Towards a high-resolution south-eastern Australia coastal ocean forecast (SEA-COFS) using advanced data assimilation

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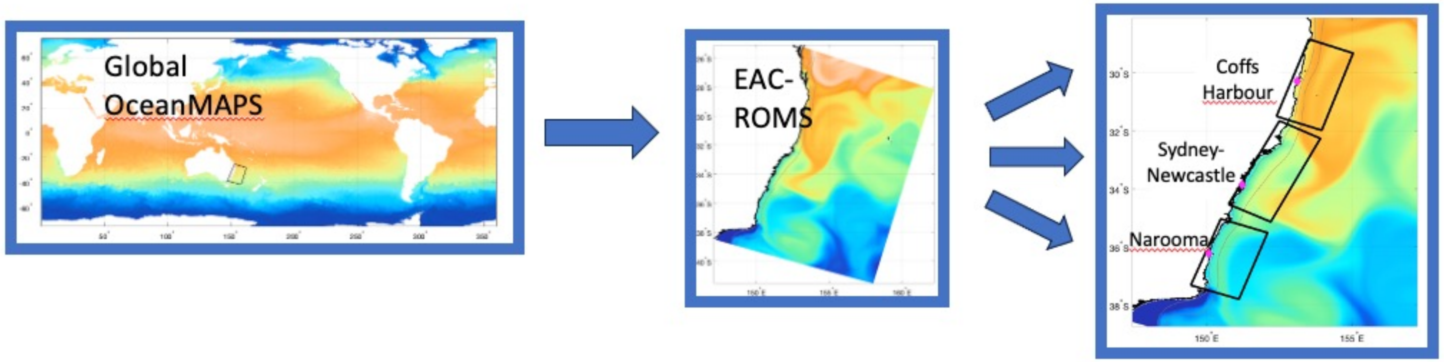
2. Bureau of Meteorology, Sydney, Australia
3. UQ, 4. CCRC, UNSW Sydney, 5. SOEST, University of Hawaii, 6. MetOcean NZ



The Bureau of Meteorology

ACCESS
Australian Earth System Simulator
National Research Infrastructure

GOOS | CoastPredict
with The Global Ocean Observing System

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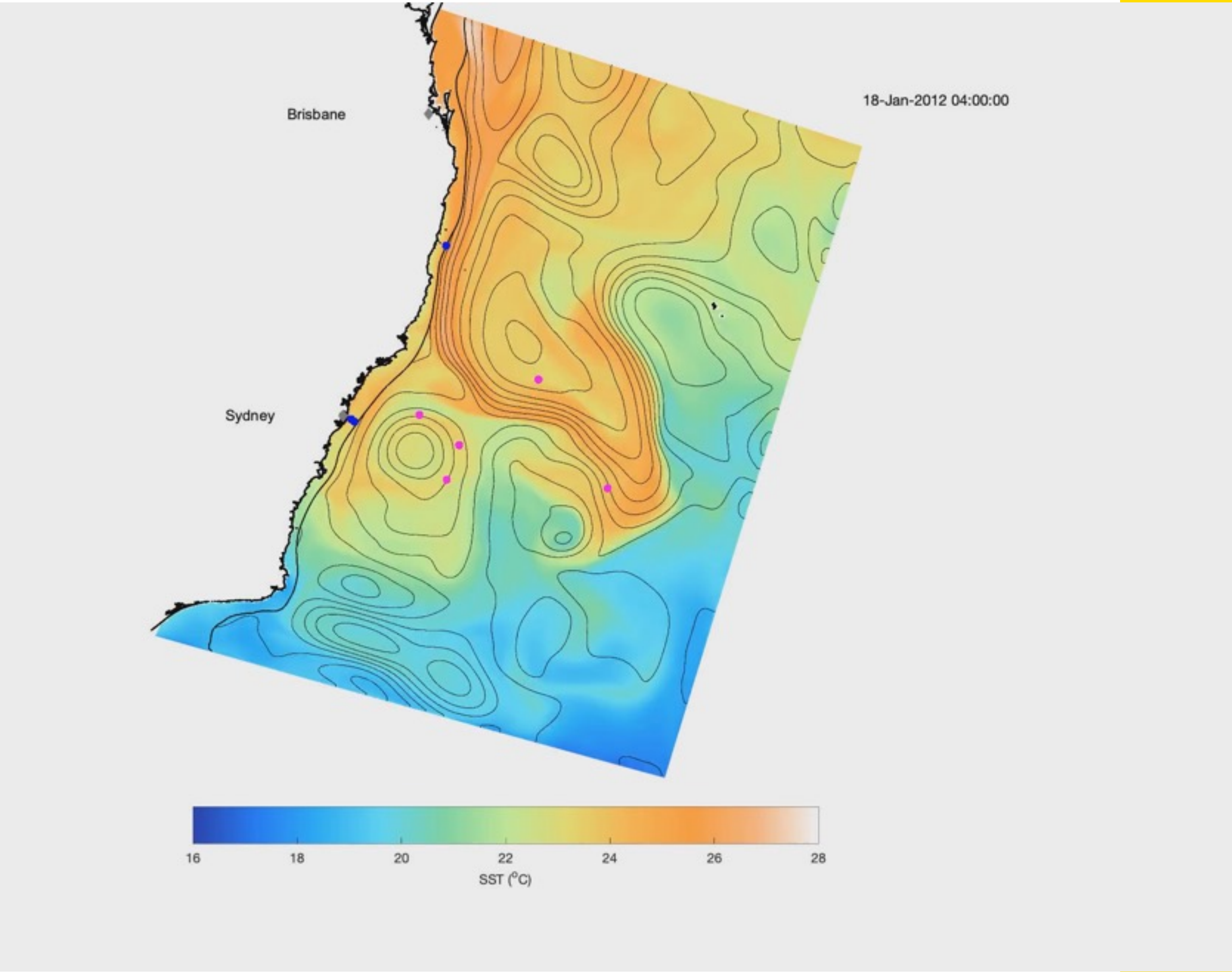
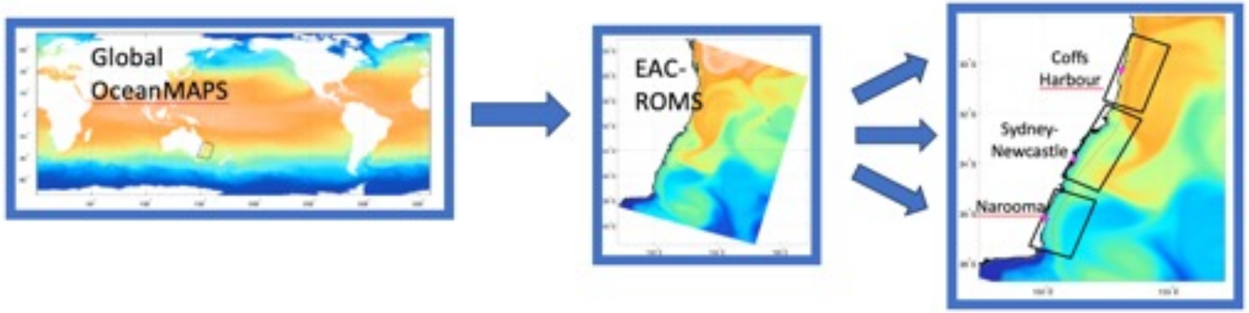
The East Australian Current System

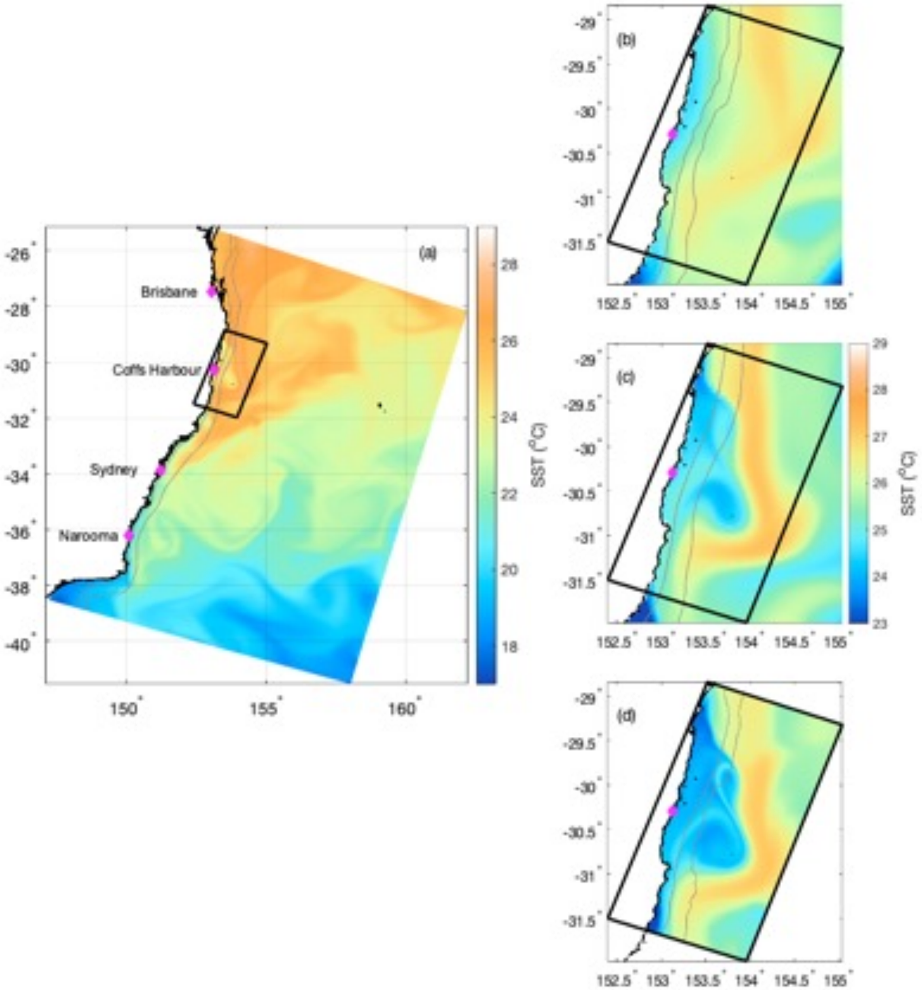
- EAC dominates the SE Australia coastal environment
- Challenging to model, observe and predict
- Interactions between the EAC (and its eddies) and coastal waters drive complex ocean currents and temperature gradients
- Accurate past estimates and future predictions of these features are crucial for
    - Understanding EAC dynamics and assessing trends
    - Biological productivity and the distribution of nutrients and biota
    - Adaptive management of fisheries
    - Search and Rescue
    - Navigation, optimal ship routes
    - MHW prediction
    - Managing pollution spills and flood plumes



Shelf and Coastal Circulation



- Complex, submesoscale circulation inshore of the EAC
- Can drive the uplift of nutrients onto the shelf
- Fronts between EAC eddies or between the EAC and coastal waters often biologically productive regions
- EAC and eddies impinging on the shelf can drive deep and long-lasting Marine Heatwaves
- Affect the structure of river plumes, pollutant and oil spills and their coastal impacts
- Larval dispersal and settlement
- Features often poorly resolved by altimetry and highly variable in time and space

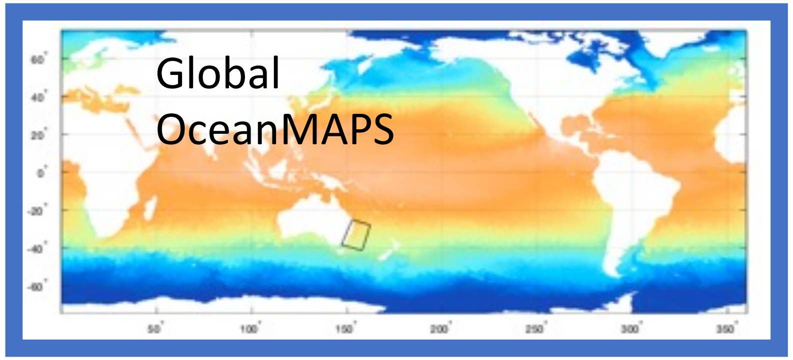


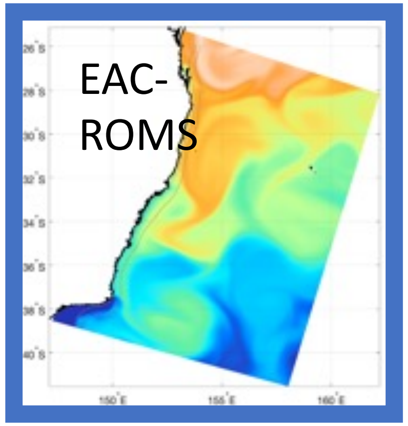
OceanMAPS (~10km)

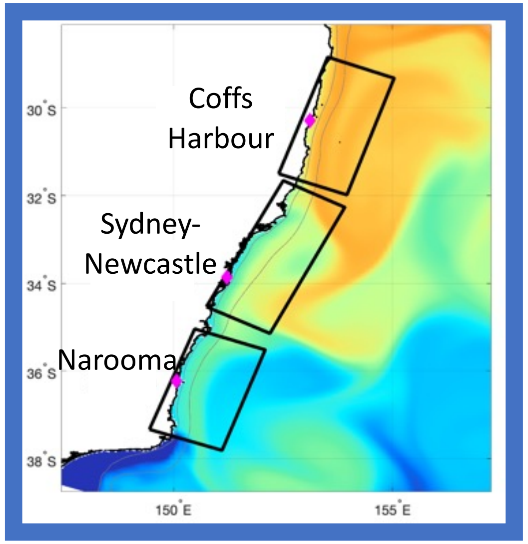
EAC-ROMS (2.5-6km)

Coffs Harbour Model (750m-1km)

The Proposed Prediction System - A series of nested hydrodynamic models







- Ocean model
  - OFAM3 – MOM5
  - 1/10° x 1/10° (10km)
  - 51 levels
- Data assimilation
  - Hybrid EnKF
  - 48 dynamic members
  - 144 low-mode stationary modes
- Atmospheric forcing
  - ACCESS-G3 (12km)
  - Bulk formulae
- Observations
  - RADS altimetry [Jason-3, Sentinnel-3A and 3B, Sentinnel-6A, Cryosat-2, SARAL]
  - Satellite SST [VIIRS/NPP, VIIRS/NOAA20, AVHRR/NAVO, AMSR2]
  - Argo, XBT, Mooring CTD, other CTDs

- Ocean model
  - ROMS
  - **2.5-5km** (increased on shelf/slope)
  - 30 levels
- Data assimilation
  - 4D-Var in initial pilot mode
  - 4D-Var extensively studied in pilot studies
- Atmospheric forcing
  - ACCESS-G3 (12km)
  - Bulk formulae
- Observations
  - **SSH, SST, profiles**
  - **HF radar Coffs and Newcastle**
  - **Gliders**
  - **Shelf moorings**
  - **FishSOOP**
  - **SWOT**

- Ocean model
  - ROMS
  - 750m-1km
  - 30 levels
- Data assimilation
  - Not yet
  - Boundary dominated
- Atmospheric forcing
  - ACCESS-R (1km)
  - Bulk formulae
- Tides

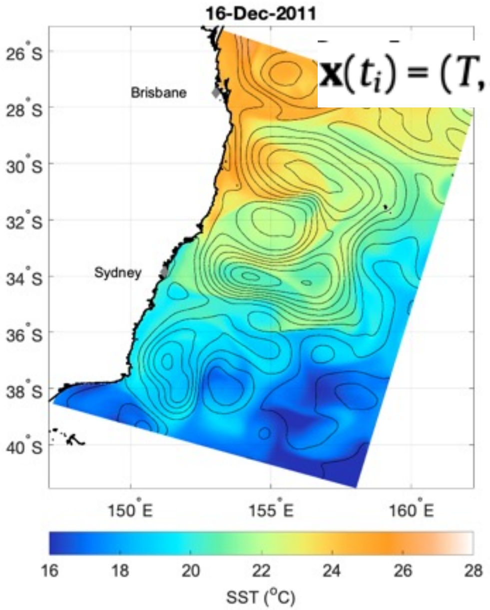
Prediction

Laplace believed that if we knew the **exact location and momentum** of every particle, their past and future values for any given time could be **predicted perfectly** from the laws of classical **mechanics.**

French scholar Pierre-Simon de Laplace (1749–1827)

An accurate forecast requires knowing;

1. ***Where we are starting from*** (i.e. an accurate and dynamically-consistent estimate of the initial conditions), ***and***
2. ***Where we are going*** (i.e. a well configured free running numerical model).



