

Towards high-resolution ensemble forecast systems with NEMO

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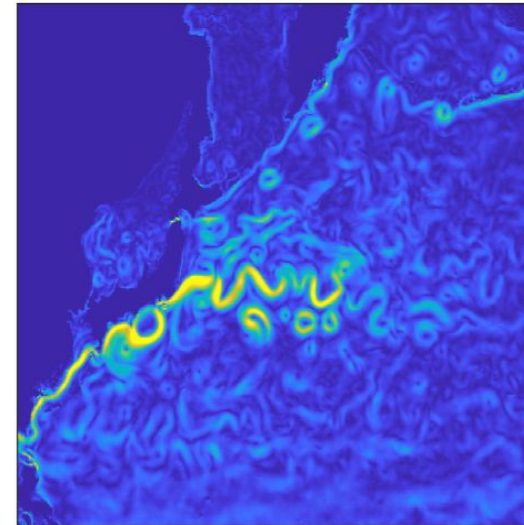


NEMO based ocean modelling at the Bureau of Meteorology, Australia

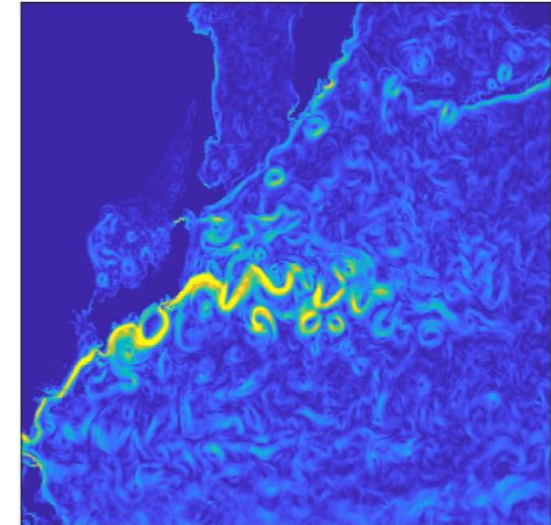
Outline

1. **Towards a high-resolution NEMO based ensemble Kalman filter ocean forecast system**
 - Motivation
 - System setup
 - Comparison of the NEMO and MOM based system
 - Next steps
2. Other developments at the BoM including NEMO ocean model
 - Regional (coupled) ocean systems
 - Global ORCA12 10 year hindcast

NEMO12 |V|, 120m, 30/12/2019, ens. mean



NEMO12 |V|, 120m, 30/12/2019, mem. 1



Motivation and background

Research R&D plan 2020-2030

- R&D plan (2020-2030)
 - Focus on seamless modelling/ Coupled ESM/ Integrated NWP/ Coupled modelling
- Tighter integration with the UK Met Office
 - Move towards 1 modelling system based on Met Office model configuration
 - Currently using MOM based global ocean and ROMS based regional models
- Historically, the Bureau has used its in-house DA system
 - Ensemble Kalman Filter data assimilation system (EnKF-C, Sakov, 2014, Brassington et al., 2023)
 - Model agnostic
- **Key step in the transitional work**
 - 1 Implementation and assessment of an EnKF-C system with the NEMO ocean model**
 - 2 Compare results of such a system with our current operational MOM based systems**



Ensemble ocean forecast systems

Timelines

	NEMO-based	Type
2023/ 2024	ORCA025 + EnKF-C	Research prototype 1 (reanalysis)
2024/ 2025	ORCA12 + EnKF-C	Research prototype 2 (reanalysis)
2025/ 2026	NEMO (ORCA12) + EnKF-C	Real-time prototype
2027/ 2028	<i>OceanMAPSv5</i> (ORCA12 + EnKF-C)	Operational

	MOM-based	Type
2023/ 2024	EnKORe ongoing	Reanalysis
2024/ 2025	OceanMAPS 4.0i	Operational
2025/ 2026	OceanMAPS4.1i	Operational
2027/ 2028	Retired	Retired

Operational systems are underpinned by a reanalysis

OceanMAPS 4.0i --> ***EnKORe 10 year reanalysis (EnKORe, Ensemble Kalman Filter Ocean Reanalysis)***

OceanMAPS 5.0 -- > ***ORCA12+ENKF-C development system***

Comparing those 2 systems in the following



Model Configurations

Overview

GOSI9 (NEMO4.0.4, ORCA12)

- Local modifications - scale parameter
- Fully global including sea ice
- Higher resolution horizontally and vertically
- Timestepping
- C vs B-Grid

	GOSI9 (eORCA12)	OFAM3 (MOM5)
Model (ocean)	NEMOv4.0.4	MOM5
Model (sea-ice)	SI³	Nil
Grid type	C-grid	B-grid
Domain	0-360, 85S-90N (4322 x 3606)	0-360, 75S-75N (3600 x 1500)
Grid (horizontal)	Orthogonal curvilinear	Orthogonal curvilinear
Resolution (horizontal)	1/12 Mercator projection, Tri-polar	1/10 Uniform
Grid (vertical)	z*	z*
Vertical levels	75	51
Surface/Bottom cell depth	1.1m / 200m	5m / 750m
No. levels top 30m	14	6
Bathymetry	GEBCO_2014	GEBCO_08 / GA
State equation	TEOS-10	UNESCO
Mixed layer	TKE (Gaspar et al., 1990)	GOTM K-epsilon
River discharge	Climatological (Bourdalle-Badie and Treguier, 2006)	Climatological (Dai and Trenberth, 2002)
Time integration	Split-explicit / Leap-frog	Split-explicit / Predictor-corrector

System configuration – Prototype 2

ORCA12 based research prototype system on NCI HPC

Model

- GOSI9 (NEMO4.0.4, ORCA12)

Hybrid DA system

- 24 dynamic members (OFAM uses 48)
- 144 static members (interpolated from ORCA025 system)
- 3-day cycle system

Atmosphere

- ERA5 atmospheric forcing

Observations

- SLA (remote, L2P) Sentinel-3A, Sentinel-3B, Cryosat-2, Jason-3, Saral (RADS);
- SST (remote, L2P) VIIRS-NPP, VIIRS-N20 (NOAA), AMSR-2 (JAXA), AVHRR-MTA, AVHRR-MTB (NAVO)
- T,S (in-situ, profiles) BoM

Simulation

- Sep 2017 – 2020 (2 years, NEMO)/ 10 years (MOM EnKORe)

Output

- 24hr 3D variables

Main difference to ORCA025 system (Prototype 1)

- *Reduced ensemble size*
- *Using 1-level NEMO restart (vs. 2-level)*
- *Using tiled NEMO restart (vs. combined)*



Overview

Computational cost

System costs

OFAM3 based (~ OceanMAPS4.0/1i)

- 48 dynamic members
- **9kSU** per 3-day cycle

ORCA12 based (~ OceanMAPS5.0)

- 24 dynamic members
- **90kSU** per 3-day cycle
- **10 times OFAM3 system**

Model sizes

OFAM3 - 1500 x 3600 x 51 - **275,400,000**

NEMO12 - 4322 x 3606 x 75 - **1,168,884,900**

- **4.2 times OFAM3**

Model timesteps

OFAM3 - **900s**

ORCA12 – **360-240s**

- Accounts for factor of **2.5 over OFAM3**

x10 ~ 4.2 (gridpoints) x 2.5 (timestep)

Cost increases of ORCA12 system explained by increased domain, resolution and reduced timestep NEMO comparable efficiency to MOM5

Storage per DA cycle

- OFAM3 - 17GB
- ORCA12 - 49GB

Storing restart ensemble

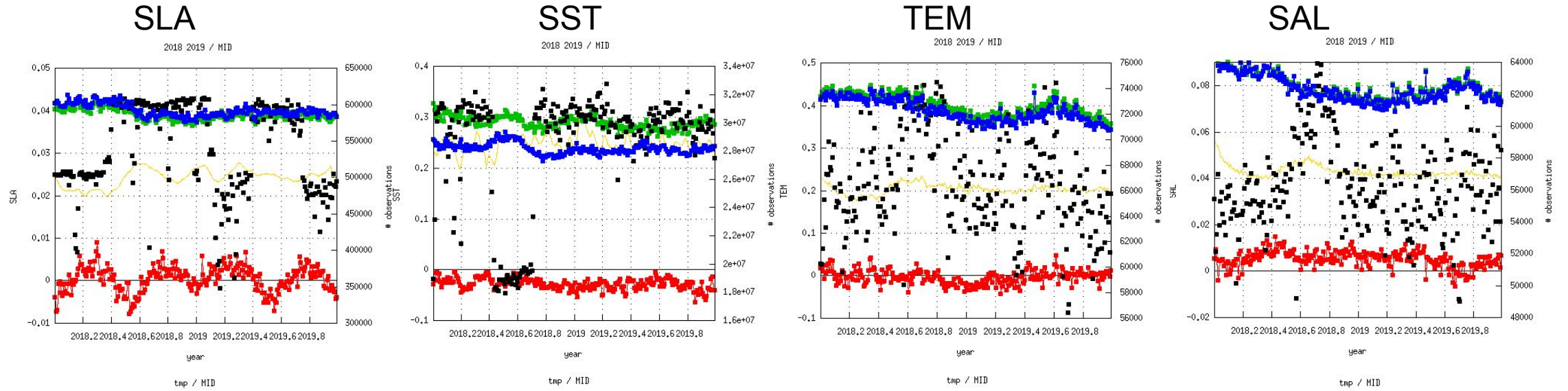
- OFAM3 - 433 GB (48 members; including both forecast and analysis for eta, T, S, U, V)
- ORCA12 - 650 GB (24 members; analysis only)



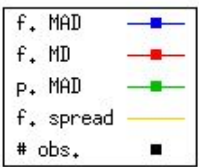
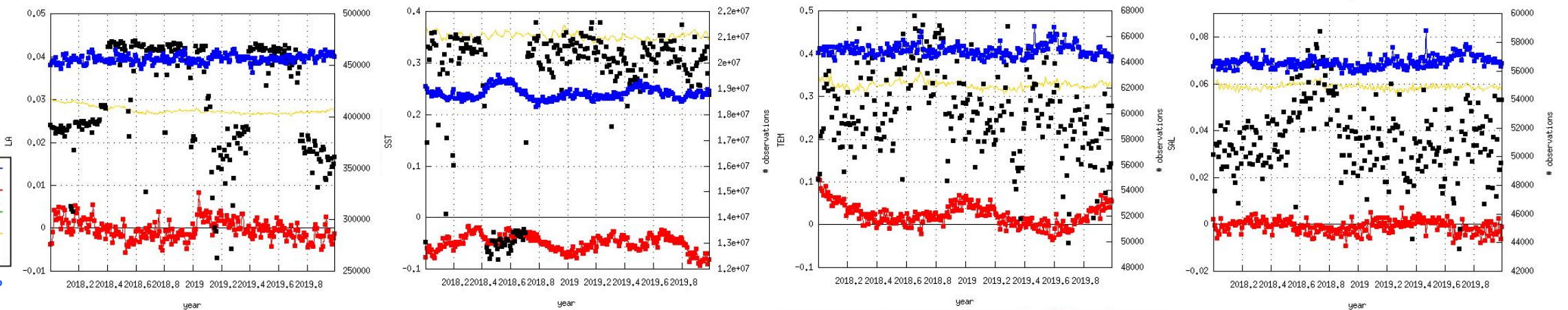
EnKORe vs. NEMO system (60S-60N)

