MOi
UK: FOAM025, FOAM12
Canada: GDPS

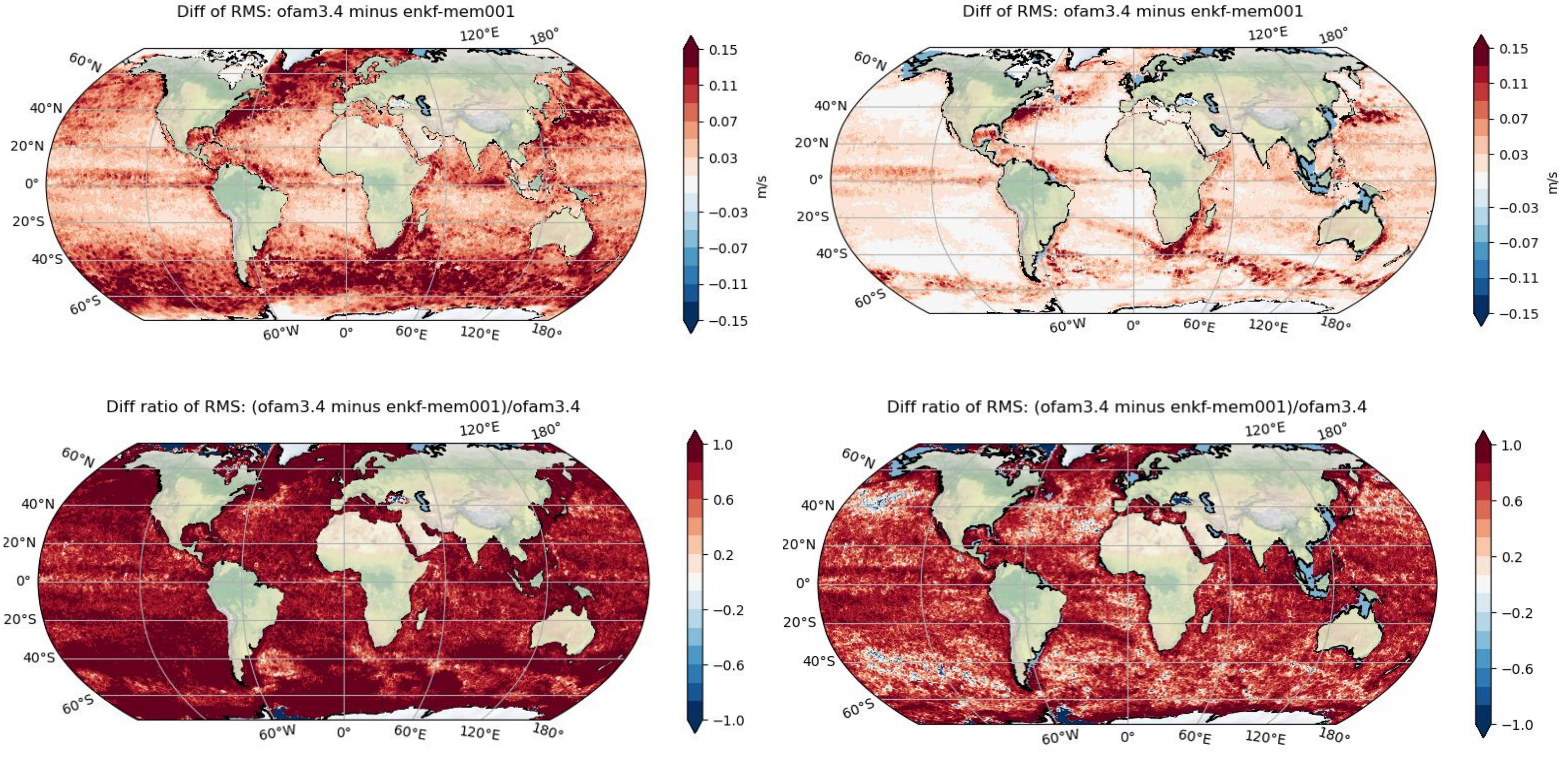
Aijaz et al. (2023), Ocean Modelling


Mean Absolute Errors, Global Temperature, March-April-May 2023
Mean Absolute Error (°C)
0.59
0.58
0.57
0.56
0.55
0.54
0.53
0.52
0.51
00
24
48
72
96
120
Forecast Lead-time (Hours)
OceanMAPS
FOAM


Mean Absolute Errors, Global Temperature, March-April-May 2024
Mean Absolute Error (°C)
0.60
0.58
0.56
0.54
0.52
0.50
0.48
00
24
48
72
96
120
Forecast Lead-time (Hours)
OceanMAPS
FOAM

$\mathbf{\Delta}$RMS($\mathbf{u}_{inc}$)

$\mathbf{\Delta}$RMS /RMS



Surface

95m

STD temperature increment

STD salinity increment