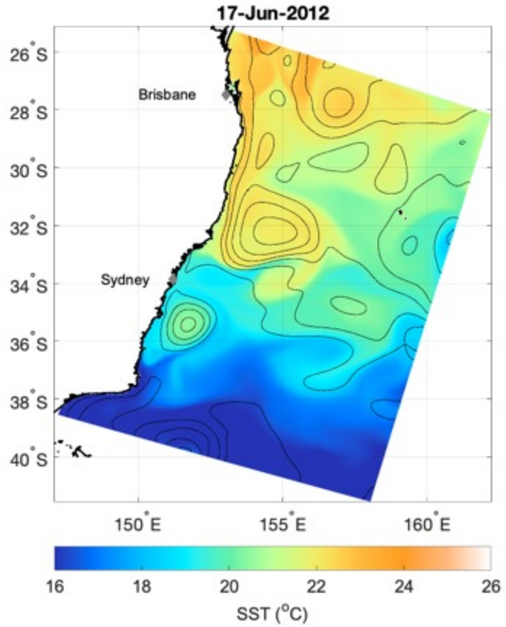
$$\mathbf{x}(t_i) = (T, S, \zeta, u, v)^T$$

$$\mathbf{x}(t_i) = M(t_i, t_{i-1})(\mathbf{x}(t_{i-1}), \mathbf{f}(t_i), \mathbf{b}(t_i))$$

$$\frac{\partial u}{\partial t} + \vec{v} \cdot \nabla u - fv = -\frac{\partial \phi}{\partial x} - \frac{\partial}{\partial z}\left(\overline{u'w'} - \nu \frac{\partial u}{\partial z}\right) + \mathcal{F}_u + \mathcal{D}_u$$

$$\frac{\partial v}{\partial t} + \vec{v} \cdot \nabla v + fu = -\frac{\partial \phi}{\partial y} - \frac{\partial}{\partial z}\left(\overline{v'w'} - \nu \frac{\partial v}{\partial z}\right) + \mathcal{F}_v + \mathcal{D}_v$$

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = -\frac{\partial}{\partial z}\left(\overline{C'w'} - \nu_\theta \frac{\partial C}{\partial z}\right) + \mathcal{F}_C + \mathcal{D}_C$$



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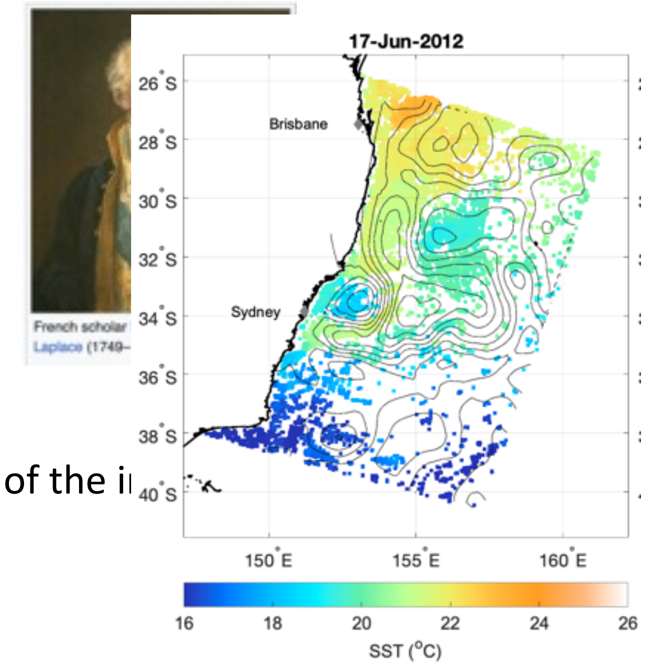

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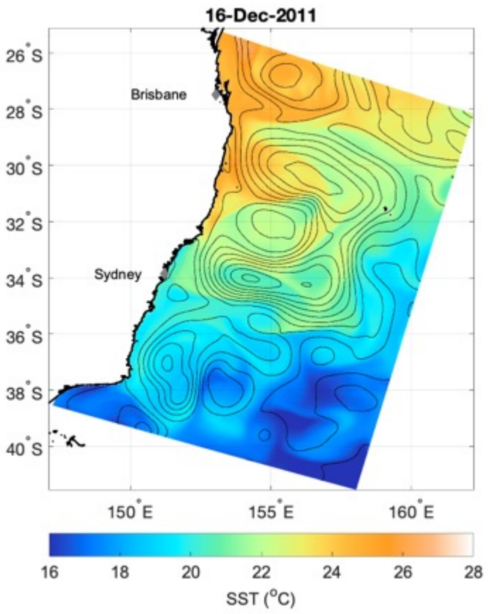

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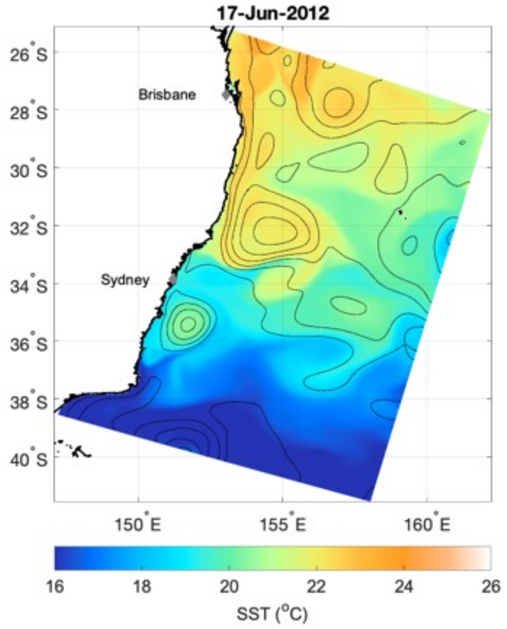

Prediction

Initial conditions are not perfect

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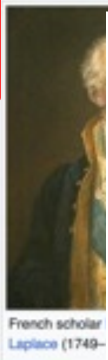
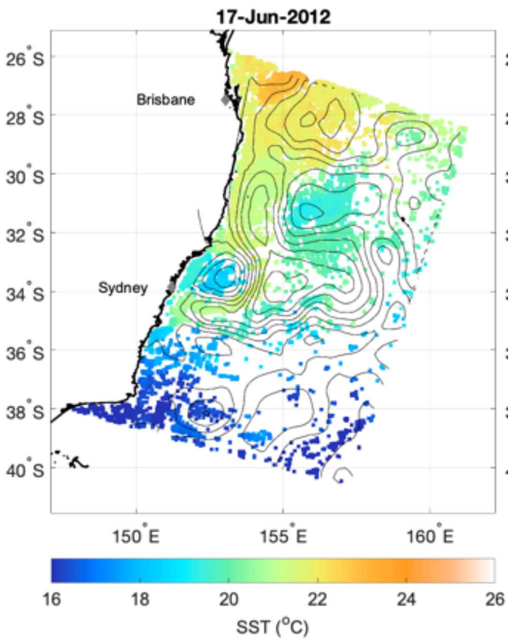
Model physics are not perfect.. discretised, parameterised…





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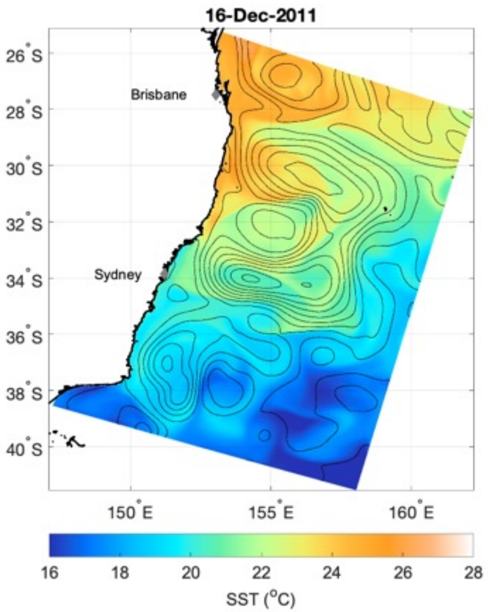
Small errors in **initial conditions** and **model physics** grow, so we cannot predict the future (unless we observe the real world and correct our models regularly)!



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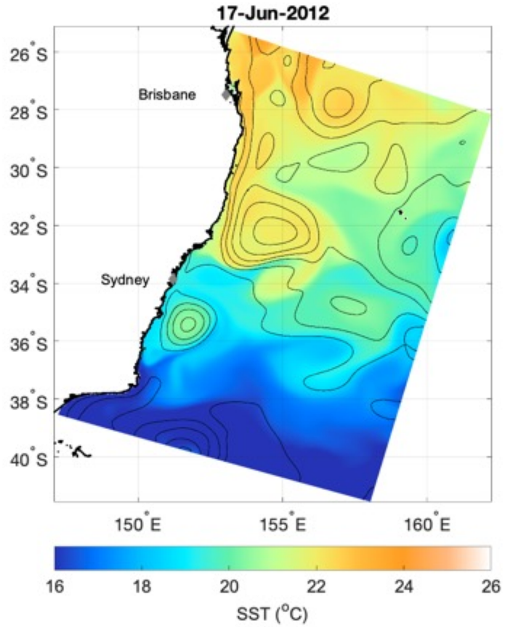

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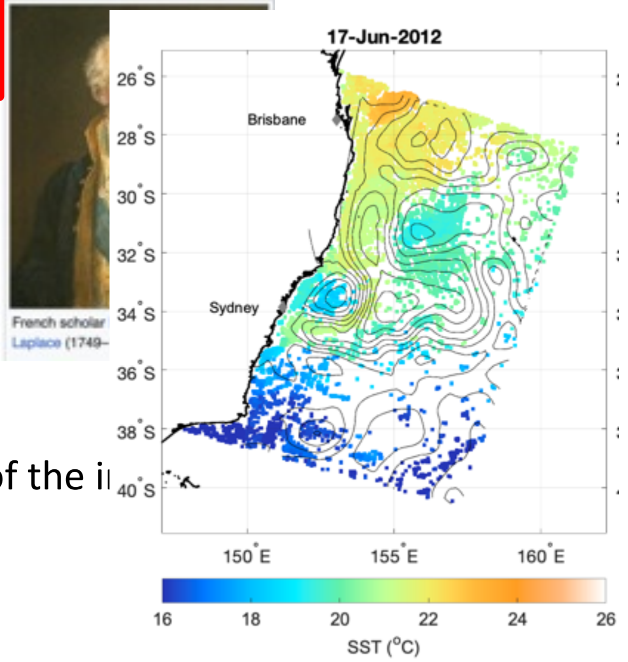

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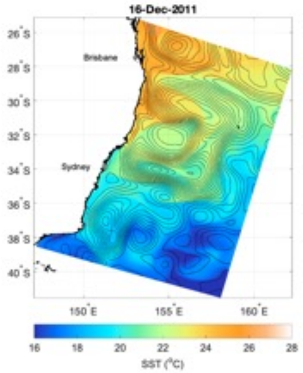
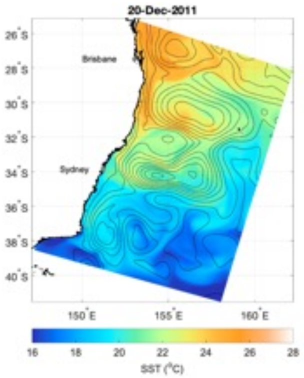
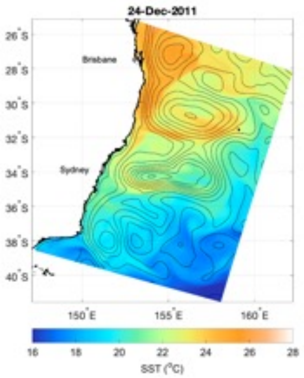


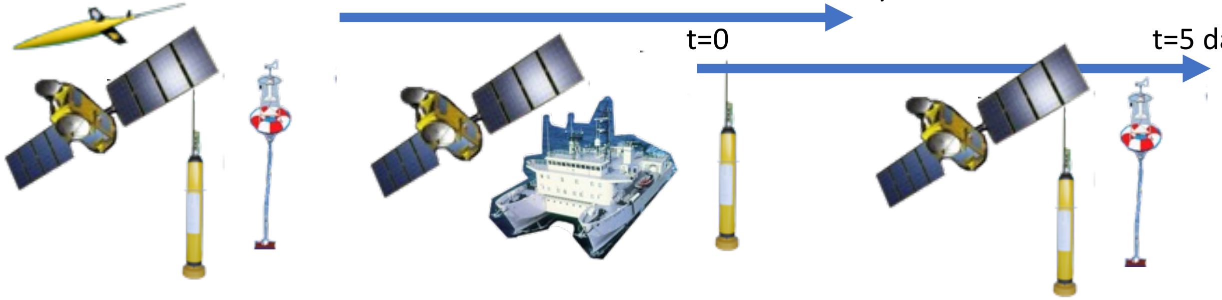


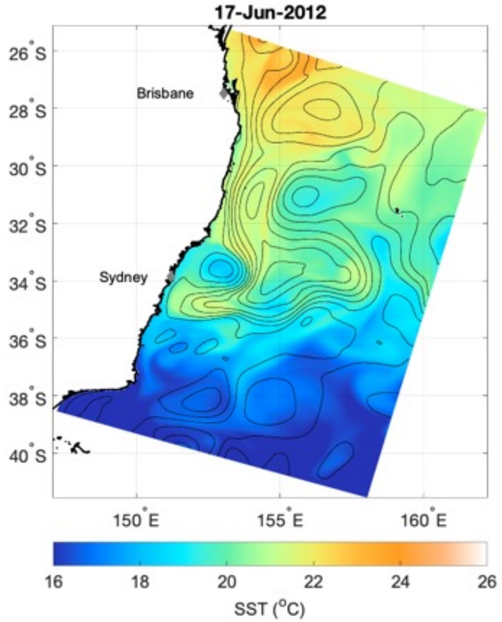


t=0 t=5 days

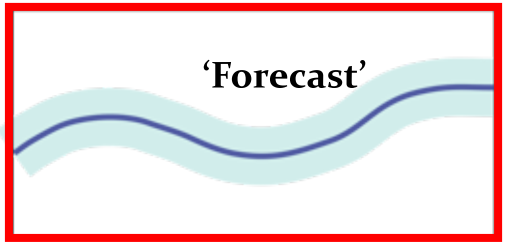
t=0 t=5 days

t=0 t=5 days



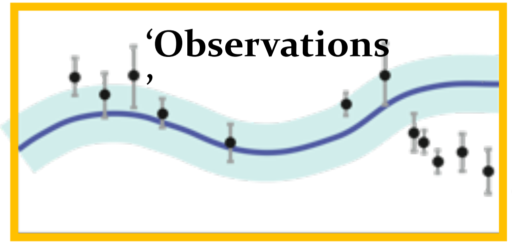


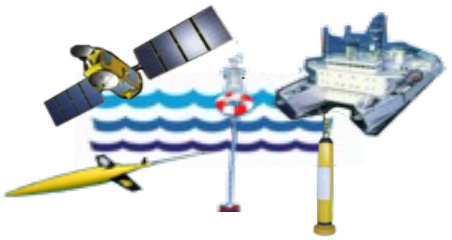
4D-Variational Data Assimilation



Forecast — Ocean Model — Initial conditions — Surface forcing — Boundary conditions

$$\boldsymbol{x}_f = \mathcal{M}(\boldsymbol{x}_o, \boldsymbol{f}, \boldsymbol{b})$$