Comparing innovation statistics over 2018-2019

NEMO



EnKORe



EnKORe vs NEMO system (MID)

- Comparing innovation statistics over 2018-2019

	SLA			SST			TEM			SAL		
	MAD	BIAS	#OBS	MAD	BIAS	#OBS	MAD	BIAS	#OBS	MAD	BIAS	#OBS
EnKORe	0.0395	-0.000403	4.17e5	0.241	-0.0504	1.91e7	0.407	0.022	6.03e4	0.0692	-0.00107	5.12e4
NEMO	0.0399	0.000373	5.38e5	0.238	-0.0286	2.84e7	0.387	-0.0045	6.65e4	0.0785	0.00513	5.63e4



EnKORe vs. NEMO system

Innovation statistics – subsurface temperature (MID, 2018-19)

0-50m

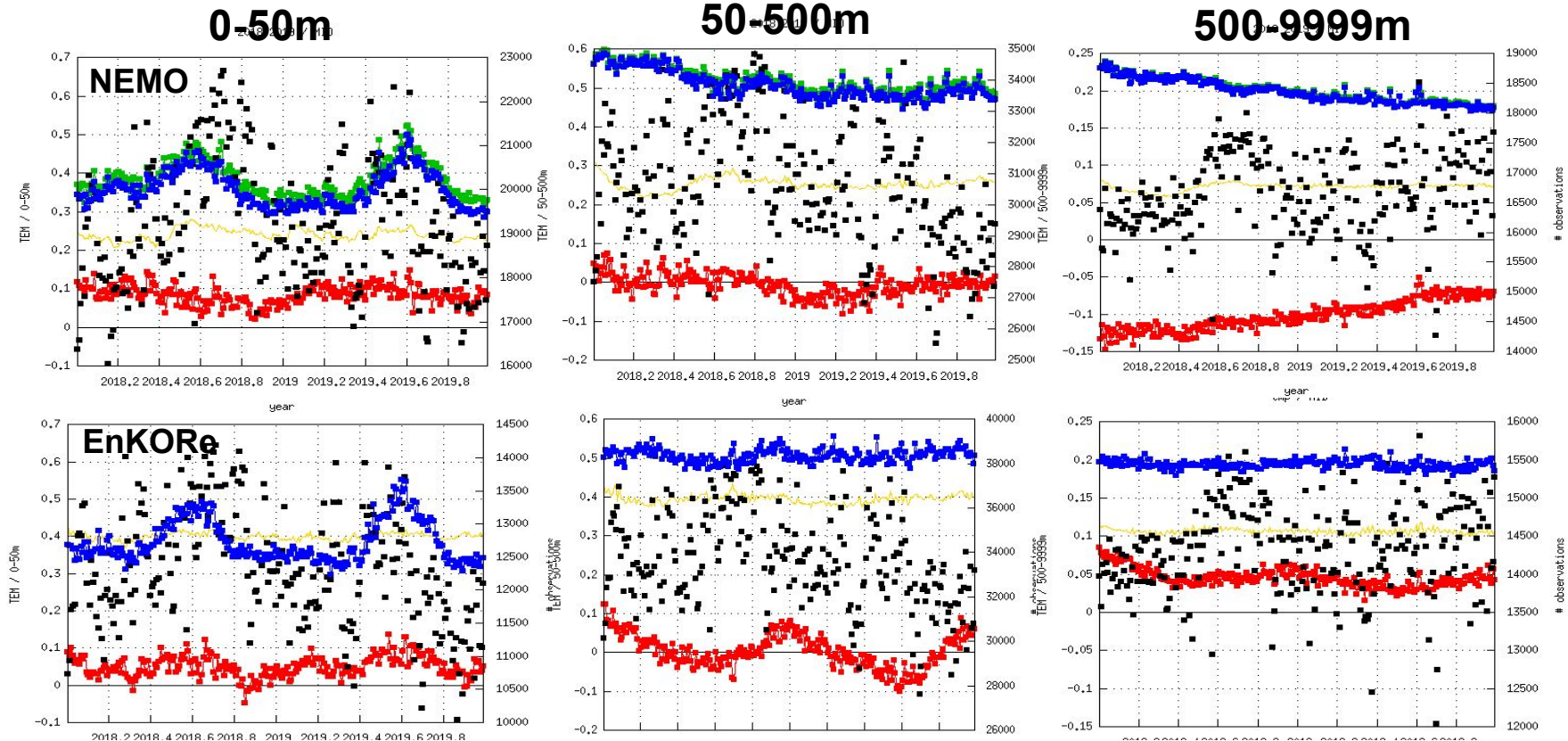
- NEMO has larger bias over upper 50m but error is smaller than seen in EnKORe

50-500m

- NEMO error improvement
- NEMO bias is stable
- EnKORe stable error and bias around zero

500-9999m

- NEMO error and bias improve with time
- NEMO error is smaller than EnKORe error
- EnKORe has consistent positive bias error improves slightly over time



	0-50m			50-500m			500-9999m		
	MAD	BIAS	#OBS	MAD	BIAS	#OBS	MAD	BIAS	#OBS
NEMO	0.358	0.0829	1.92e4	0.508	-0.00652	3.06e4	0.198	-0.102	1.66e4
EnKORe	0.384	0.0493	1.23e4	0.507	0.00211	3.37e4	0.194	0.045	1.43e4

EnKORe vs. NEMO system

Innovation statistics – Subsurface salinity (MID, 2018-19)

0-50m

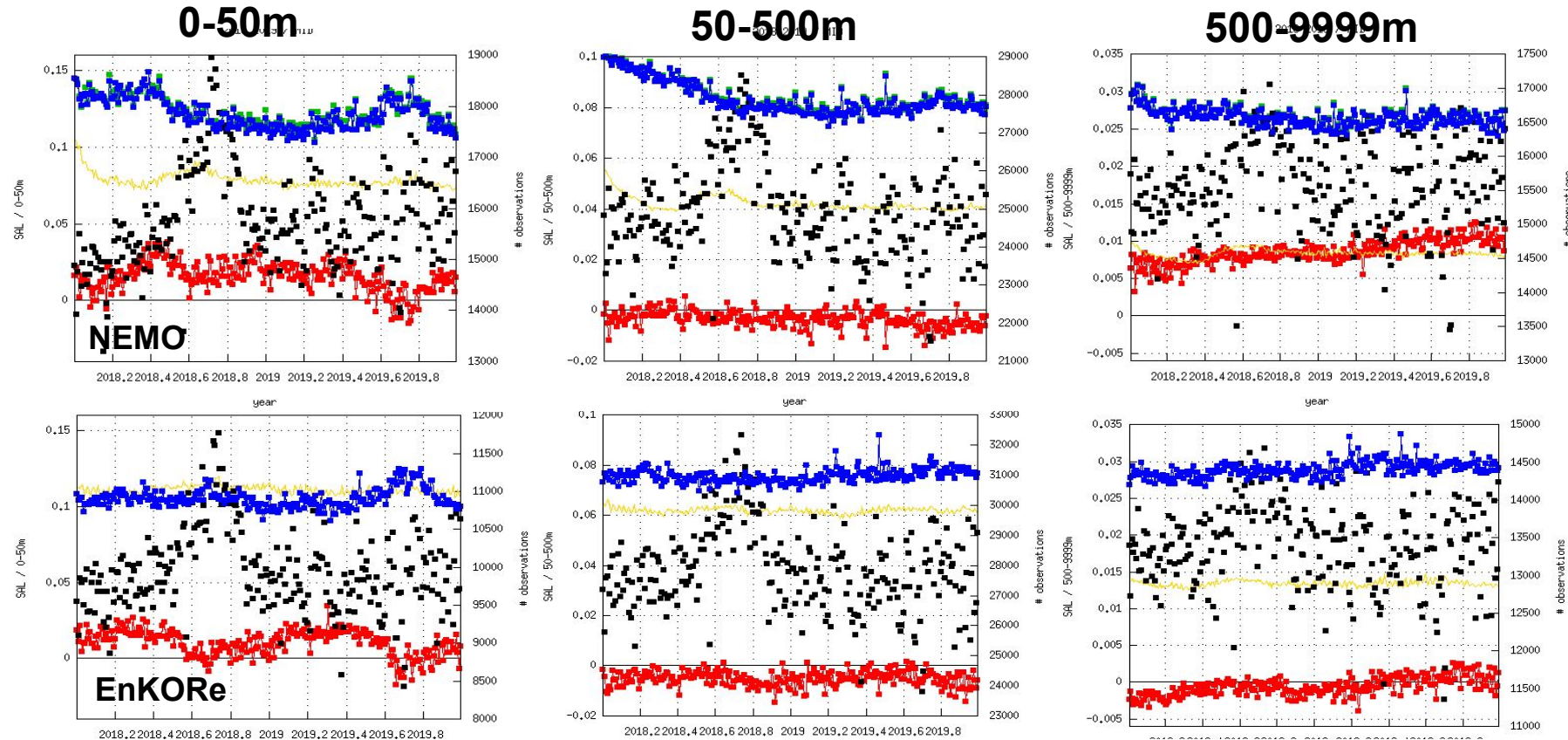
- NEMO positive bias
- NEMO bias and error improve over time
- Similar variation in bias and error as seen for EnKORe
- EnKORe shows better statistics

50-500m

- NEMO large error over first ¼ year
- NEMO bias reasonably stable
- EnKORe negative bias similar to NEMO

500-9999m

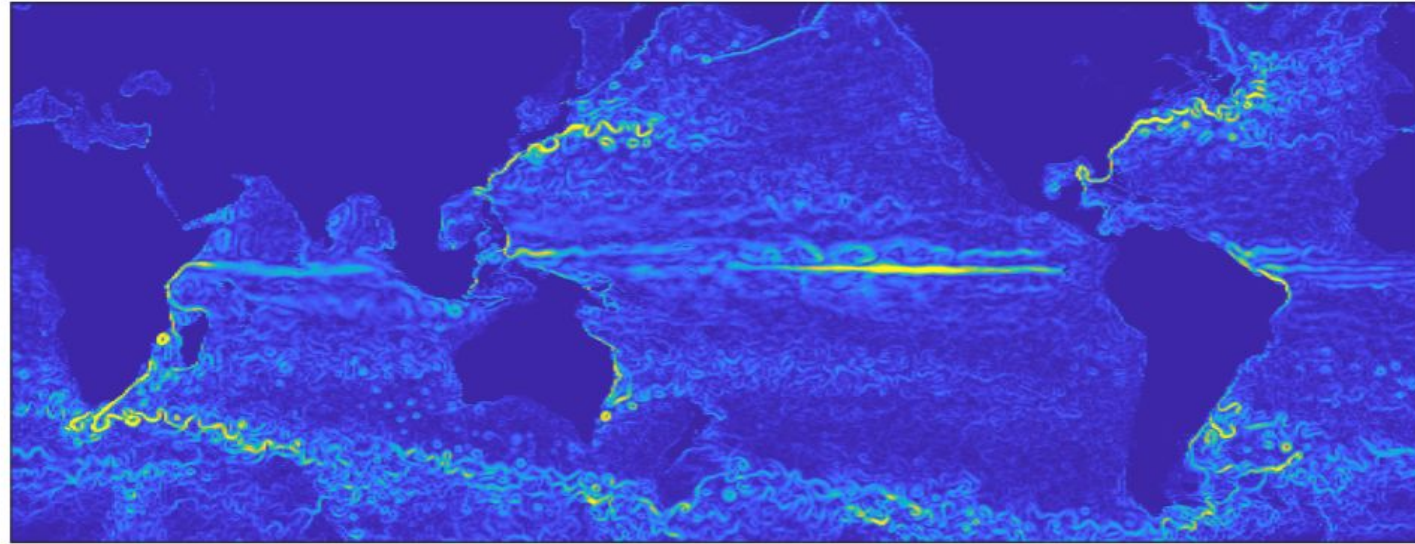
- NEMO error improves - smaller than EnKORe
- NEMO bias increases over time this needs further investigation
- Potentially new initialisation