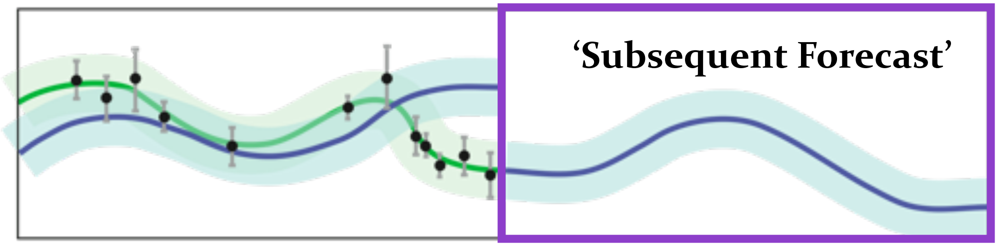
4-D Variational Data Assimilation

Find the increment that minimises the cost function

$$\delta \boldsymbol{z} = (\delta \boldsymbol{x}_0, \delta \boldsymbol{f}(t), \delta \boldsymbol{b}(t))$$

Analysis — Ocean Model

$$\boldsymbol{x}_a = \mathcal{M}(\boldsymbol{x}_o + \delta \boldsymbol{x}_0, , \boldsymbol{f} + \delta \boldsymbol{f}(t), \boldsymbol{b} + \delta \boldsymbol{b}(t))$$



Cost function

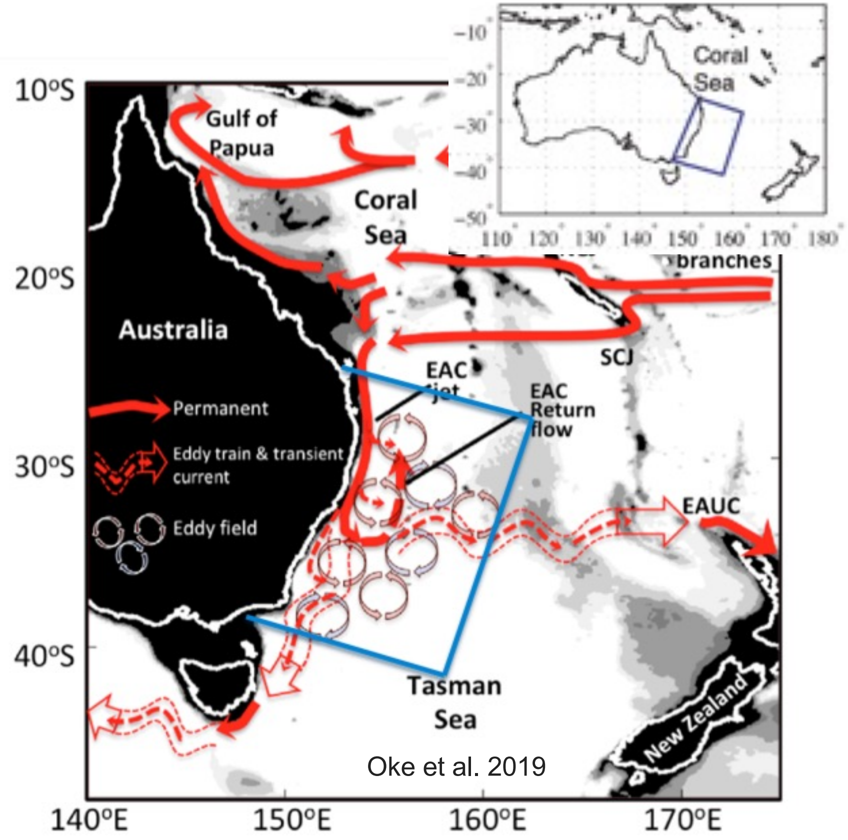
$$J(\delta z) = \frac{1}{2}\sum_{i=0}^{n}(\mathbf{H}_i\mathbf{M}(t_i,t_0)\delta z - \boldsymbol{d}_i)^T \mathbf{R}_i^{-1}(\mathbf{H}_i\mathbf{M}(t_i,t_0)\delta z - \boldsymbol{d}_i) + \frac{1}{2}(\delta z)^T \mathbf{P}^{-1}(\delta z)$$

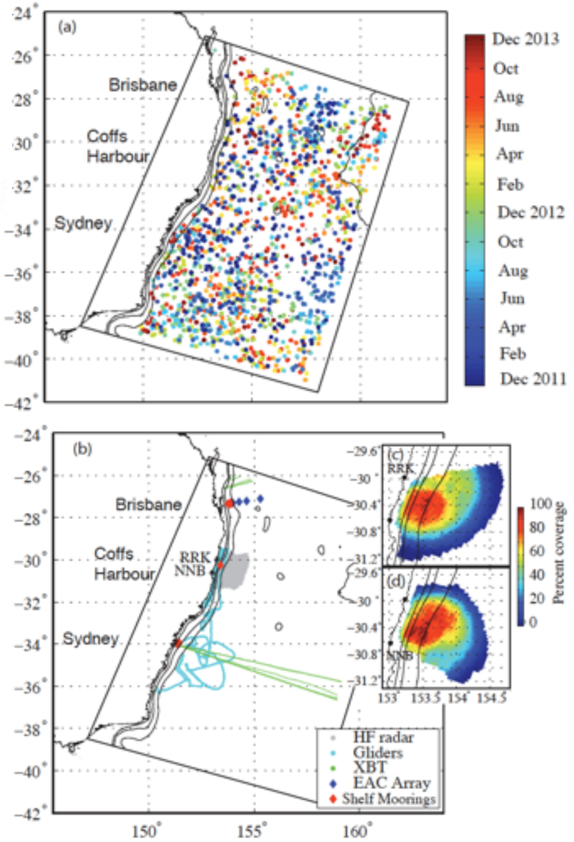
Observation error covariances ($\mathbf{R}_i^{-1}$); Difference between model (given the increment) and observations ($\mathbf{H}_i\mathbf{M}(t_i,t_0)\delta z - \boldsymbol{d}_i$); Increment ($\delta z$); Background error covariances ($\mathbf{P}^{-1}$)

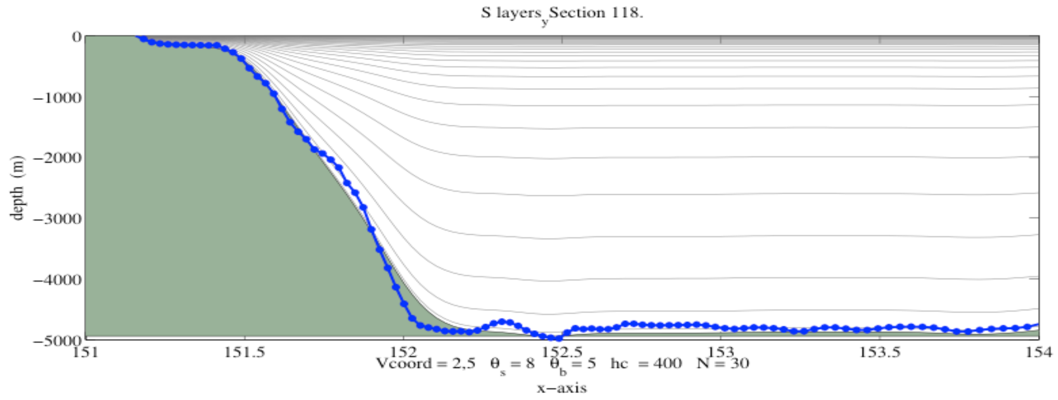
- **4-D Var uses** subsequent iterations of the tangent linear and adjoint models to compute increments in the model initial conditions, boundary conditions and surface forcing such that the difference between the new model solution and the observations is minimised.
- The analysis is a complete solution of the non-linear model equations so is dynamically consistent.
- Observations are assimilated over 5-day windows and can have impact up- and downstream and forward and backwards in time due to the 4-D nature of the DA system.

The pilot studies: EAC-ROMS for 2012-2013 period

- Regional Ocean Modelling System Configuration
- Well tested EAC-ROMS model
- Variable horizontal resolution
  - 2.5-6km cross shore
  - 5km alongshore
  - 30 s-levels
- ACCESS-G 12km for atmospheric forcing
- Nested inside BRAN
- 4D-Var data assimilation scheme
- A crucial downscaling step from the global 10km model to the shelf regions

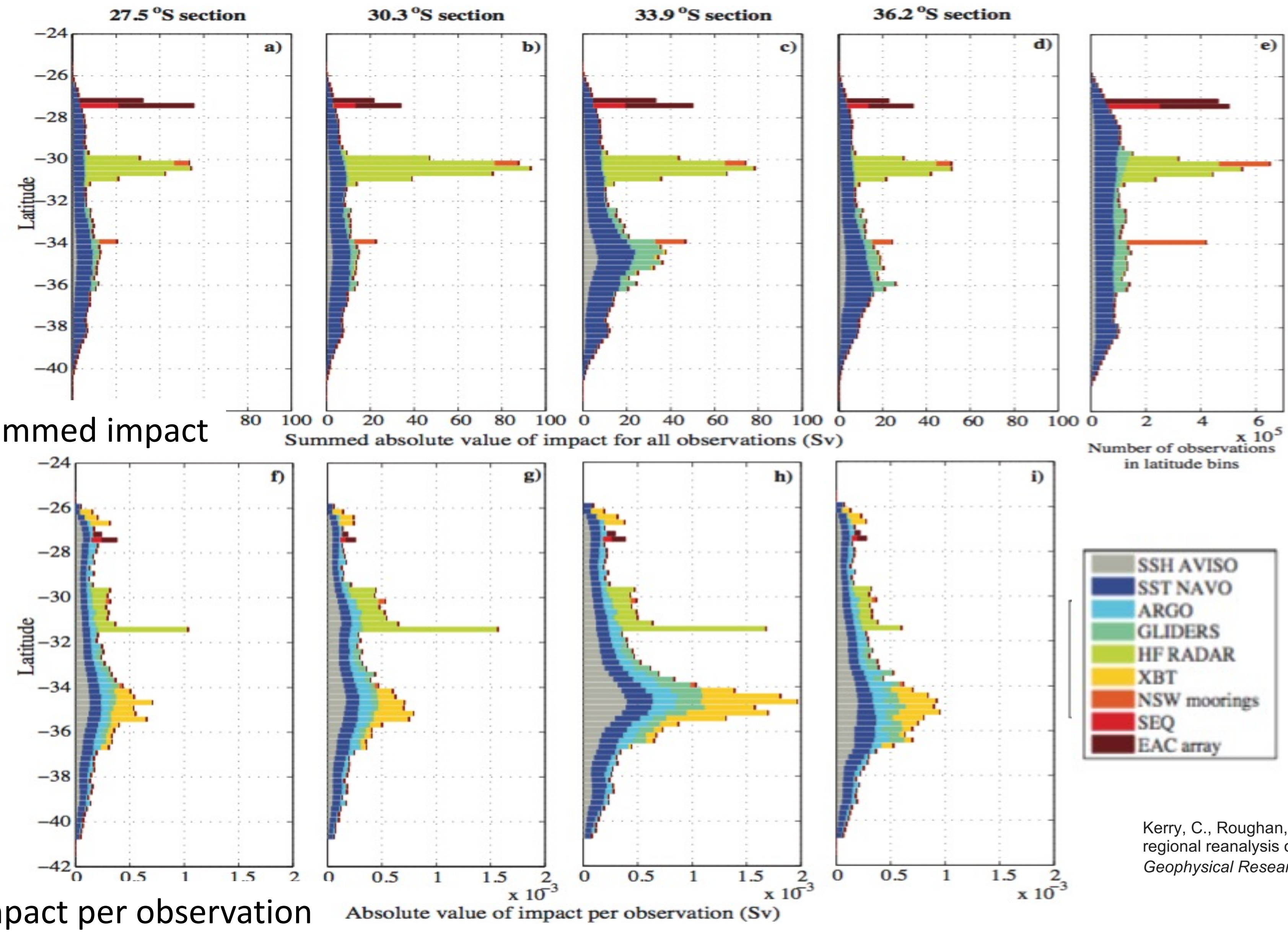






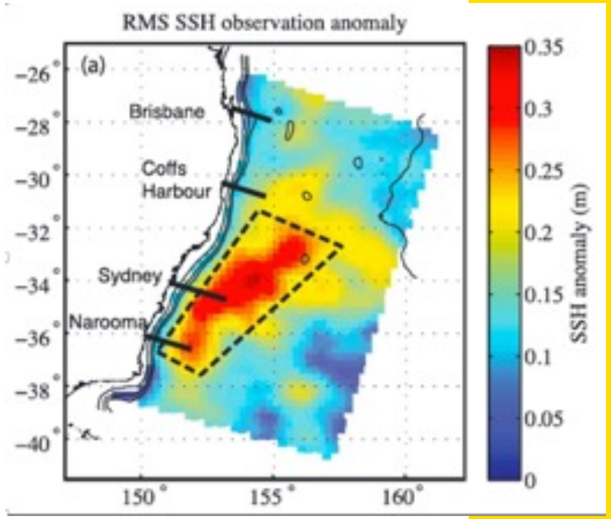
Kerry, C., Powell, B., Roughan, M. and Oke, P., 2016. Development and evaluation of a high-resolution reanalysis of the East Australian Current region using the Regional Ocean Modelling System (ROMS 3.4) and Incremental Strong-Constraint 4-Dimensional Variational (IS4D-Var) data assimilation. *Geoscientific Model Development*, *9*(10), pp.3779-3801.