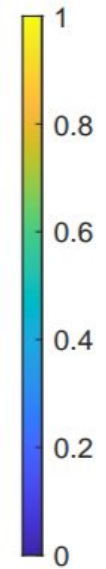
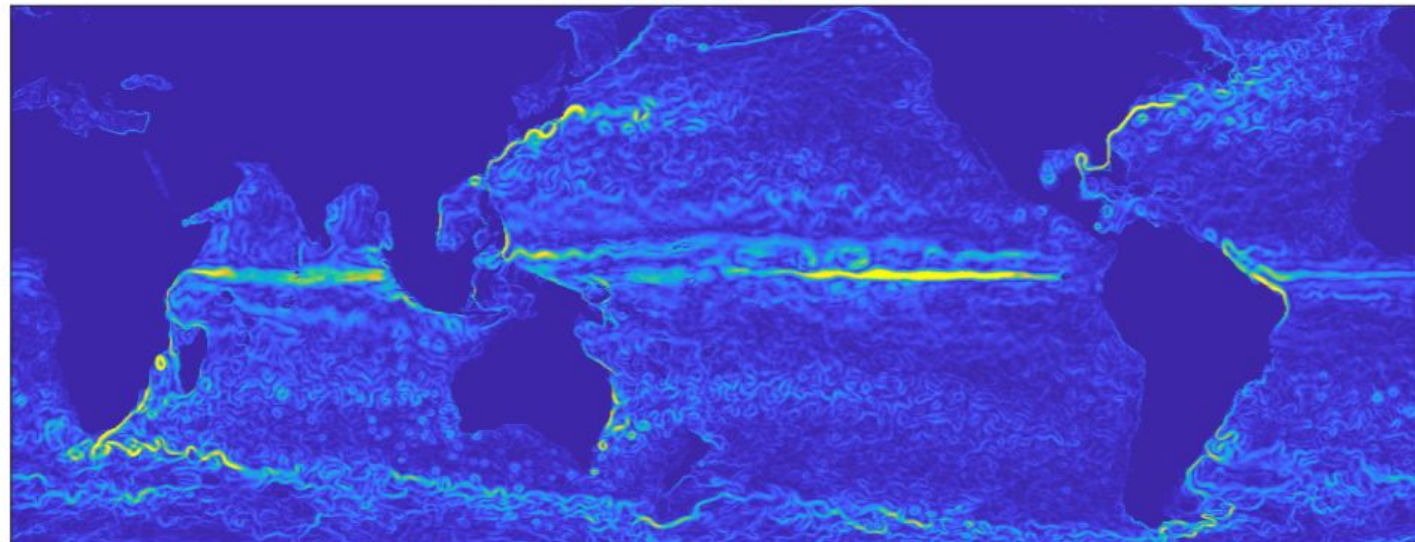
	0-50m			50-500m			500-9999m		
	MAD	BIAS	#OBS	MAD	BIAS	#OBS	MAD	BIAS	#OBS
NEMO	0.122	0.0829	1.92e4	0.0835	-0.00353	2.49e4	0.0265	0.00856	1.56e4
EnKORe	0.105	0.0101	9.95e3	0.0756	-0.00524	2.79e4	0.0289	-0.000651	1.34e4

Velocity fields: Comparison with EnKORe

NEMO12 |V|, 120m, 30/12/2019

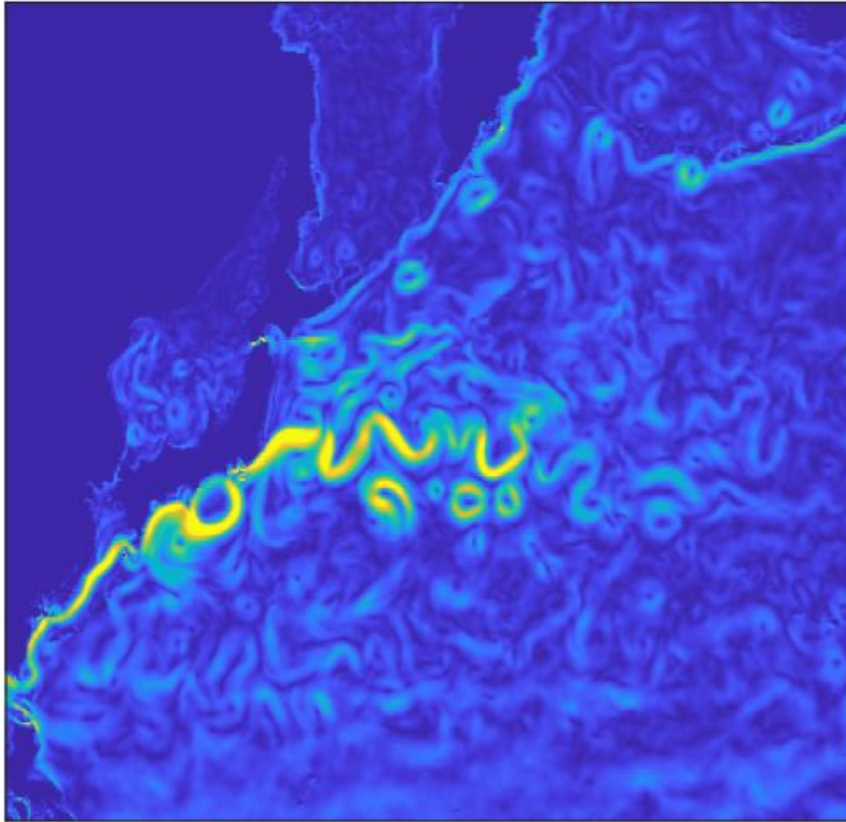


EnKORe |V|, 115m, 30/12/2019

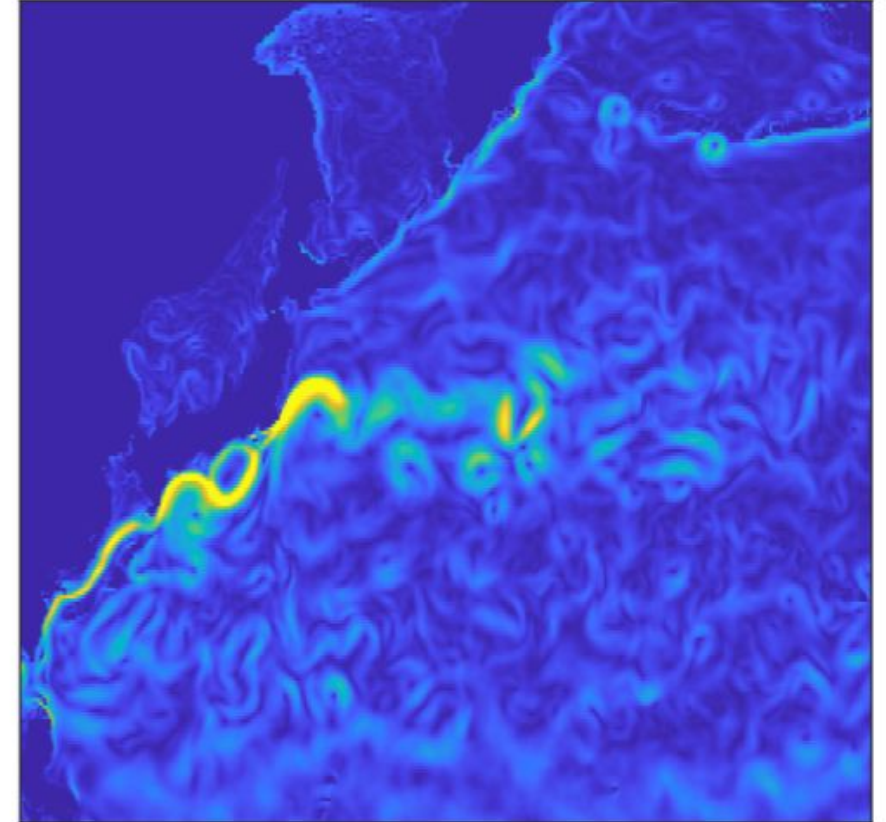


Velocity fields: Comparison with EnKORe (Kuroshio)