Alongshore volume transport: Impact with latitude



Summed impact

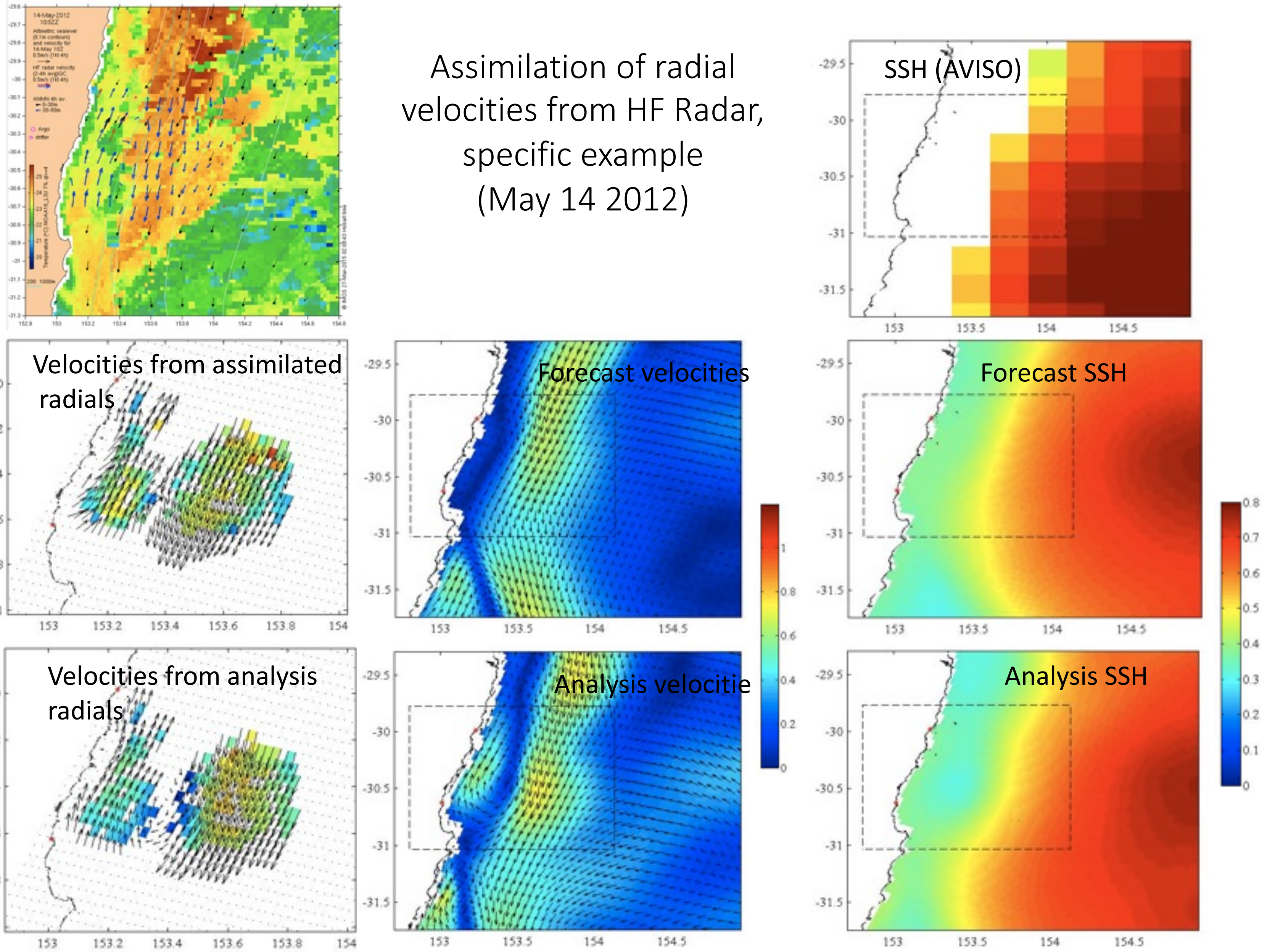
Impact per observation



Kerry, C., Roughan, M. and Powell, B., 2018. Observation impact in a regional reanalysis of the East Australian Current System. *Journal of Geophysical Research: Oceans*, *123*(10), pp.7511-7528.

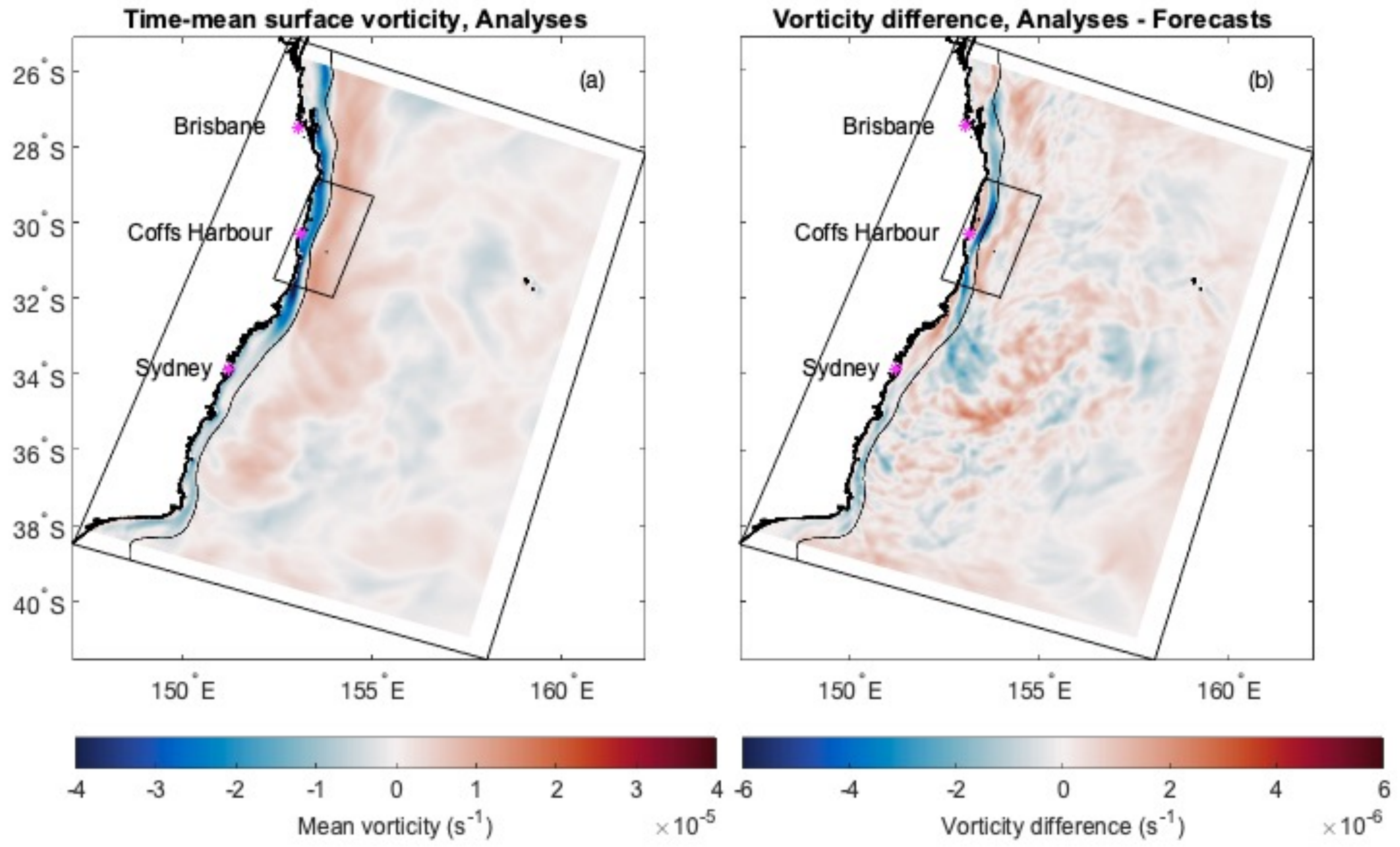
HF radar impact example

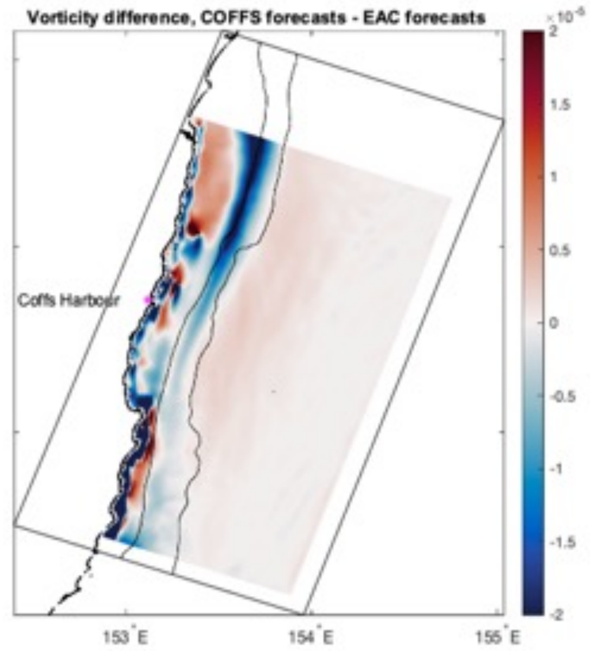
Assimilation of radial velocities from HF Radar, specific example (May 14 2012)



Ocean surface vorticity

- Data assimilation of HF radials at results in increased cyclonic vorticity inshore of the EAC and a sharper vorticity gradient along the EAC's inshore edge
- The impacts are seen both up- and down-stream



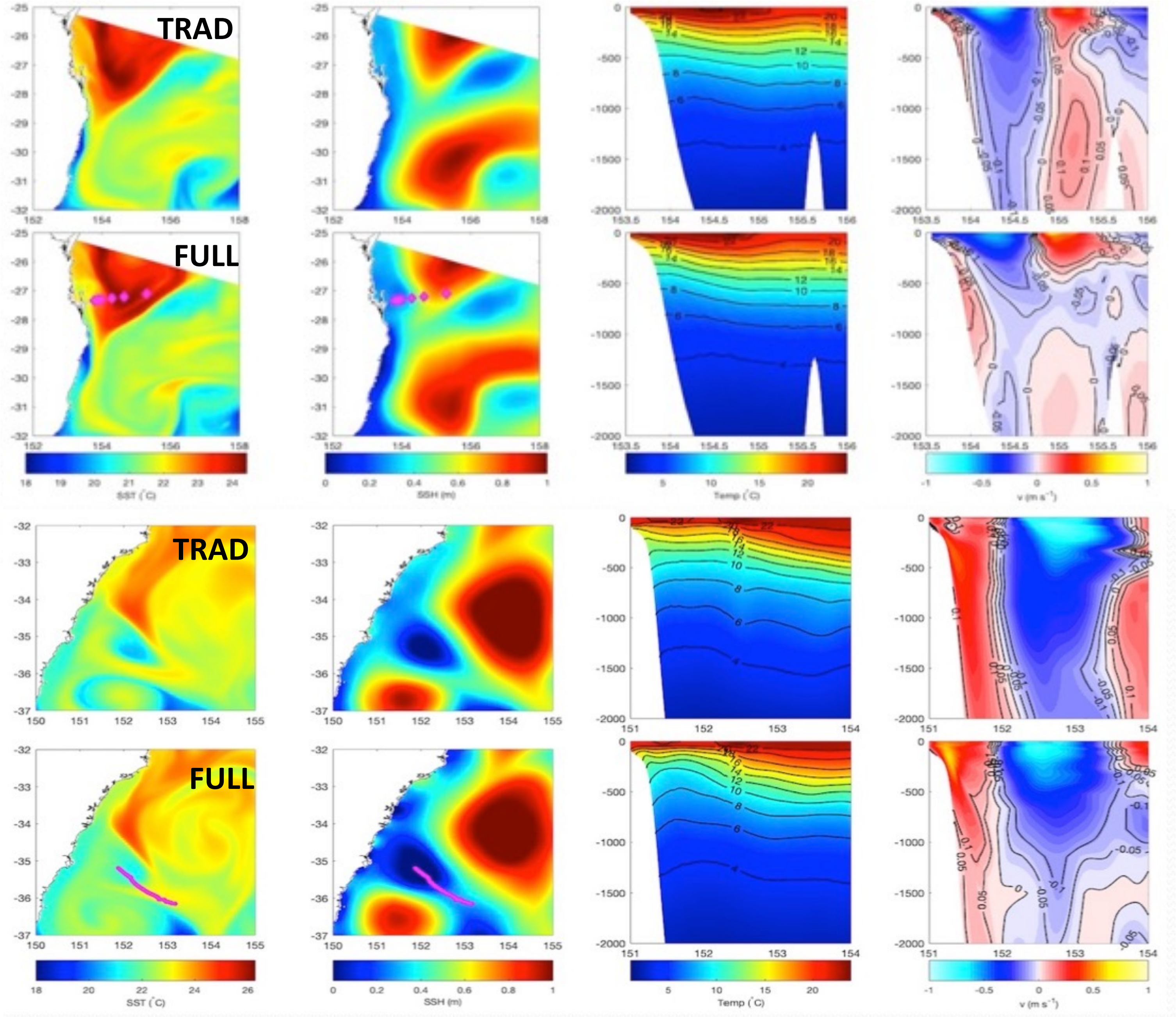


Kerry, C., Roughan, M. and Powell, B., 2020. Predicting the submesoscale circulation inshore of the East Australian Current. *Journal of Marine Systems*, *204*, p.103286.

The importance of subsurface observations

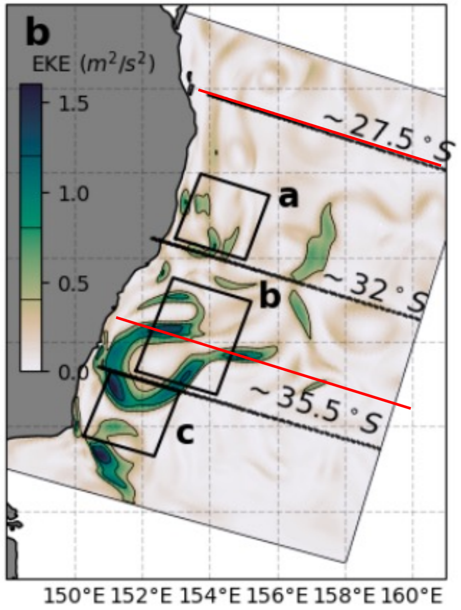
EAC Mooring Array
(temp., salinity, u and v)