NEMO12 |V|, 120m, 30/12/2019

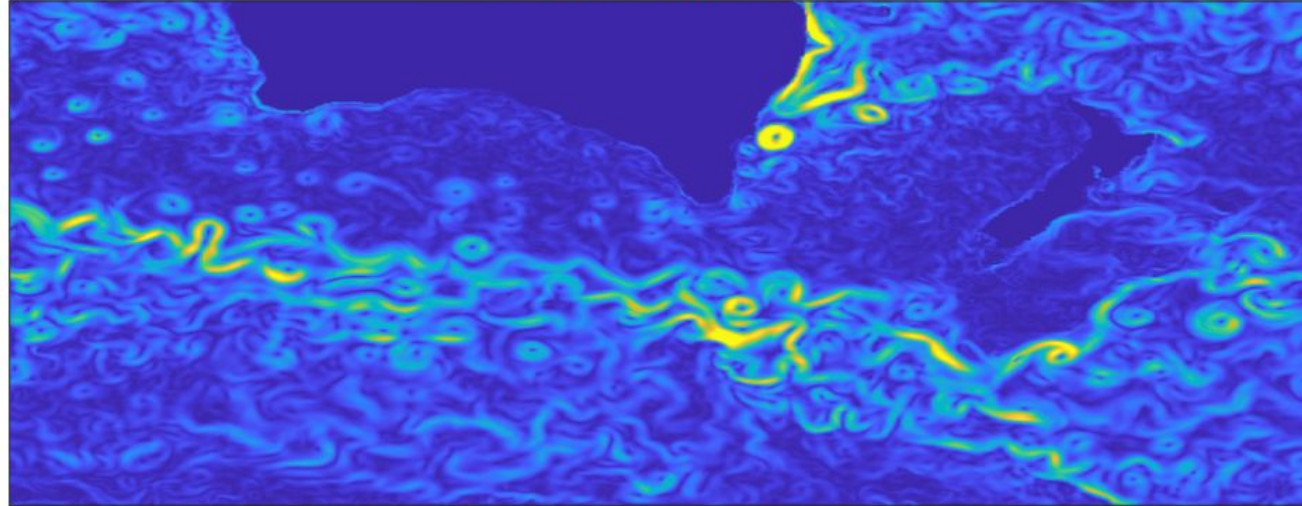


EnKORe |V|, 115m, 30/12/2019

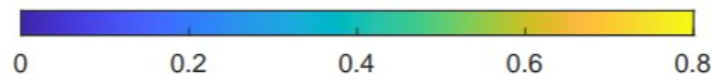
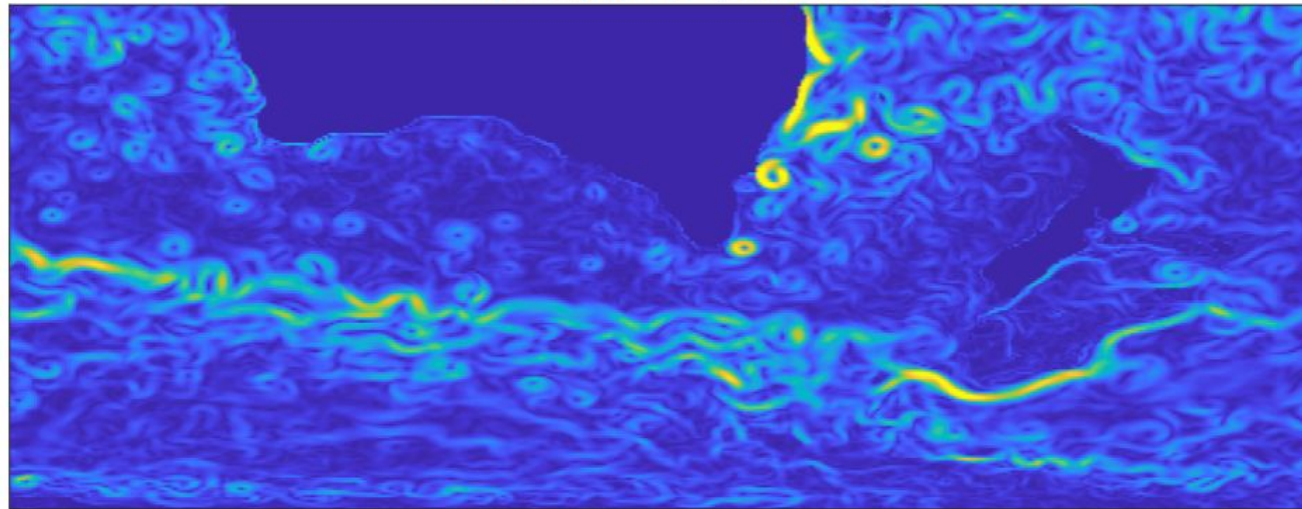


Velocity fields: Comparison with EnKORe

NEMO12 |V|, 120m, 30/12/2019



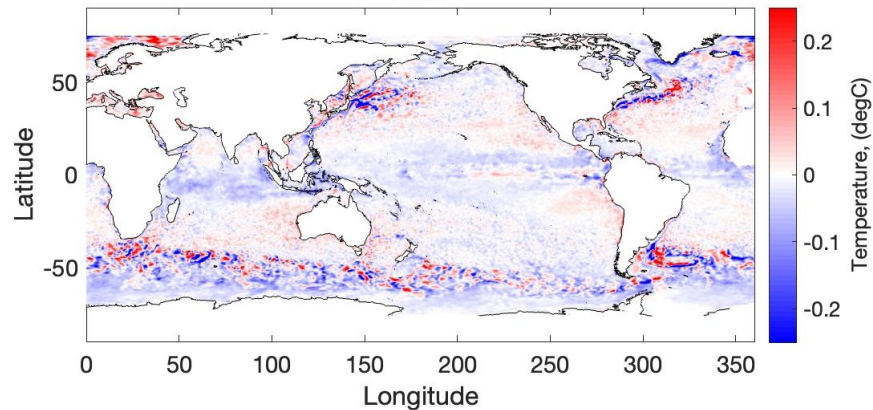
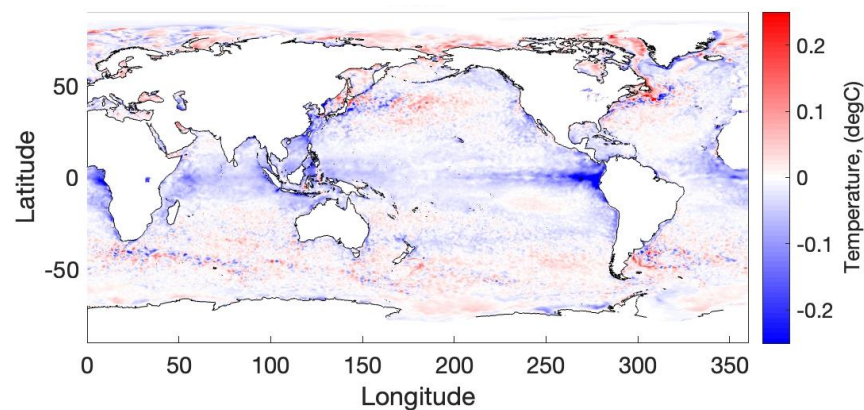
EnKORe |V|, 115m, 30/12/2019



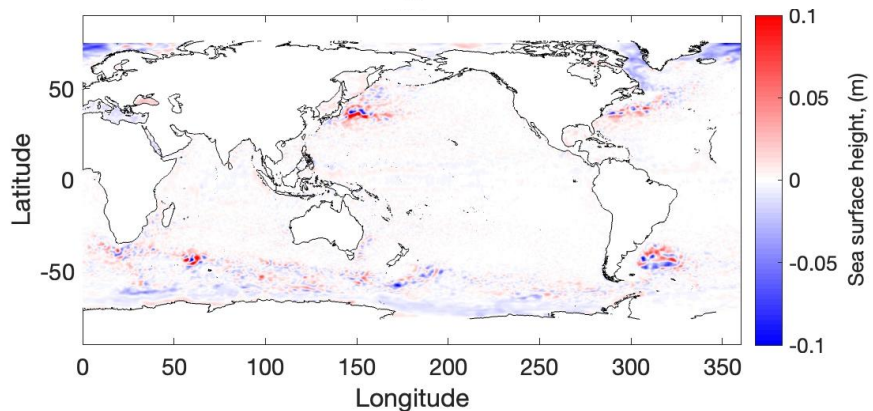
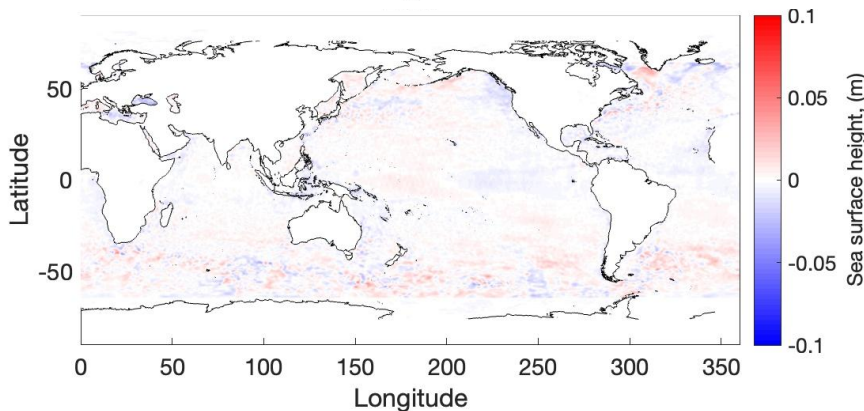
Hindcast performance

OFFICIAL

Mean increments



SST



SSH

NEMO
(2019)

OceanMAPS
(2024)

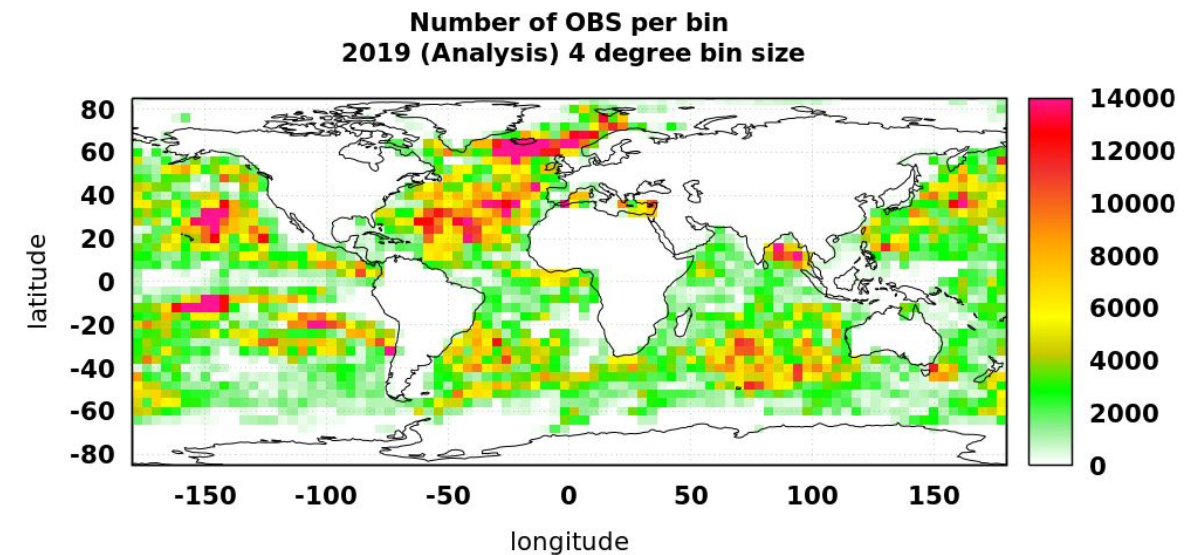
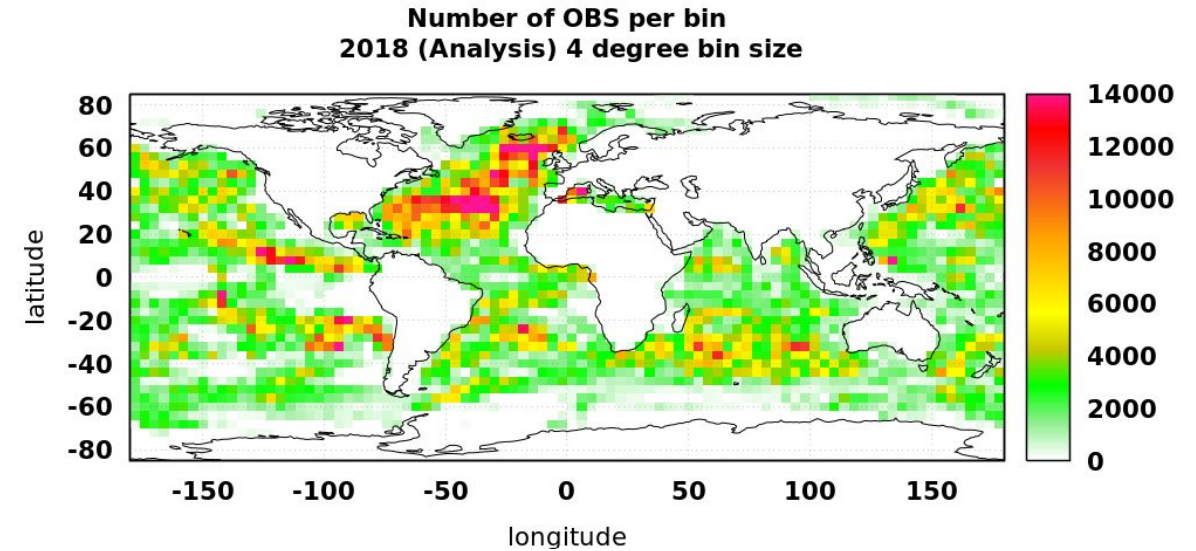
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Ocean currents vs drifting buoys

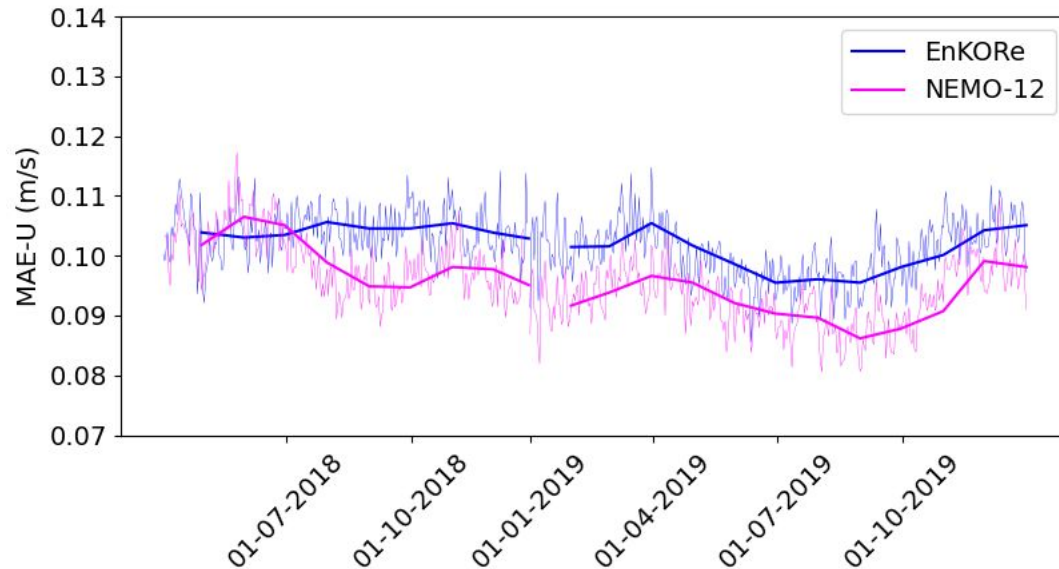
2018-2019 EnKORe vs NEMO-12

- Comparing to currents is high value
- Not assimilated – Independent dataset
- Observations from the global drifter dataset
- Produced by the Data Buoy cooperation Panel (<https://www.ocean-ops.org/DBCP/>) and collected from the GTS
- Drifters track the currents at 15m depth.
- Use of a filtered dataset (not avail online)
- Shown are number of drifter observations available for 2018 and 2019



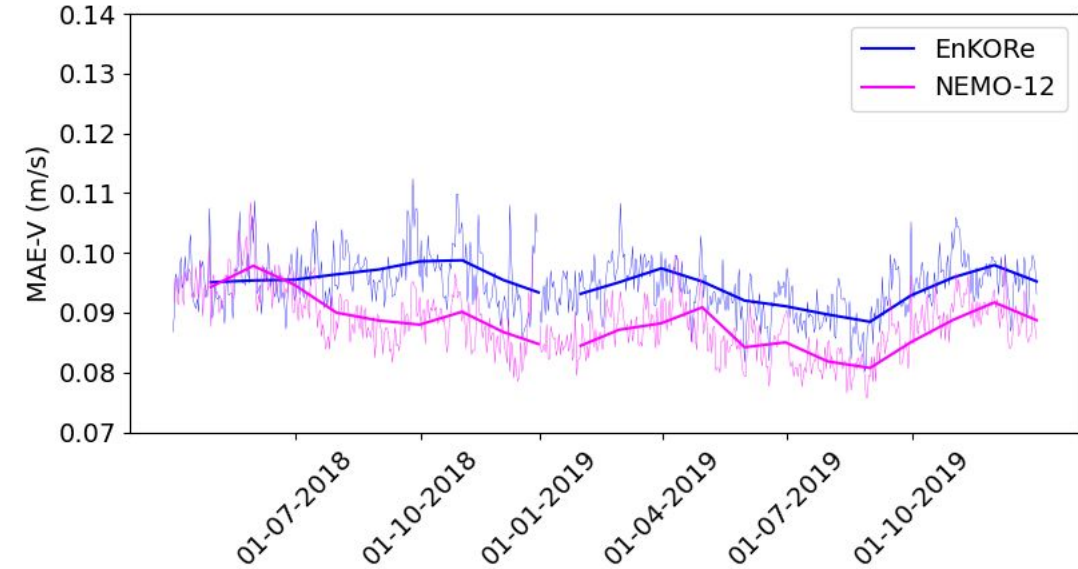
Ocean currents vs drifting buoys

Mean Absolute error



2018, N = 5,894,906

	EnKORe	NEMO-12
MAE-U	0.105	0.100
MAE-V	0.097	0.092
Rcomplex	0.74	0.77



2019, N = 7,596,806

	EnKORe	NEMO-12
MAE-U	0.101	0.094
MAE-V	0.094	0.088
Rcomplex	0.72	0.79

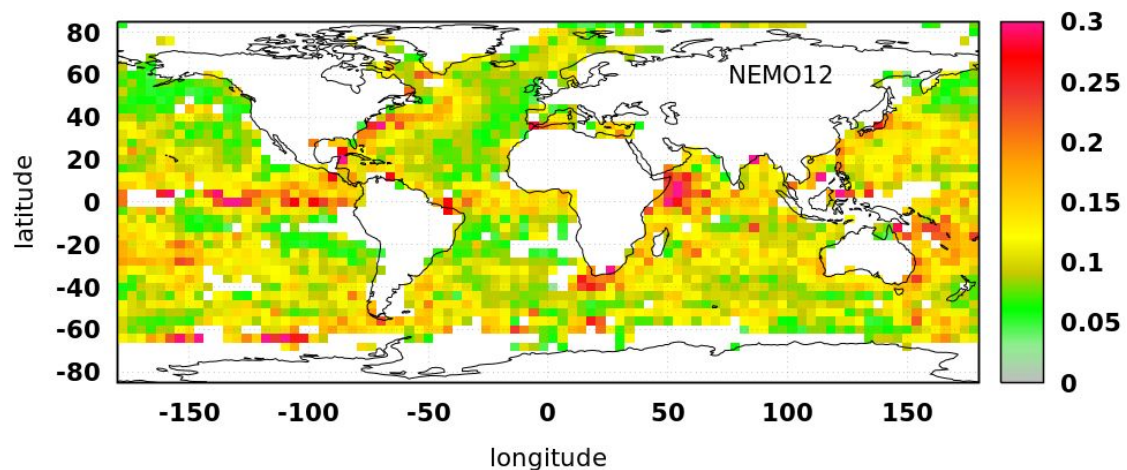




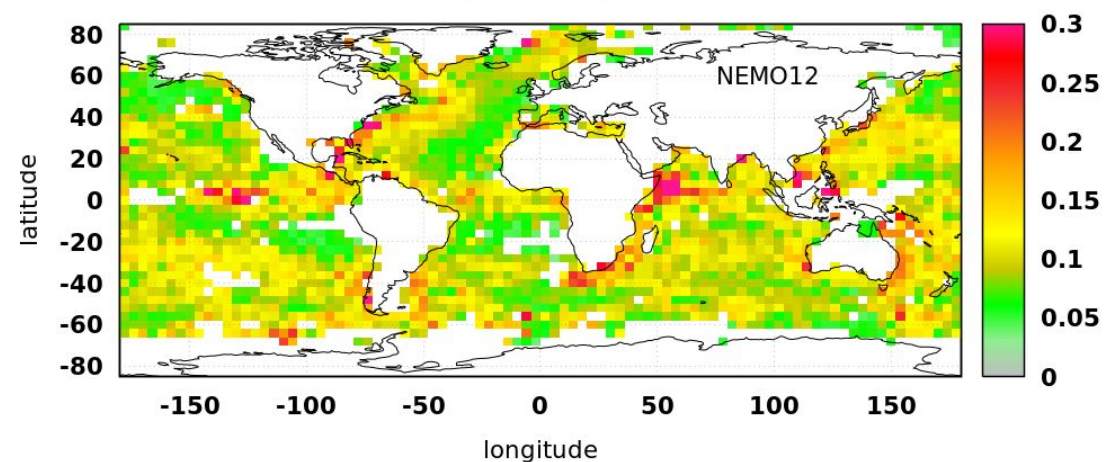
MAE NEMO12 & EnKORe, 2019

Timeframe: 20190101 - 20191215

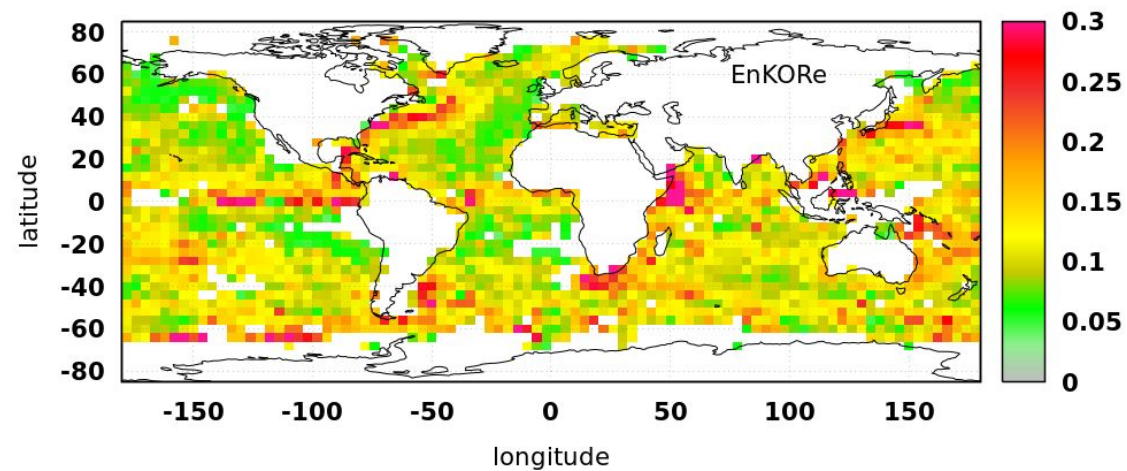
MAE-U (NEMO12 - OBS)
2019 (Analysis) 4 degree bin size