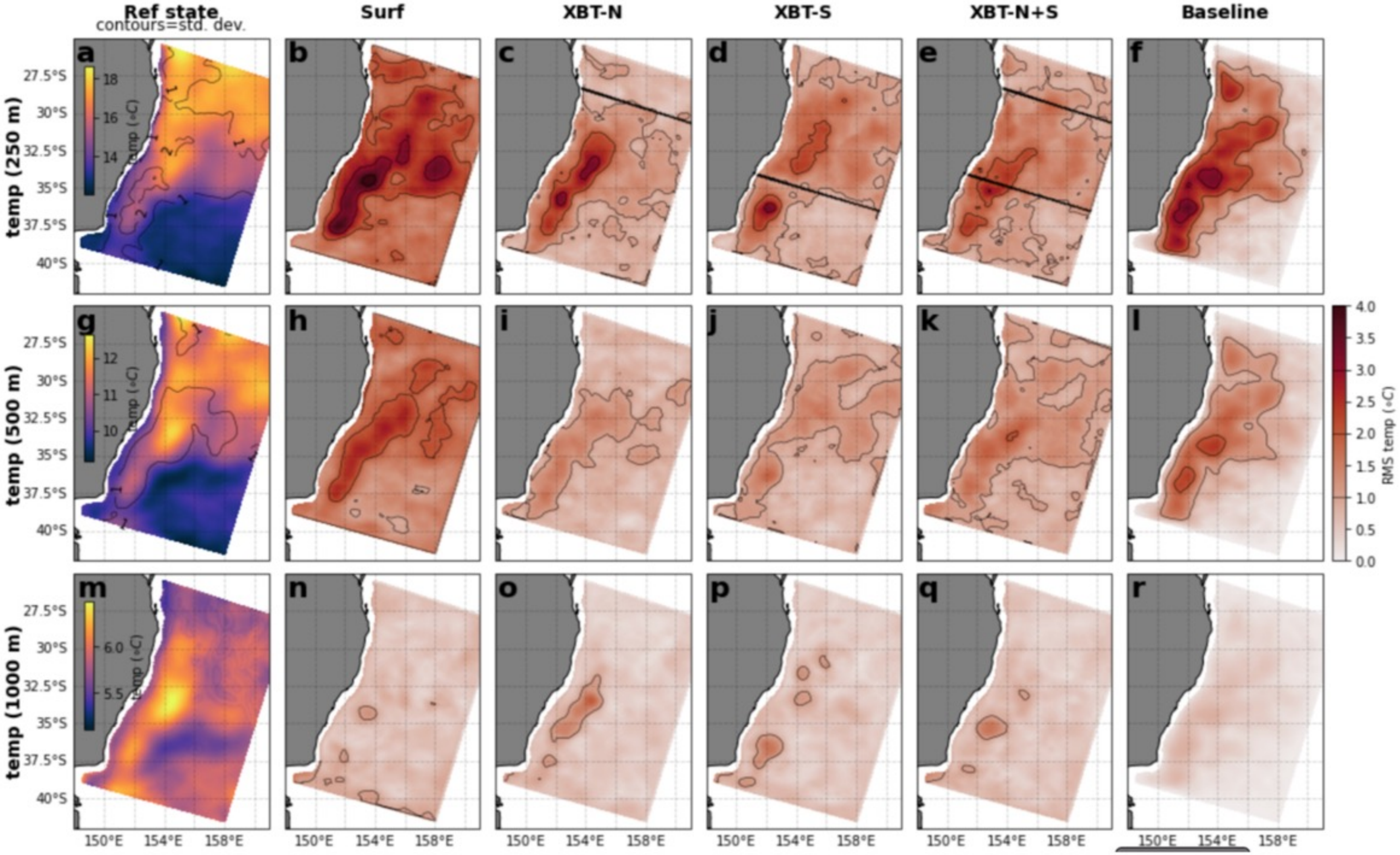
Gliders
(temp. and salinity)



Siripatana, A., Kerry, C., Roughan, M., Souza, J.M.A. and Keating, S., 2020. Assessing the impact of nontraditional ocean observations for prediction of the east australian current. *Journal of Geophysical Research: Oceans*, *125*(12), p.e2020JC016580..

OSSEs: Subsurface temperature representation



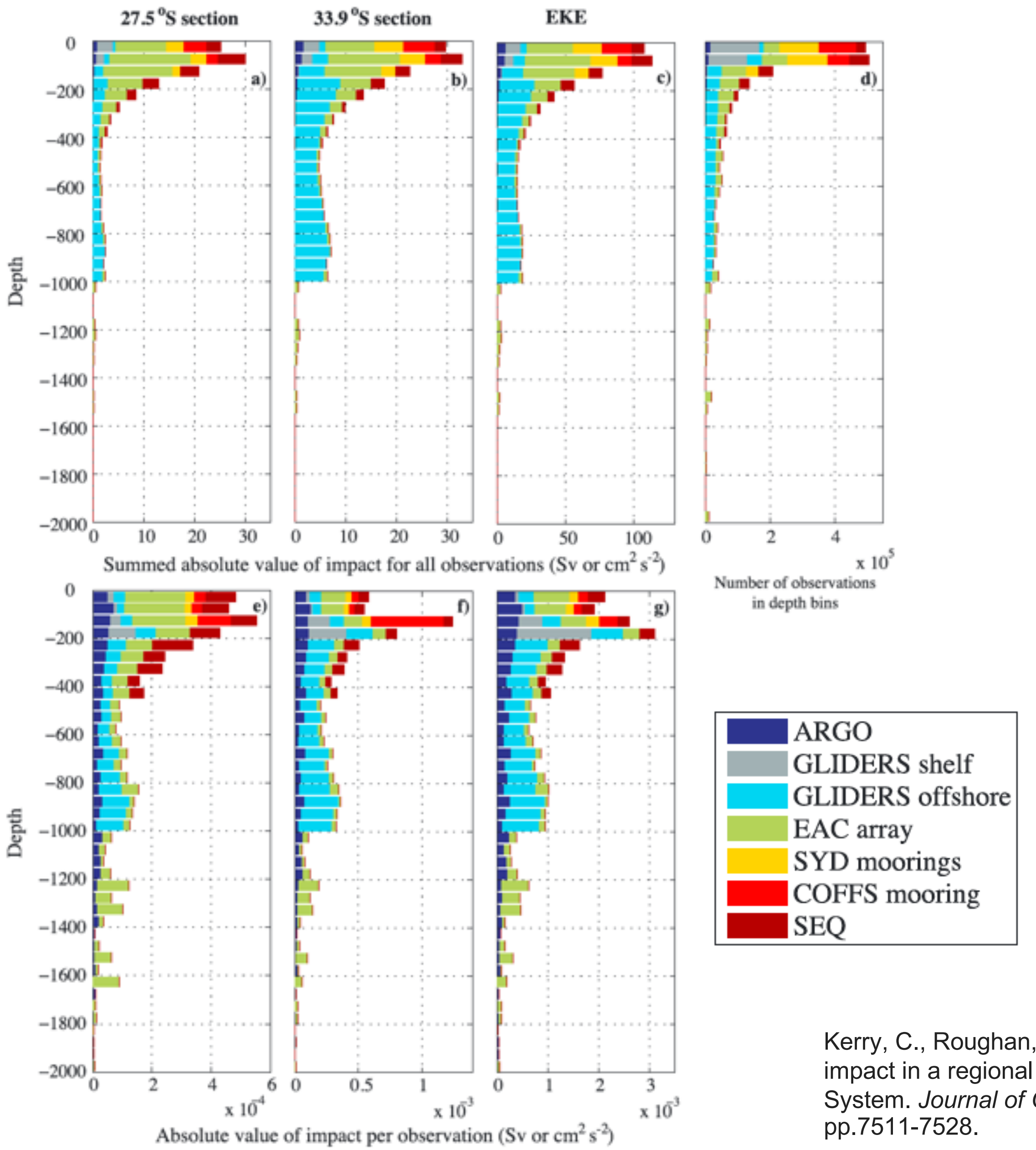


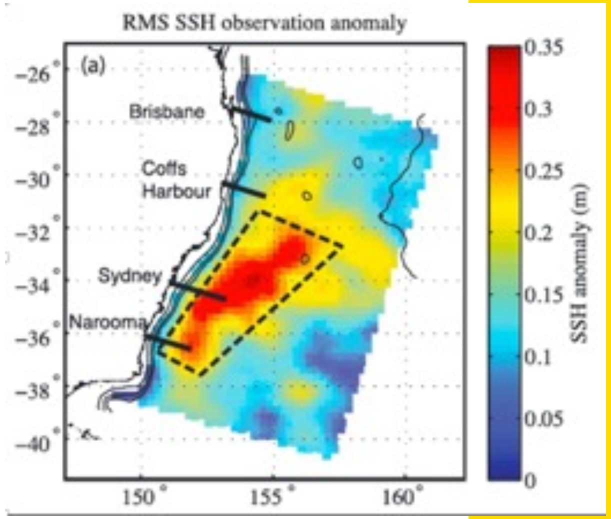
Gwyther, D.E., Kerry, C., Roughan, M. and Keating, S.R., 2022. Observing system simulation experiments reveal that subsurface temperature observations improve estimates of circulation and heat content in a dynamic western boundary current. *Geoscientific Model Development*, *15*(17), pp.6541-6565.

Alongshore volume transport: Impact with depth

Summed impact

Impact per observation





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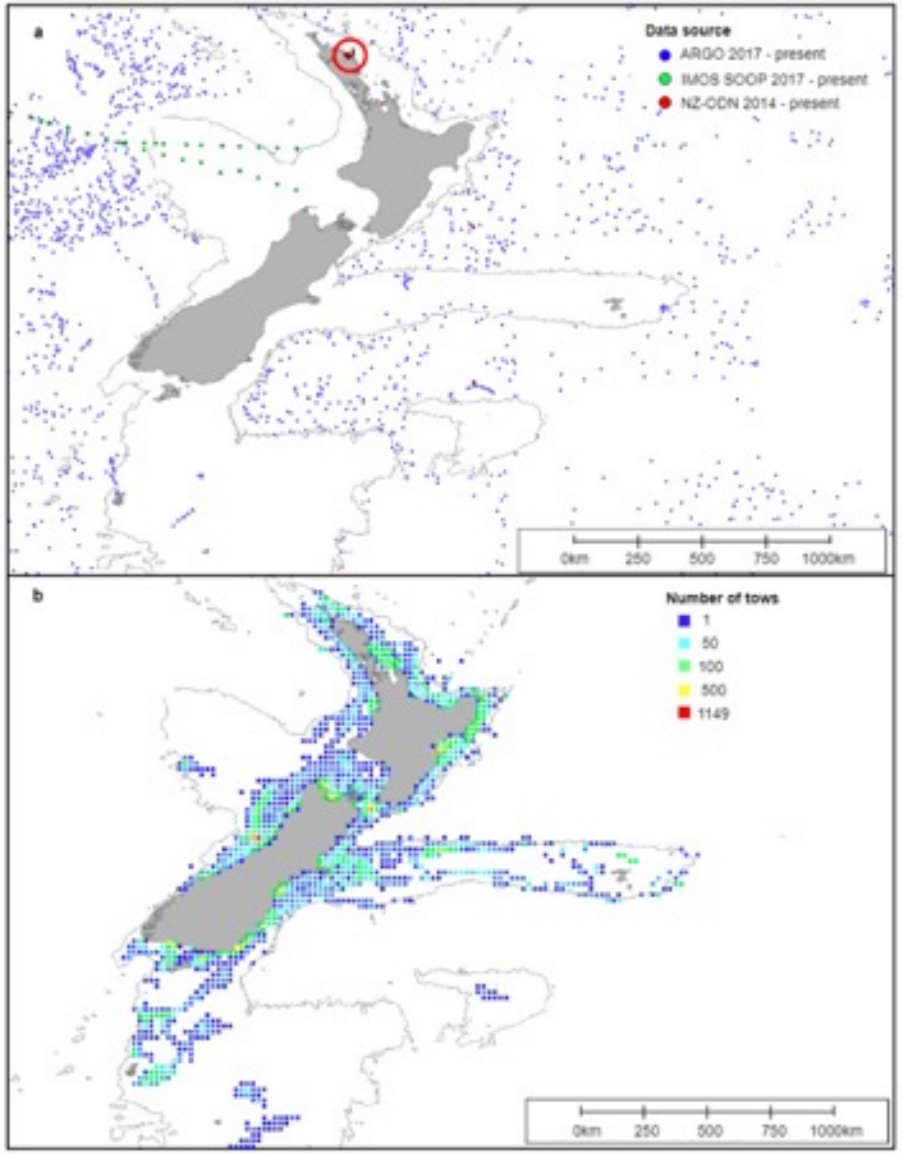
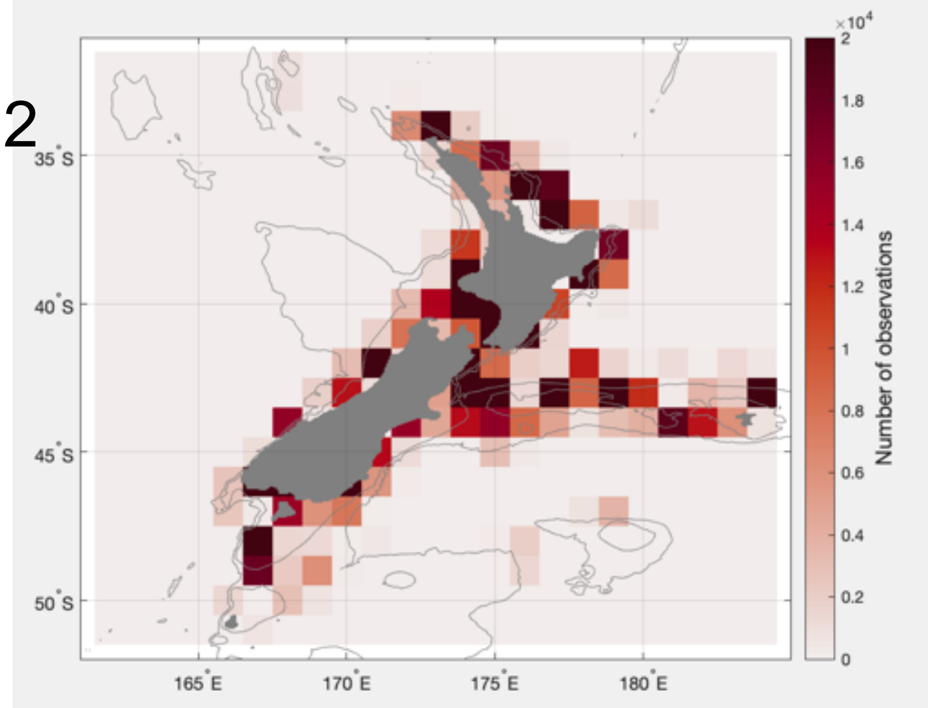
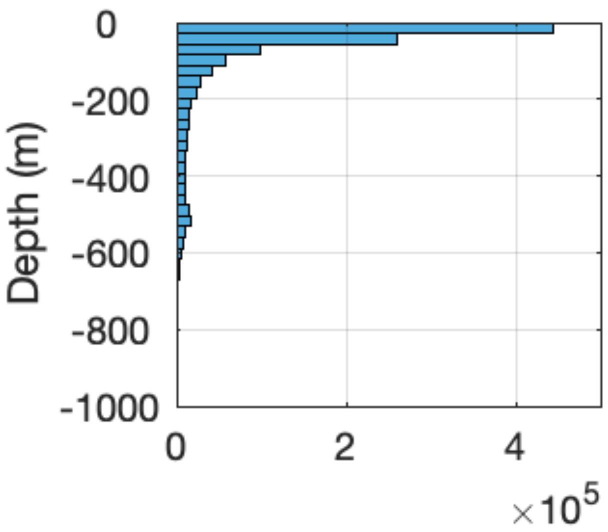
Fishing vessel mounted temperature sensors

2018



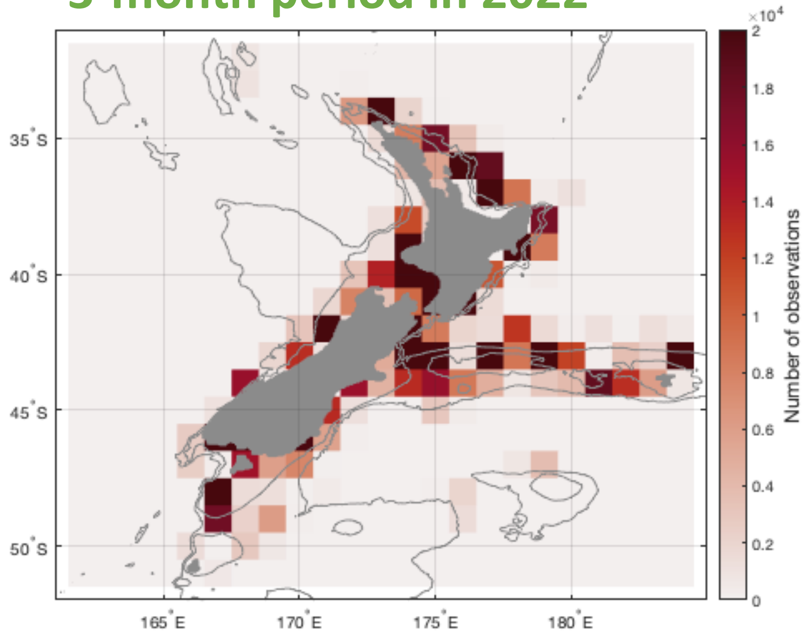
2022

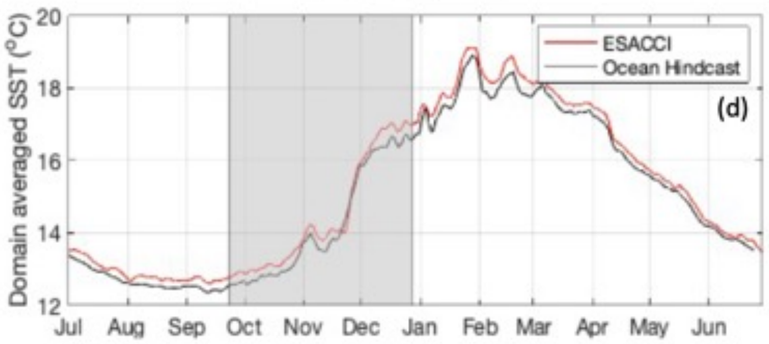




NZ example - Fishing vessel mounted temperature sensors

Num. obs,
3-month period in 2022

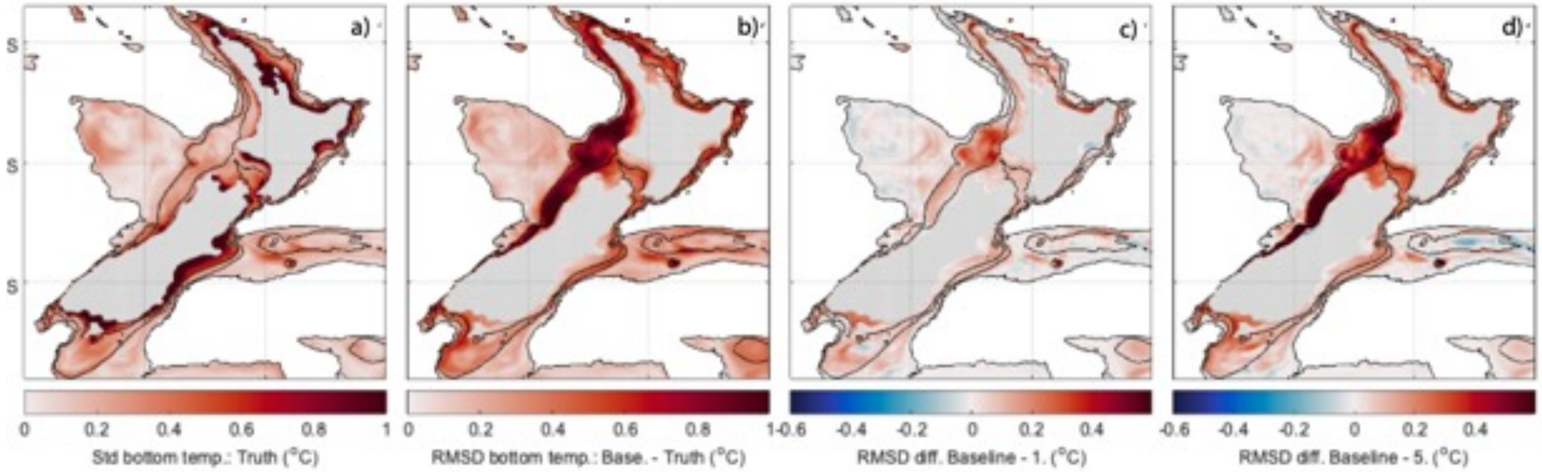




Bottom temp. improvement

Surface only

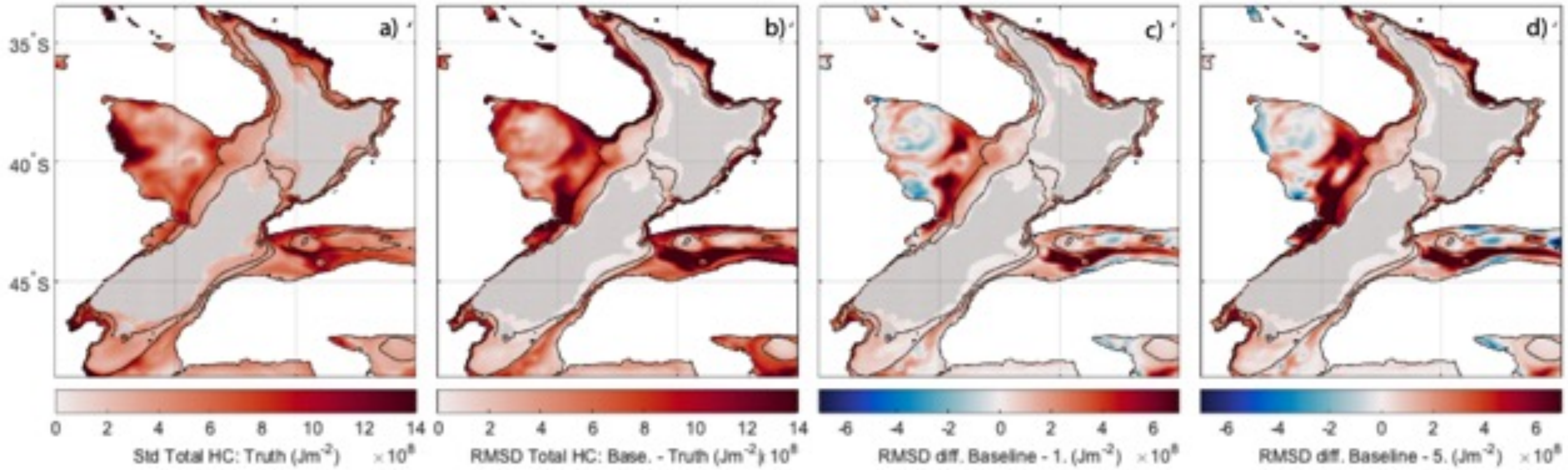
Surface + FishingVesselObs



Heat content improvement

Surface only

Surface + FishingVesselObs



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NZ example - Fishing vessel mounted temperature sensors

Subsurface obs vs. Surface only

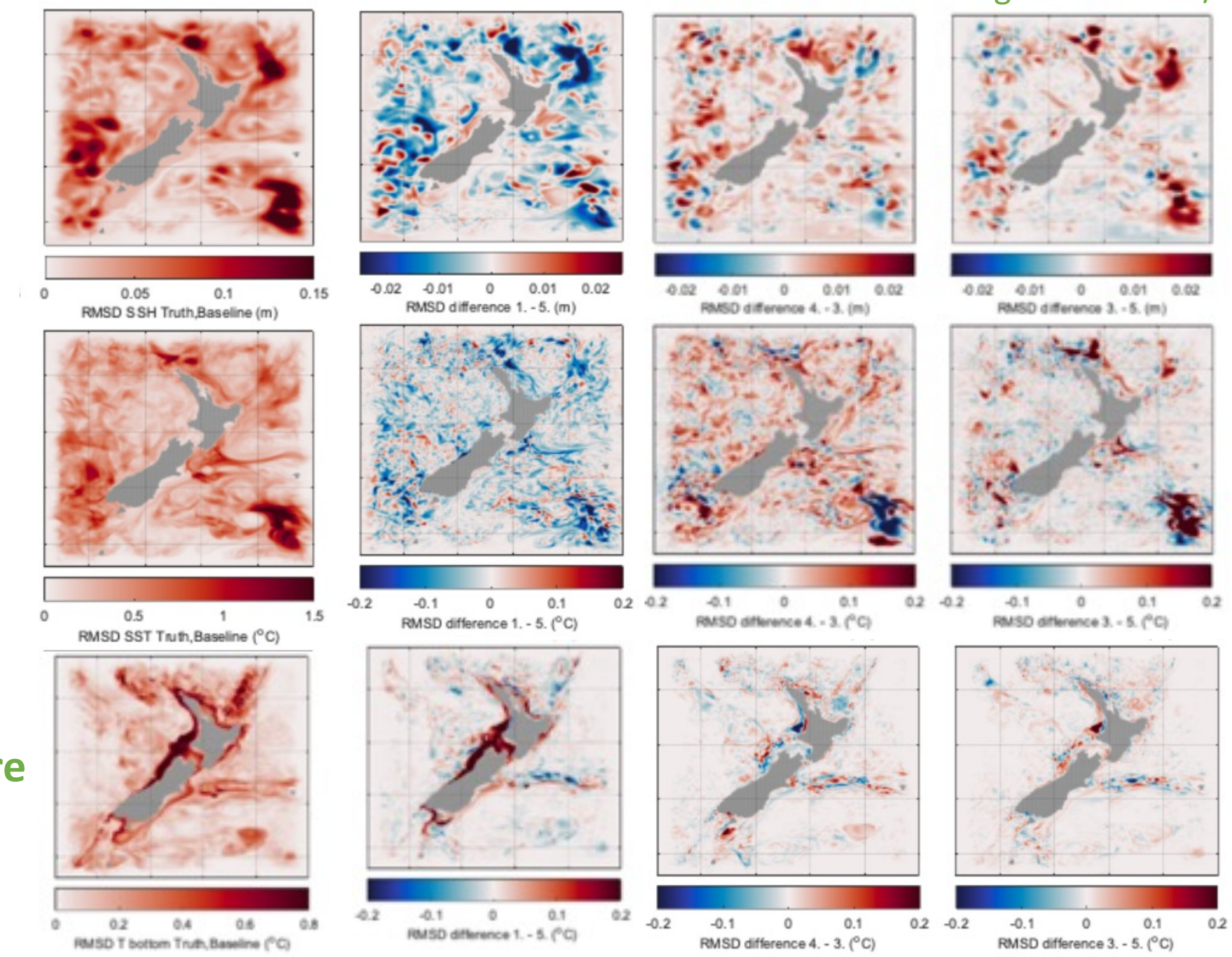
Loser fit to subsurface obs

Shorter decorrelation length scale for T/S

SSH

SST

Bottom temperature



Kerry, Roughan, Marcos A. C. Souza, *Assessing the impact of subsurface temperature observations from fishing vessels on temperature and heat content estimates in shelf seas: A New Zealand case study using Observing System Simulation Experiments*. Submitted to Frontiers, 2023.

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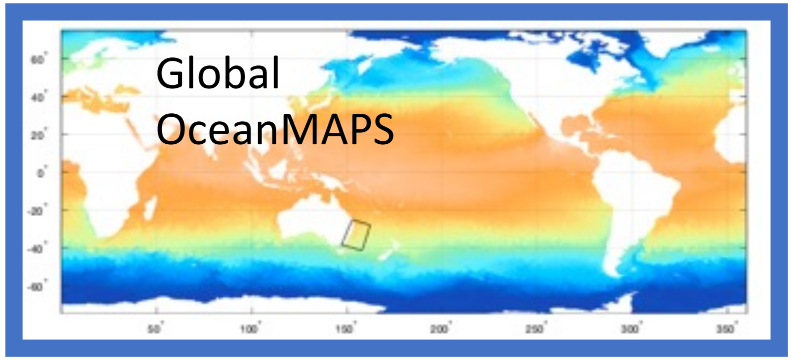
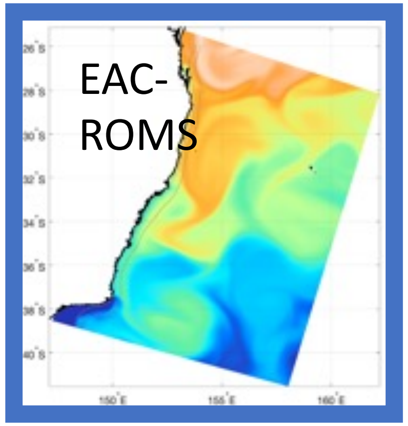
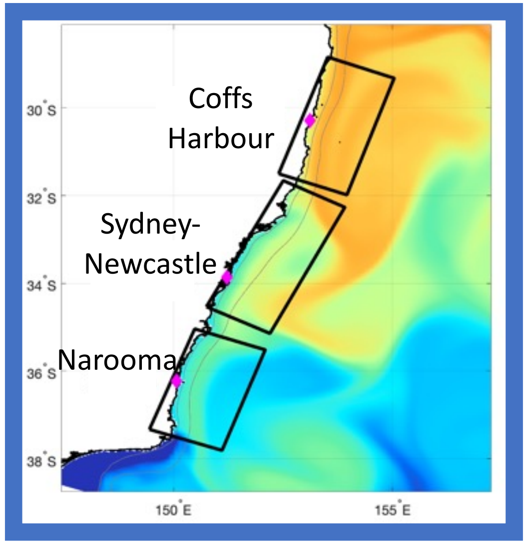
SEA-COFS- A series of nested hydrodynamic models



- Ocean model
  - OFAM3 – MOM5
  - 1/10° x 1/10° (10km)
  - 51 levels
- Data assimilation
  - Hybrid EnKF
  - 48 dynamic members
  - 144 low-mode stationary modes
- Atmospheric forcing
  - ACCESS-G3 (12km)
  - Bulk formulae
- Observations
  - RADS altimetry [Jason-3, Sentinnel-3A and 3B, Sentinnel-6A, Cryosat-2, SARAL]
  - Satellite SST [VIIRS/NPP, VIIRS/NOAA20, AVHRR/NAVO, AMSR2]
  - Argo, XBT, Mooring CTD, other CTDs