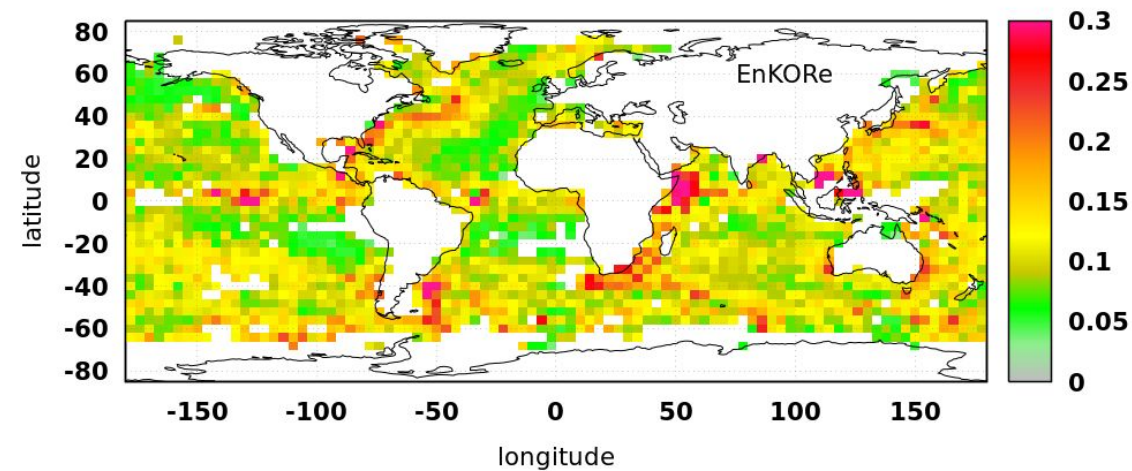
MAE-V (NEMO12 - OBS)
2019 (Analysis) 4 degree bin size



MAE-U (EnKORe - OBS)
2019 (Analysis) 4 degree bin size



MAE-V (EnKORe - OBS)
2019 (Analysis) 4 degree bin size

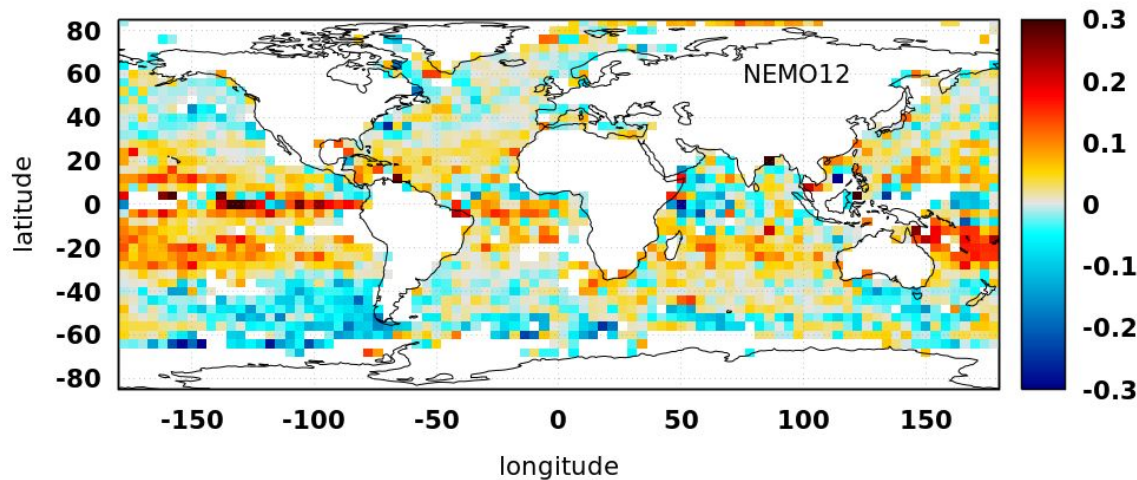




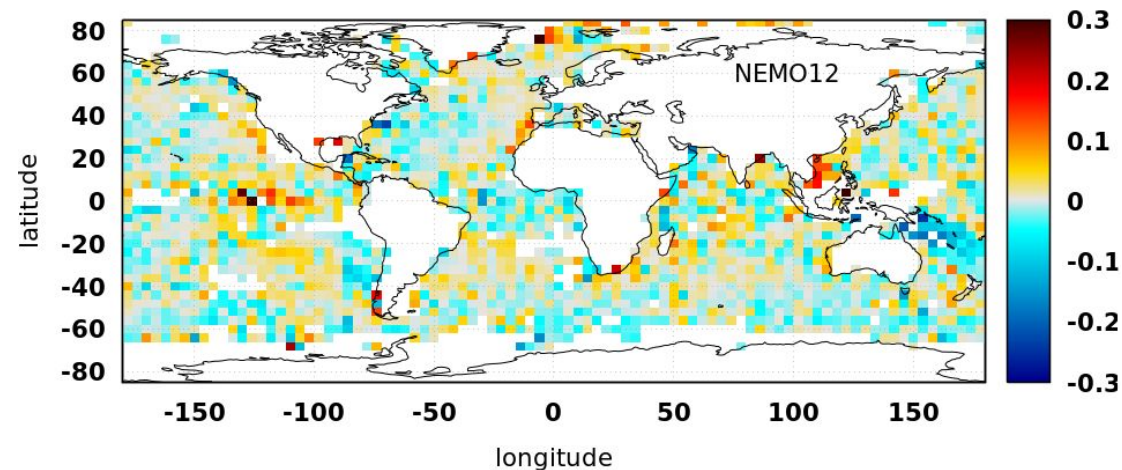
Mean Bias NEMO12 & EnKORe, 2019

Timeframe: 20190101 - 20191215

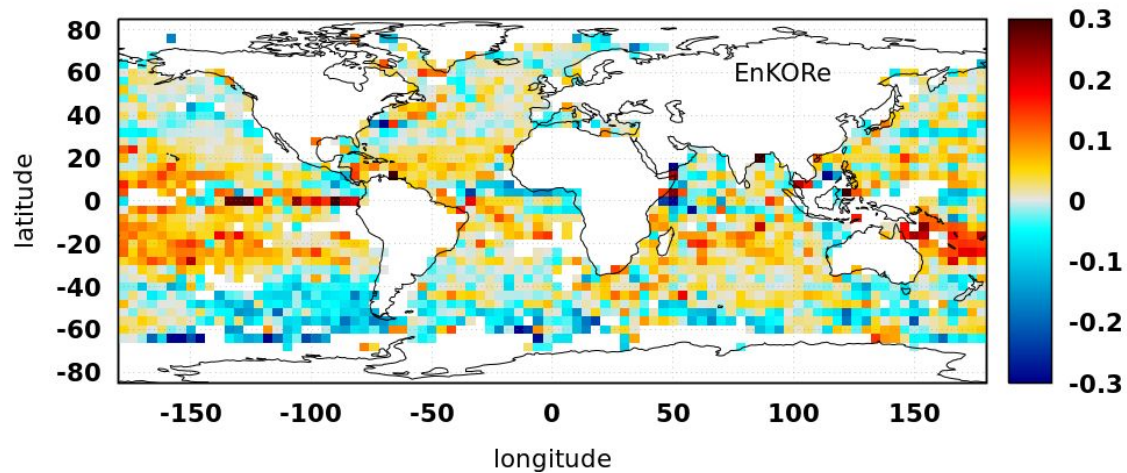
**Mean Bias-U (NEMO12 - OBS)
2019 (Analysis) 4 degree bin size**



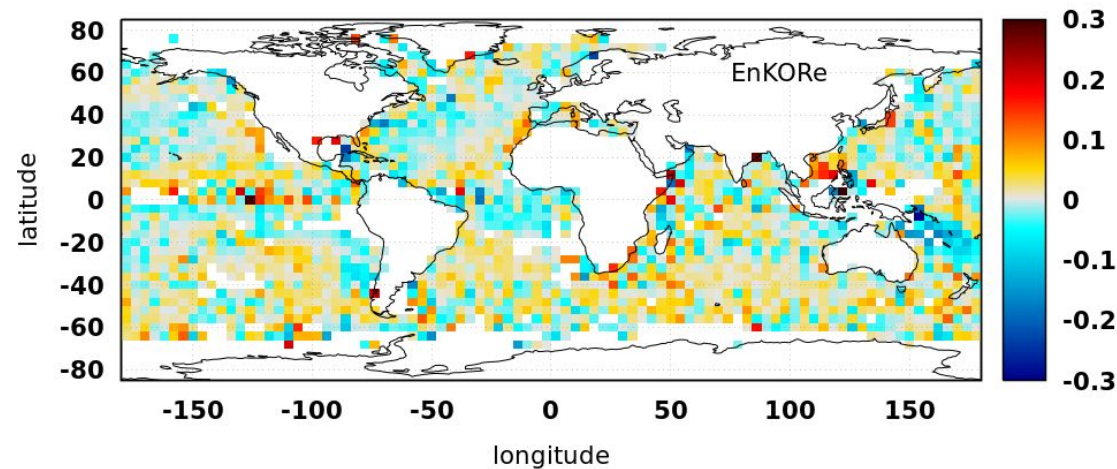
**Mean Bias-V (NEMO12 - OBS)
2019 (Analysis) 4 degree bin size**



**Mean Bias-U (EnKORe - OBS)
2019 (Analysis) 4 degree bin size**



**Mean Bias-V (EnKORe - OBS)
2019 (Analysis) 4 degree bin size**



Summary

- A 1/12-degree EnKF/NEMO system based on GOSI9 has been developed and run from November 2017 to December 2019
- The computational cost is high compared to the current operational system
- Improvements in computational performance are expected after transition to NEMO v5.0
- Improvements in DA performance may be possible after adding output in in-situ T and S

Evidence further performance gains is achievable

- Gains in currents expected to translate to maritime safety
- Gains obtained despite smaller ensemble
- Gains obtained despite increased resolution/variability
- Notable refinement of eddies and boundary currents
- Salinity abyssal bias will be a focus for further improvement

Computational cost

- 24-member NEMO ~ 10 x 48-member EnKORe
- Cost is attributable to the increased domain, resolution and reduced timestep



Next steps

To do

Analysis and evaluation needs to be extended

- Transfer the model to Bureau's HPC
- Further optimization, extended stationary ensemble
- Salinity abyssal bias will be a focus for further improvement

Limited attention given to sea-ice

- Detailed evaluation and optimisation

Extend to full hindcasts and evaluation of forecast skill

- ACCESS-G, R/T observations,
- Comparisons with OceanMAPSv4

NEMOv5.0 uptake and development at the Bureau

by EoFY 2025

- Possible compilation of NEMOv5.0 on NCI HPC
- Initial look into XIOSv3.0

December 2025:

- Configuration of early NEMOv5.0 GOSI10 development suite on Gadi
- Optimisation of XIOSv3 on Gadi
- Analysis of computational performance of NEMOv5 compared to NEMOv4
- Configuration of NEMOv5 on DR machine

June 2026

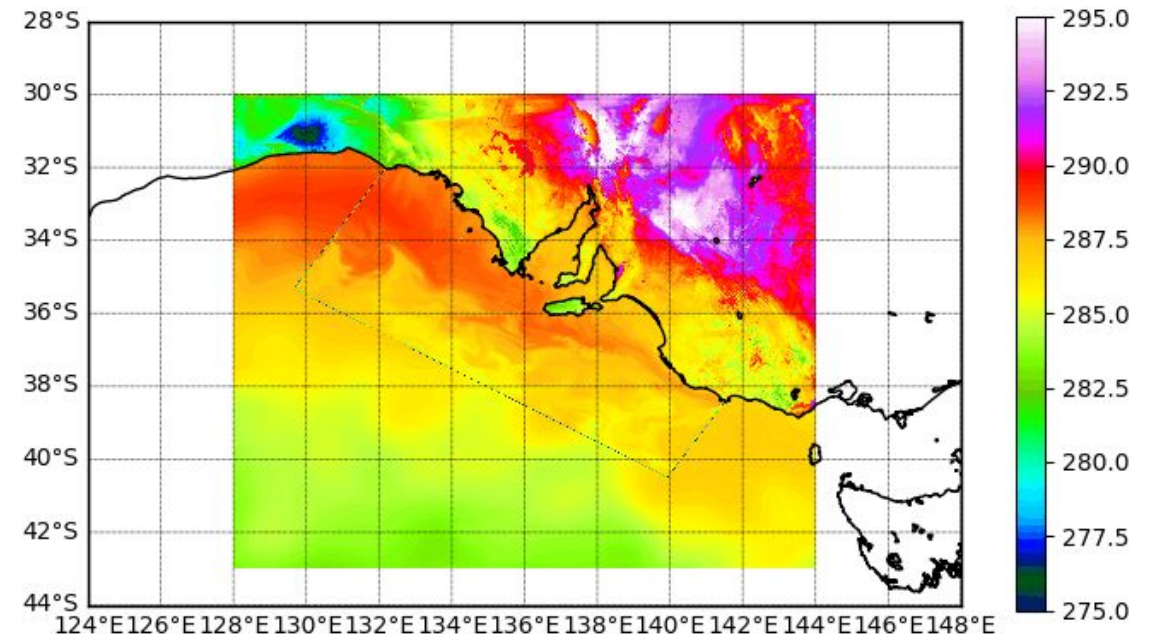
- Integrate eORCA12 NEMOv5 GOSI10 and into development of NEMO-based EnKF model



NEMO based ocean modelling at the Bureau of Meteorology, Australia

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2. **Other developments at the BoM including NEMO ocean model**
 - *Regional (coupled) ocean systems*
 - *Global ORCA12 10 year hindcast*



Regional NEMO based systems

Regional ocean modelling systems for defence

- DA/ large domains high resolution

Coupled model utilising RCS infrastructure/ framework

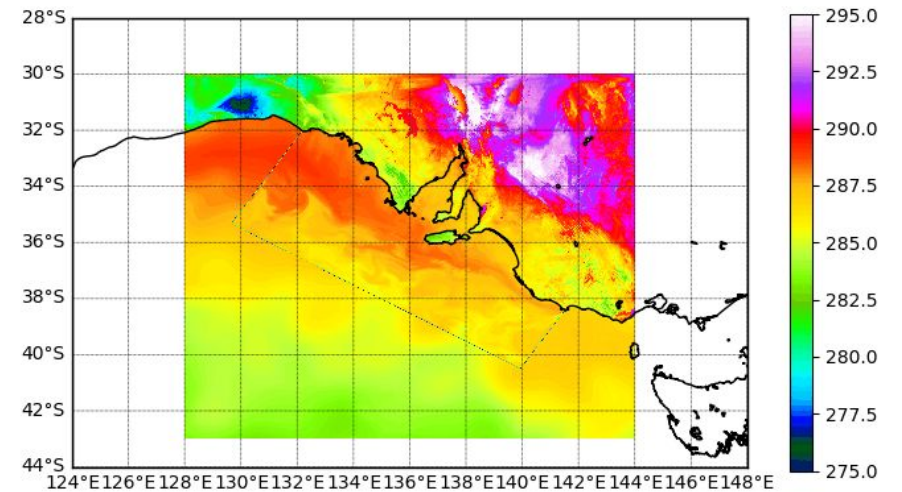
- Fully coupled/ partially coupled

Prototype system 1

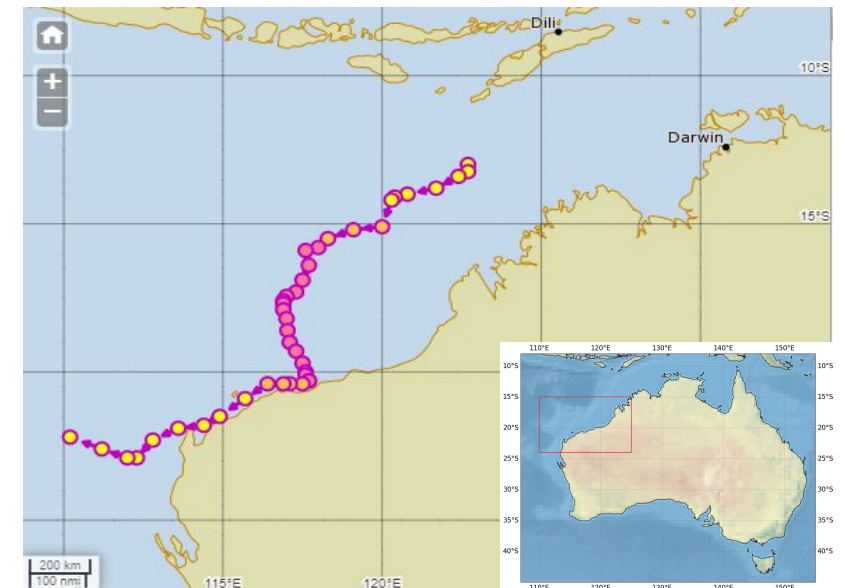
- Regional coupled atmosphere-ocean model over SA shelf
- Ocean – atmosphere coupling

Prototype system 2

- Tropical cyclone test case over the NW Shelf
- Ocean-wave-atmosphere coupling



Coupled system over South Australia

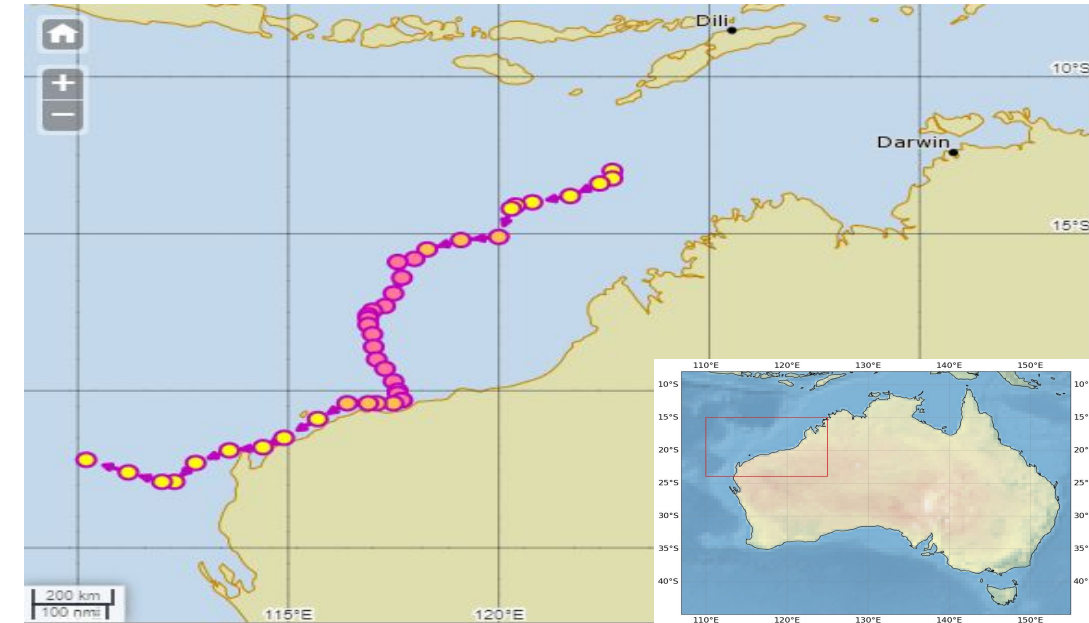


Tropical cyclone Veronica (18-3-2019 to 28-3-2019)

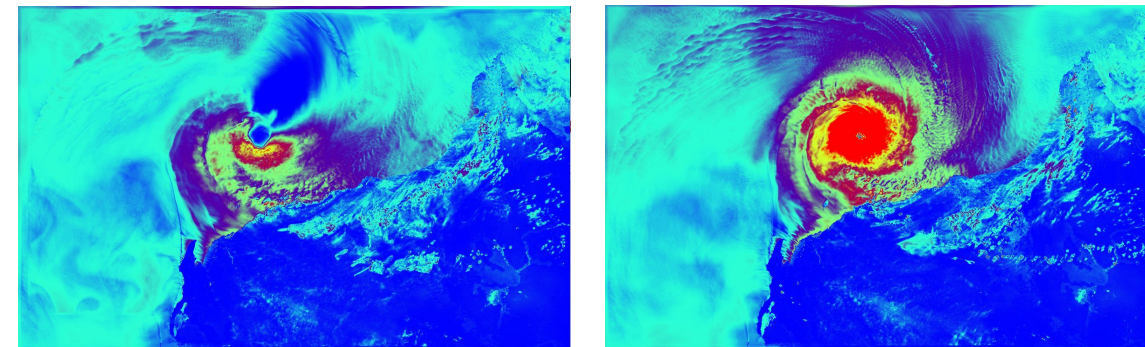


Regional coupled modelling

- Coastal hazards are affecting communities, sea safety
- Offshore industry (structures) are affected by waves and currents
- Varying seas affect harbour activities and shipping
 - Affecting operational times and cost
 - Important for land operations, mining, infrastructure
- Tropical cyclones are extreme low-pressure systems which develop over high sea-surface temperatures in tropical seas
- Cost associated with this TC ~ \$2 bil AUD
- Loss of cattle (~2000)