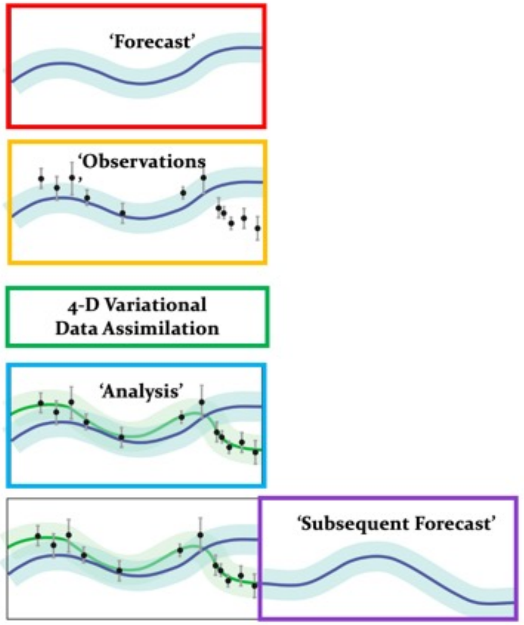


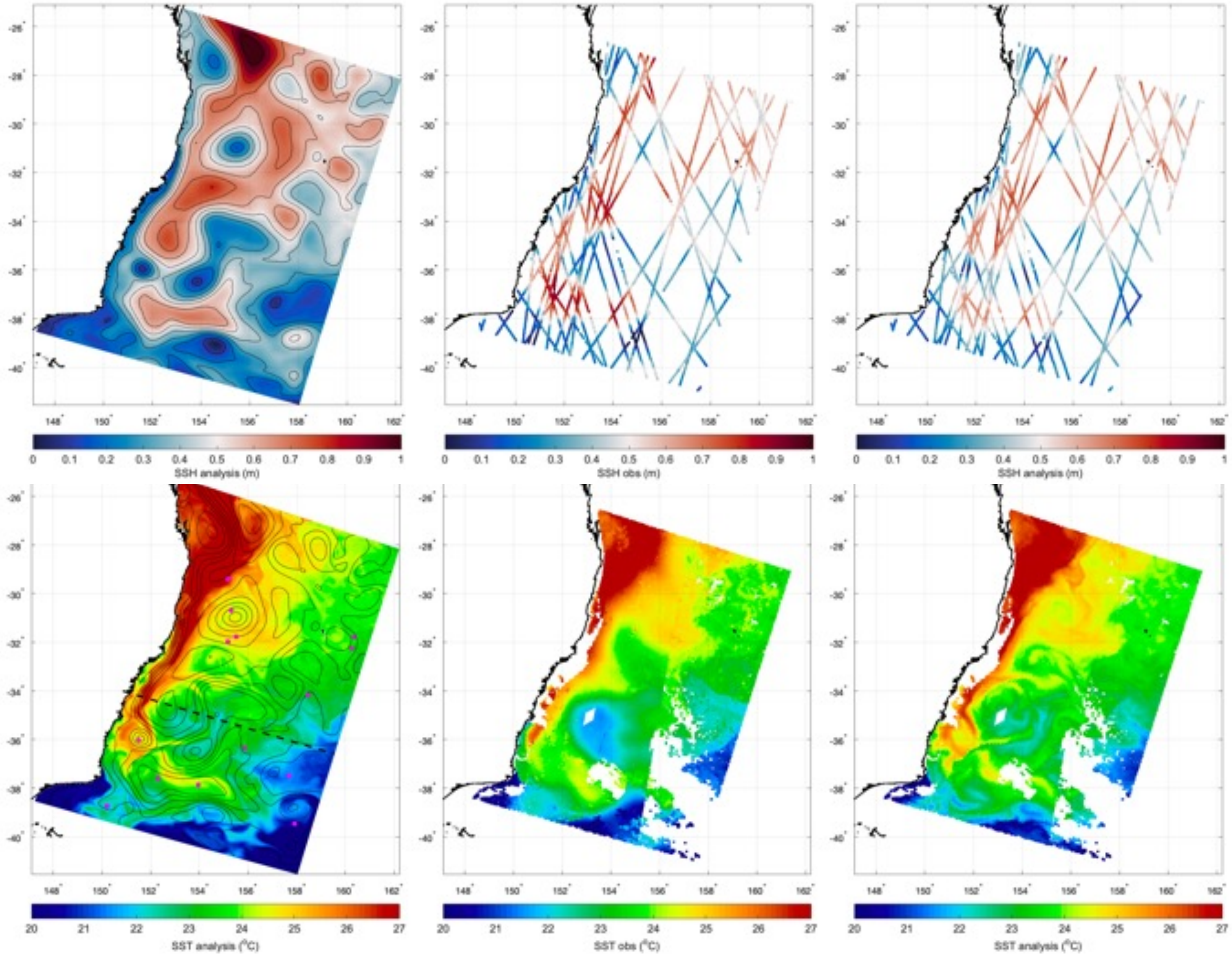
- Ocean model
  - ROMS
  - 2.5-5km (increased on shelf/slope)
  - 30 levels
- Data assimilation
  - 4D-Var in initial pilot mode
  - 4D-Var extensively studied in pilot studies
- Atmospheric forcing
  - ACCESS-G3 (12km)
  - Bulk formulae
- Observations
  - **SSH, SST, profiles**
  - **HF radar Coffs and Newcastle**
  - **Gliders**
  - **Shelf moorings**
  - **FishSOOP**
  - **SWOT**



- Ocean model
  - ROMS
  - 750m-1km
  - 30 levels
- Data assimilation
  - Not yet
  - Boundary dominated
- Atmospheric forcing
  - ACCESS-R (1km)
  - Bulk formulae
- Tides

3-month pilot study

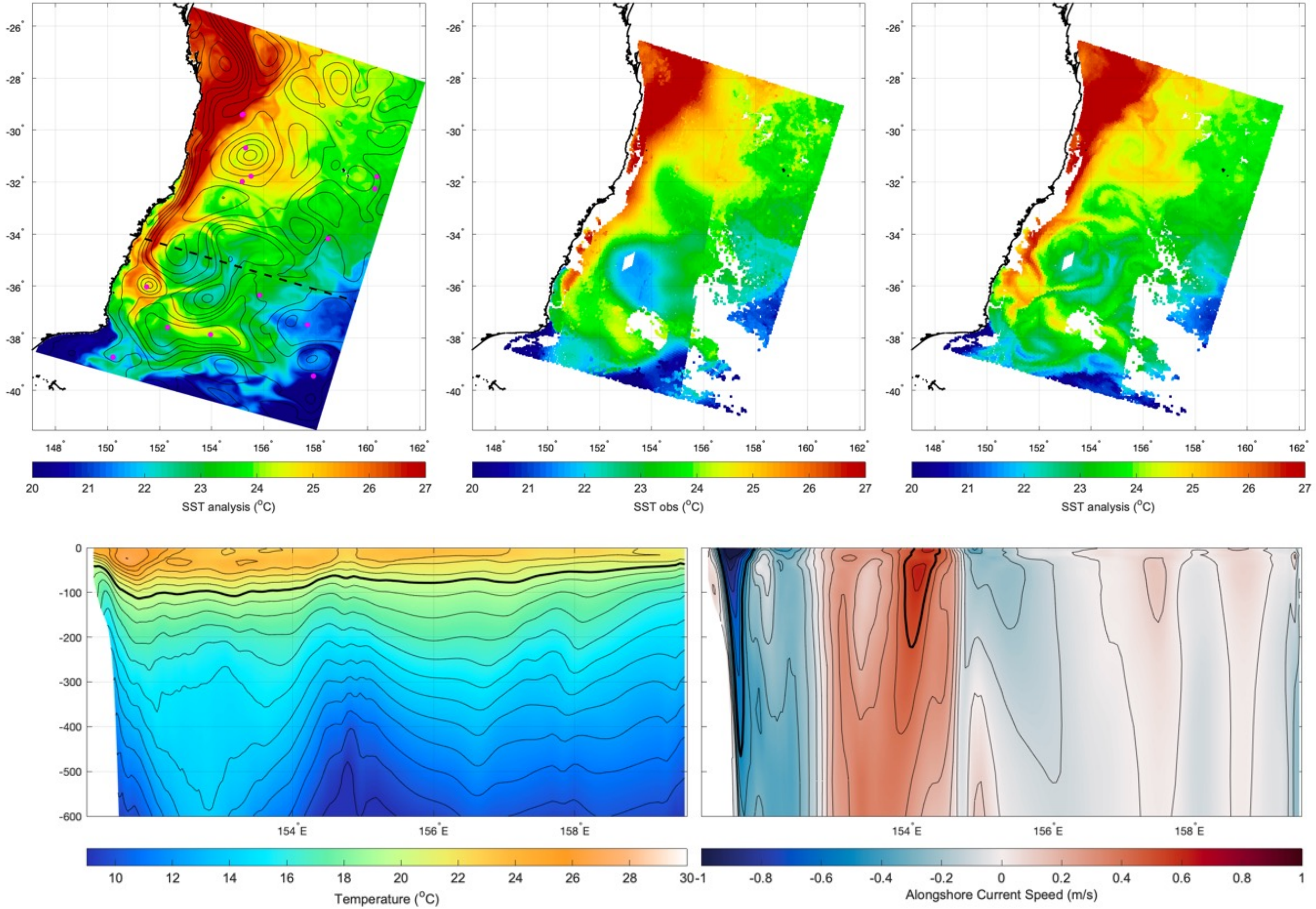




Assimilated observations

- SSH, SST, profiles
- 6-day cycles

3-month pilot study



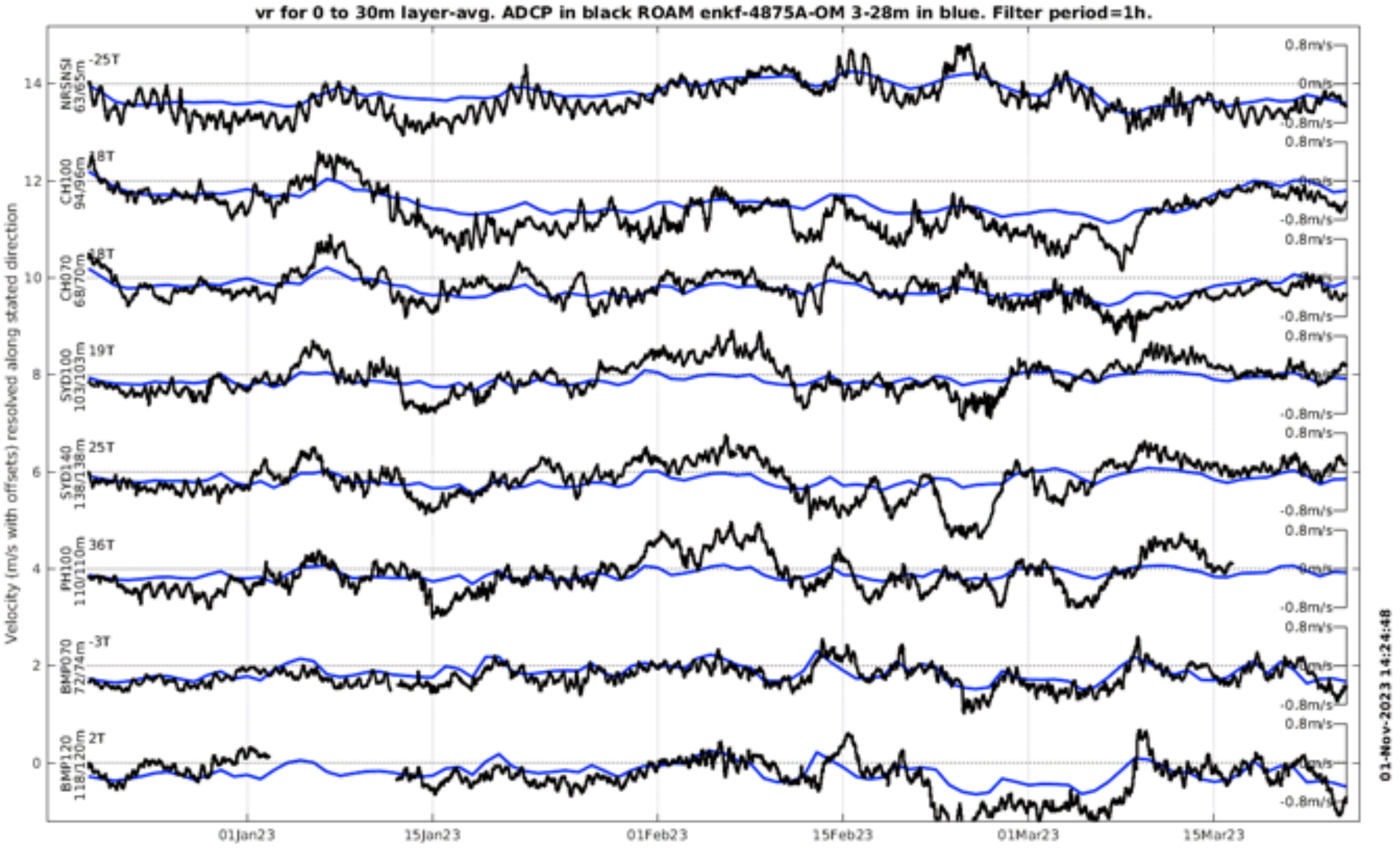
3-month pilot study

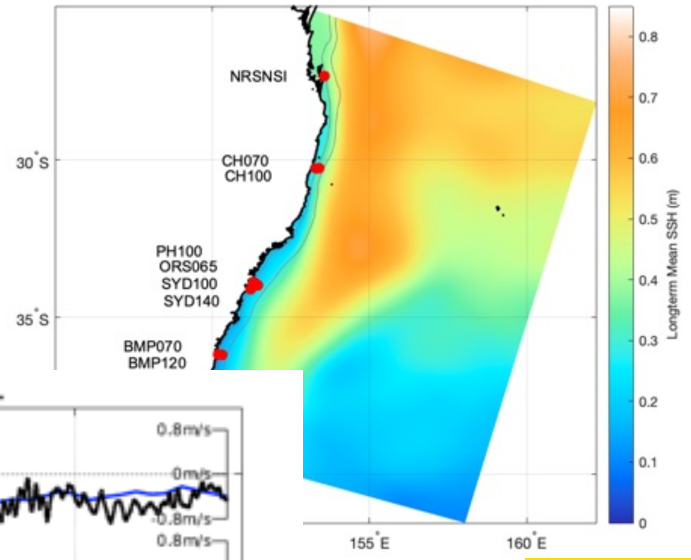
10km resolution

Assimilated observations (EnKF)