Tropical cyclone Veronica starting 18-3-2019 and ending 28-3-2019

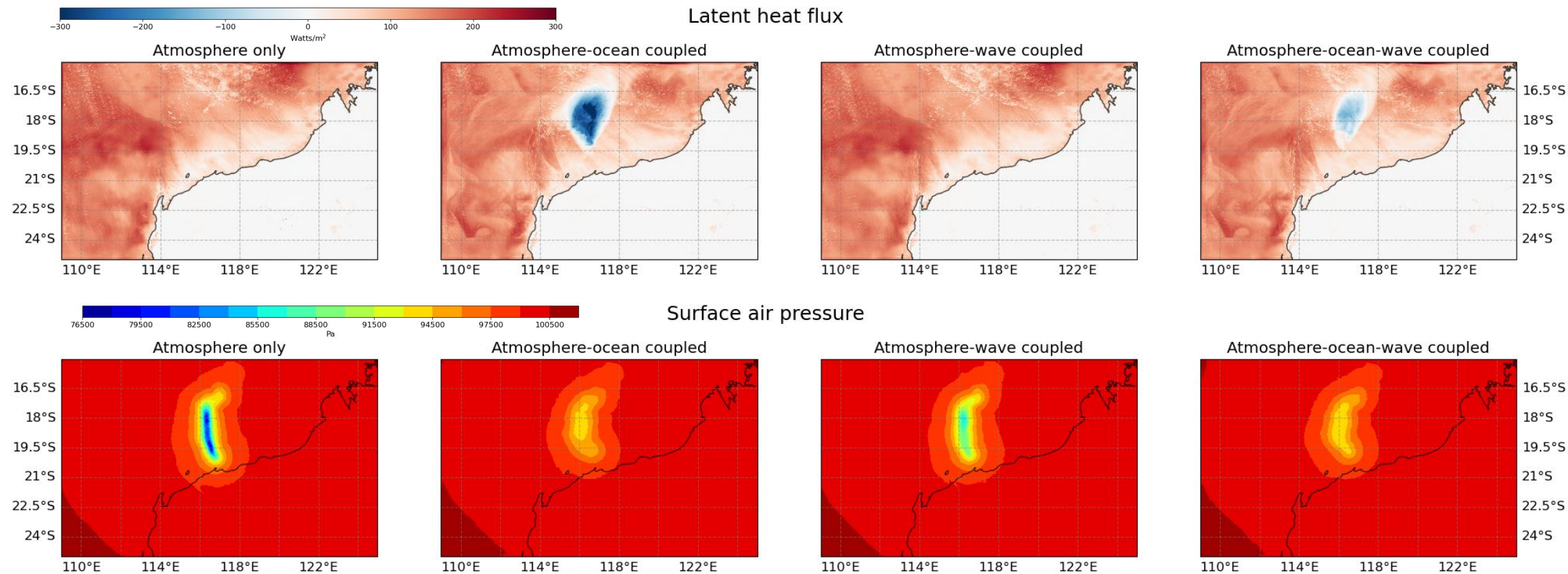
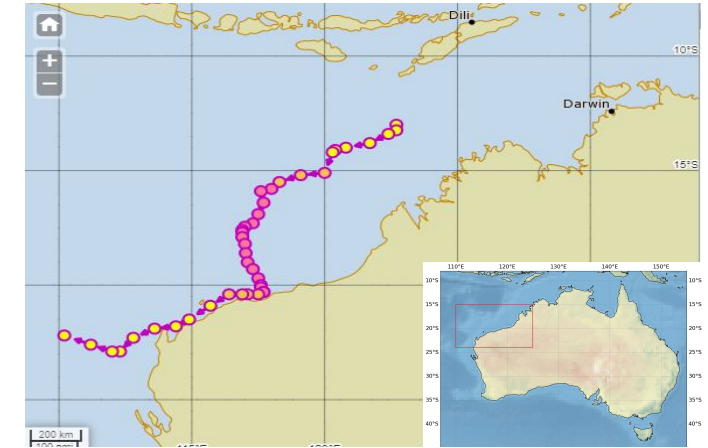


Latent heat flux: Left Coupled. Right: Uncoupled.

Regional coupled modelling – first results

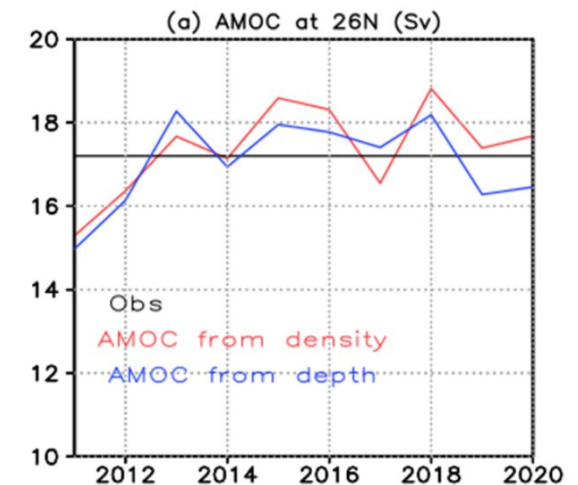
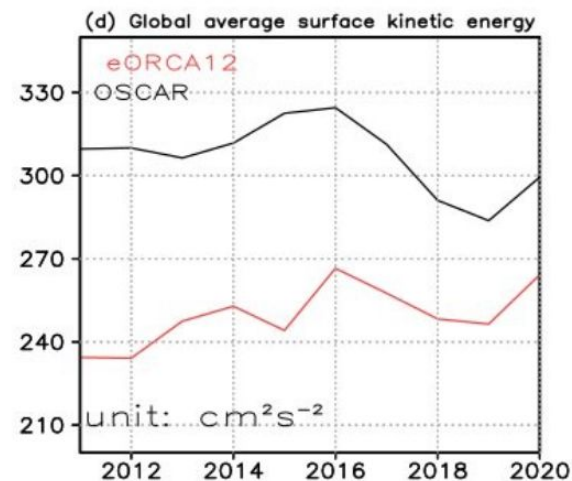
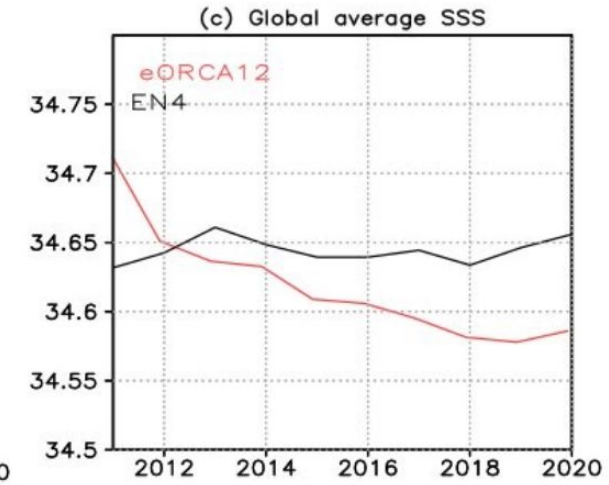
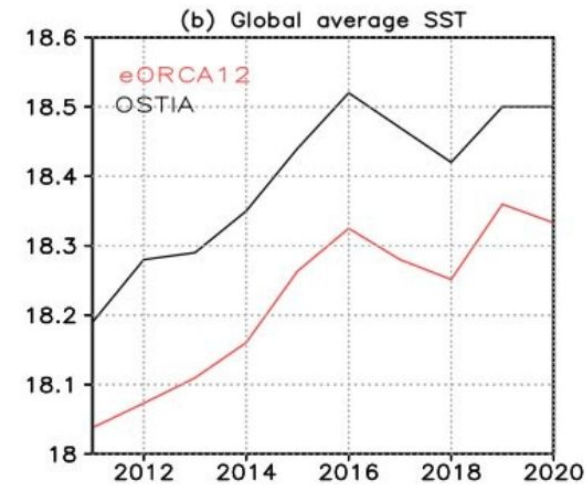
TC Veronica over the NW Shelf, Australia

- Upper: Minimum upward latent heat flux over 5 days
- Lower: Minimum air pressure at sea level over 5 days



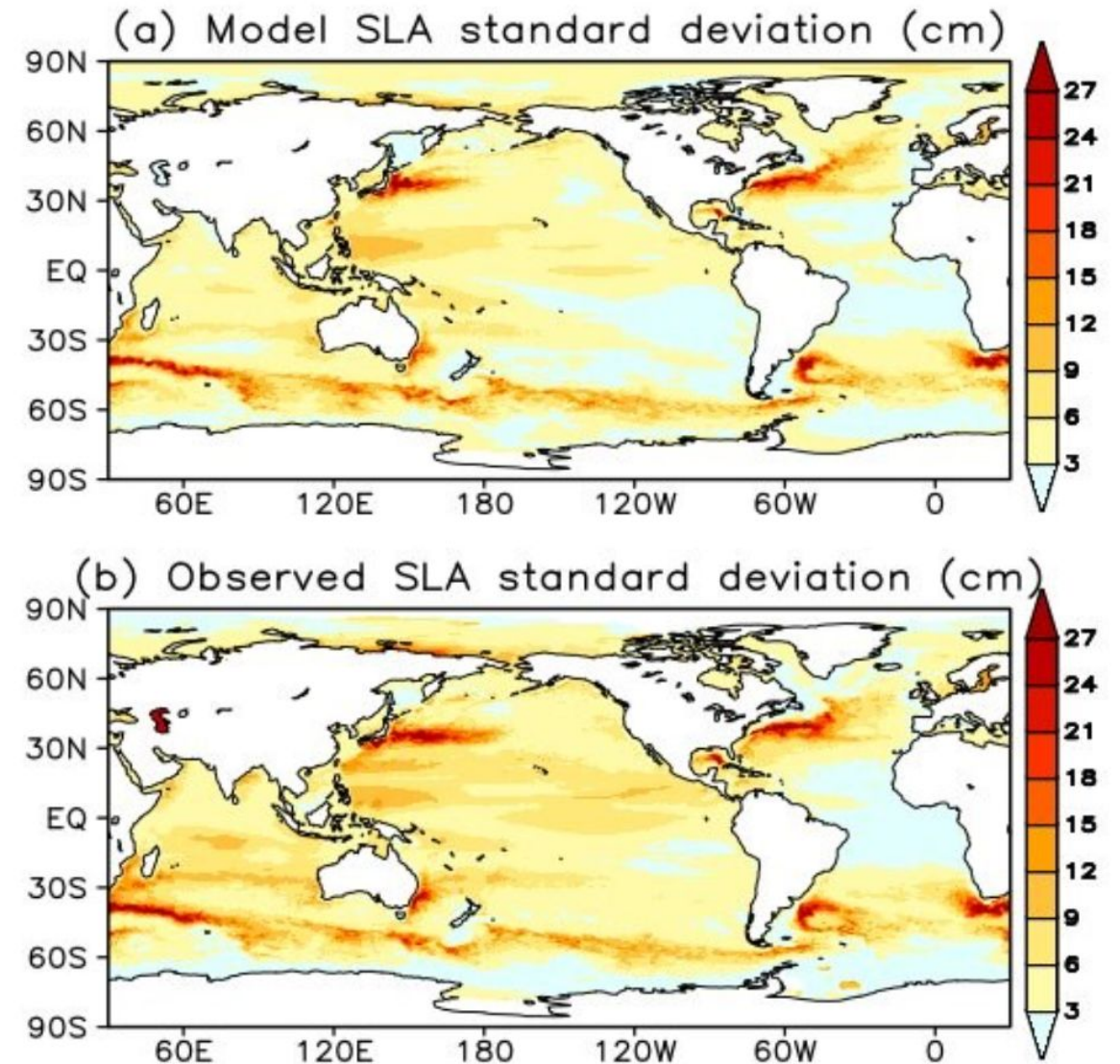
Global modelling ORCA12 hindcast forced by ERA5

- Additional evaluation to Guivarch et al, 2024
- Initial motivation
 - understand NEMO system
 - preparation for ORCA12 DA system
- A 10-year hindcast simulation run between 2011-2022.
- Initialisation: EN4 climatology
- ERA5 surface forcing
 - NCAR bulk formula.
 - Specific humidity computed from dewpoint temperature.
- Analysis of a suite of diagnostic KPIs was used to evaluate suitability of GOSI9 for ocean DA.
- Overall good representation of global fields compared with observational datasets.



Global SSH variance

- SSH variance shows variability in sea surface height.
- Using monthly averaged values indicated area of high energetics at monthly time scales.
- Captured variability associated with high energetics of Western Boundary Currents.
- Generally surface currents and global transports are well represented in GOSI9.



Thank you

- Established NEMO modelling presence at the Bureau
 - Global and regional
- Main priority has been in developing the global EnKF system – results are promising
- Regional systems are being developed (including transition of storm surge systems and coupled systems)
- Collaboration with Momentum partnership continues to be important on our NEMO journey