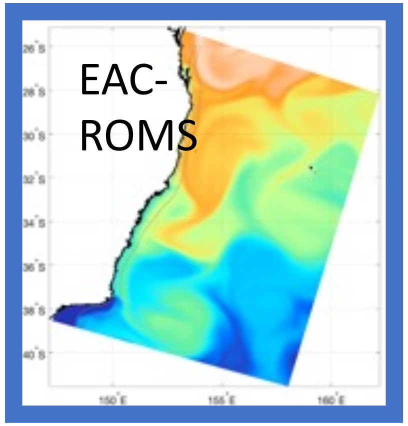
- SSH, SST, profiles

ADCPs - OM





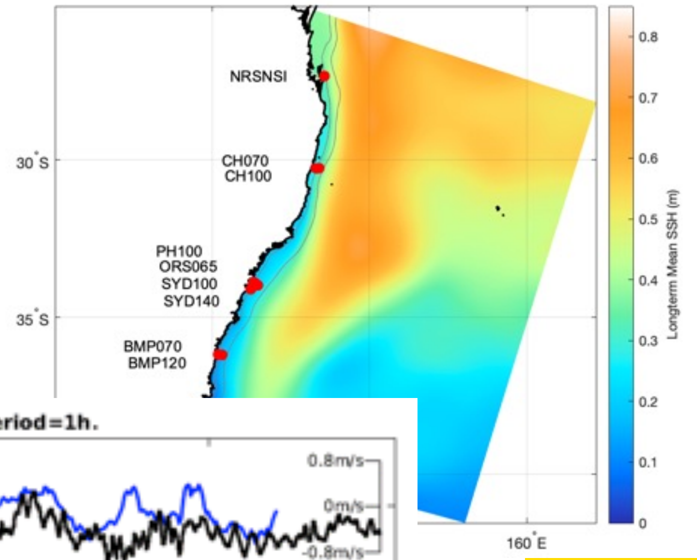
3-month pilot study

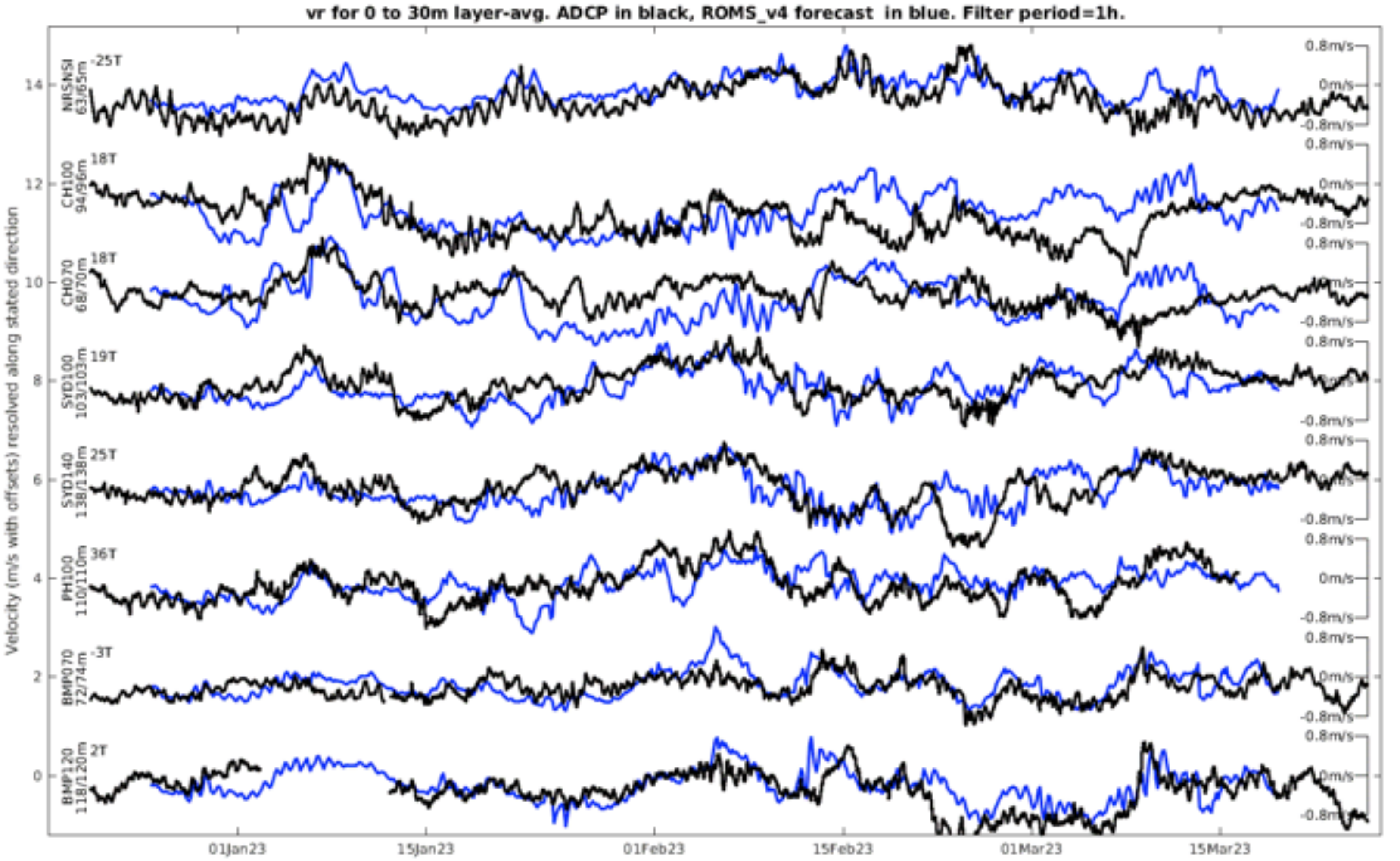


Assimilated observations (4D-Var)

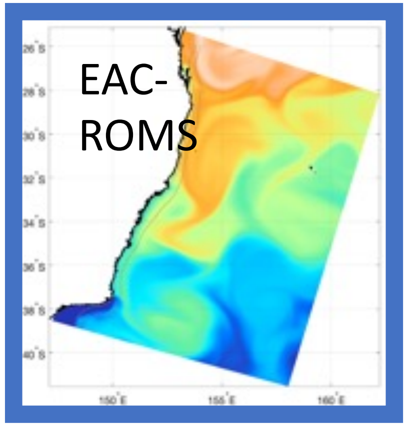
- SSH, SST, profiles
- 6-day cycles

ADCPs



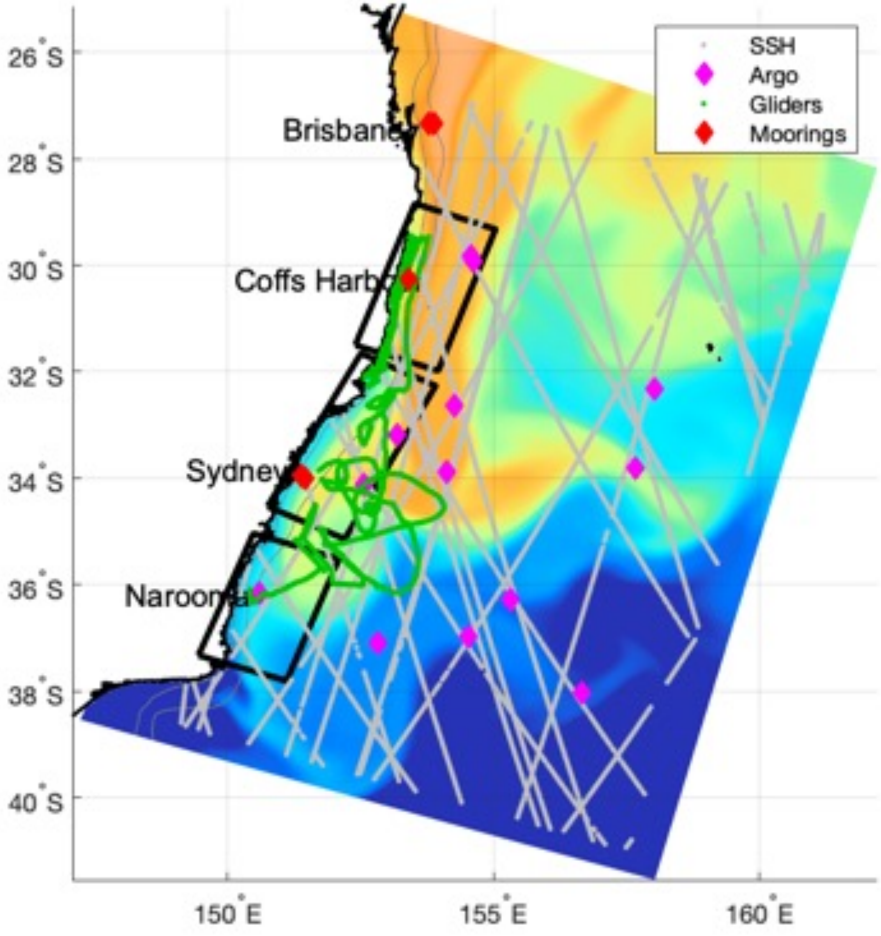


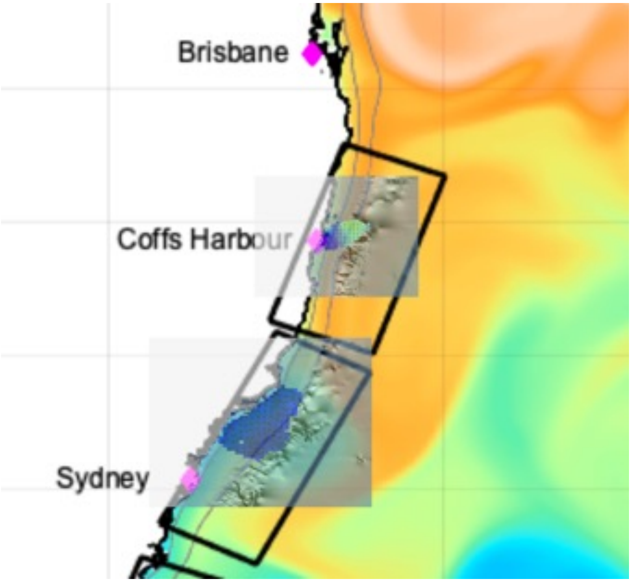
Next Steps – What we can already do



Assimilated observations (4D-Var)

- SSH, SST, profiles
- Gliders
- Shelf moorings
- HF radar Coffs and Newcastle
- FishSOOP
- SWOT





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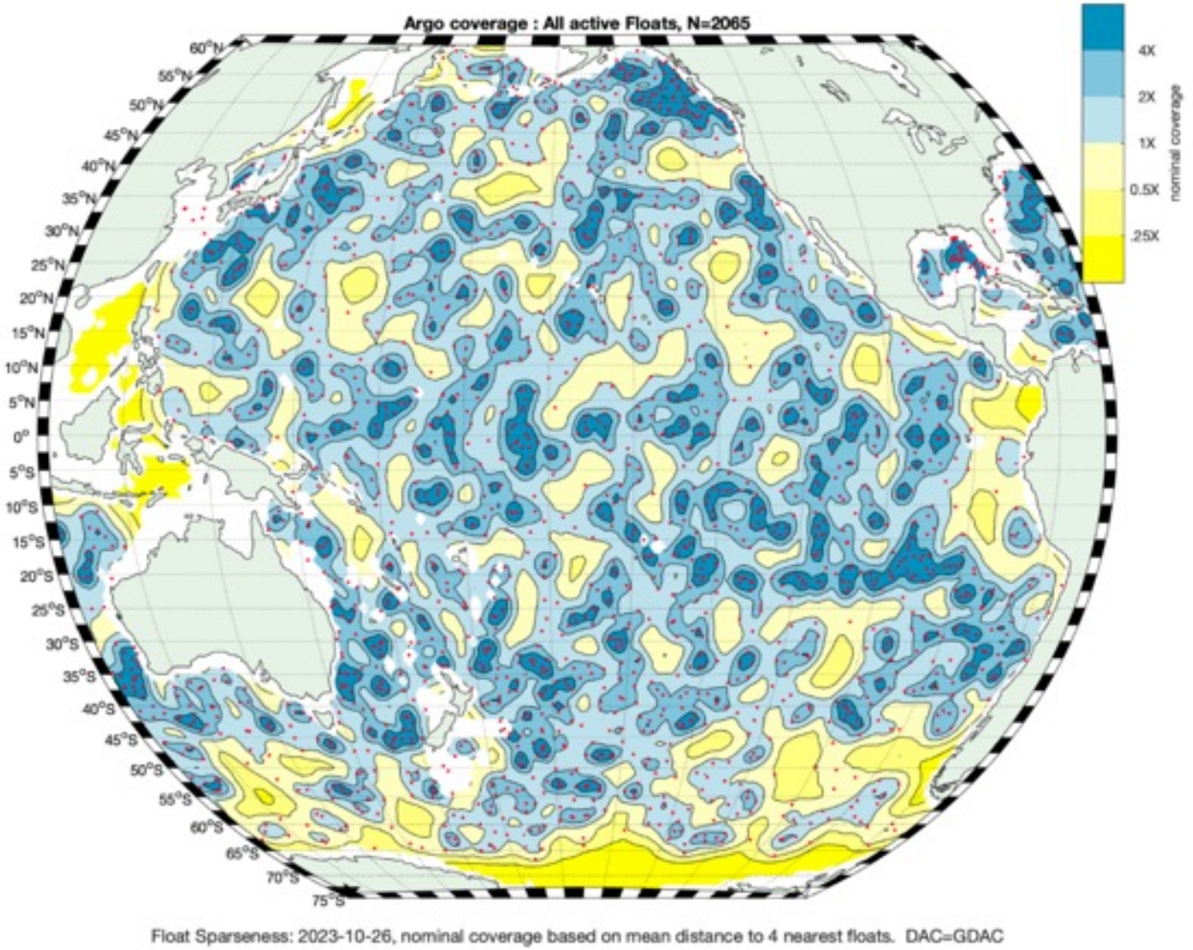
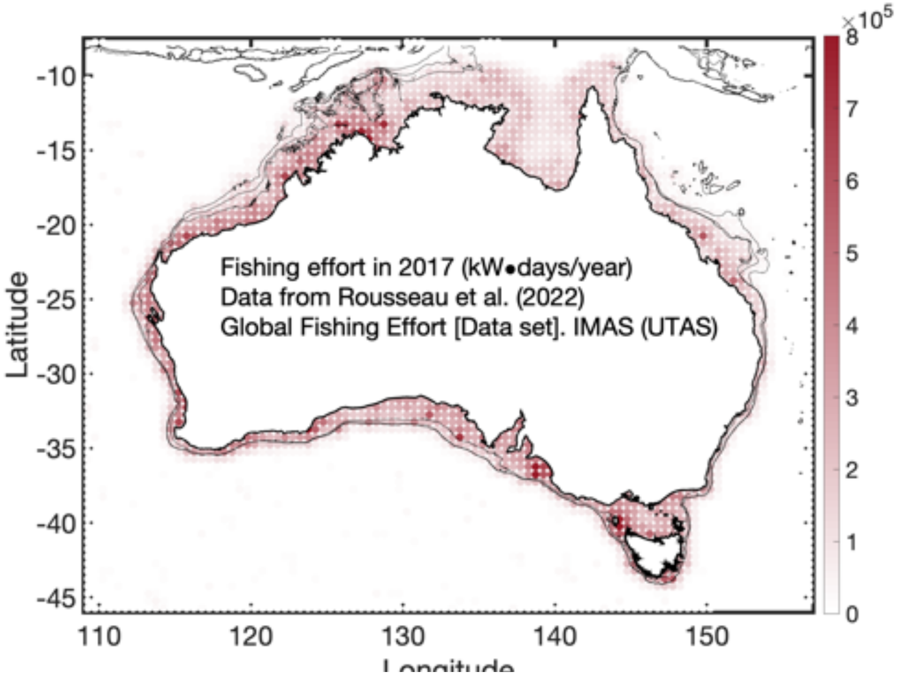
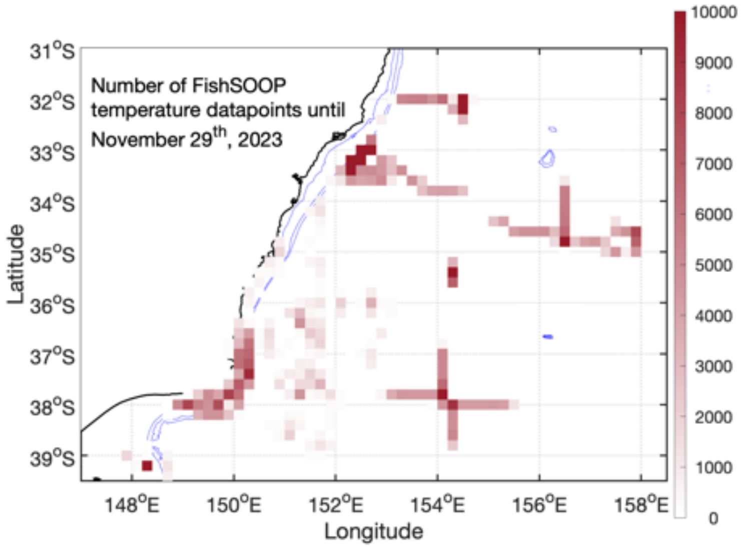
Next Steps – “FishSOOP - Argo of the coastal ocean”







Next Steps – The challenges of assimilating SWOT

ARC Linkage Project
"Next-generation ocean current forecasting to improve maritime safety"

The Bureau of Meteorology

AMSA

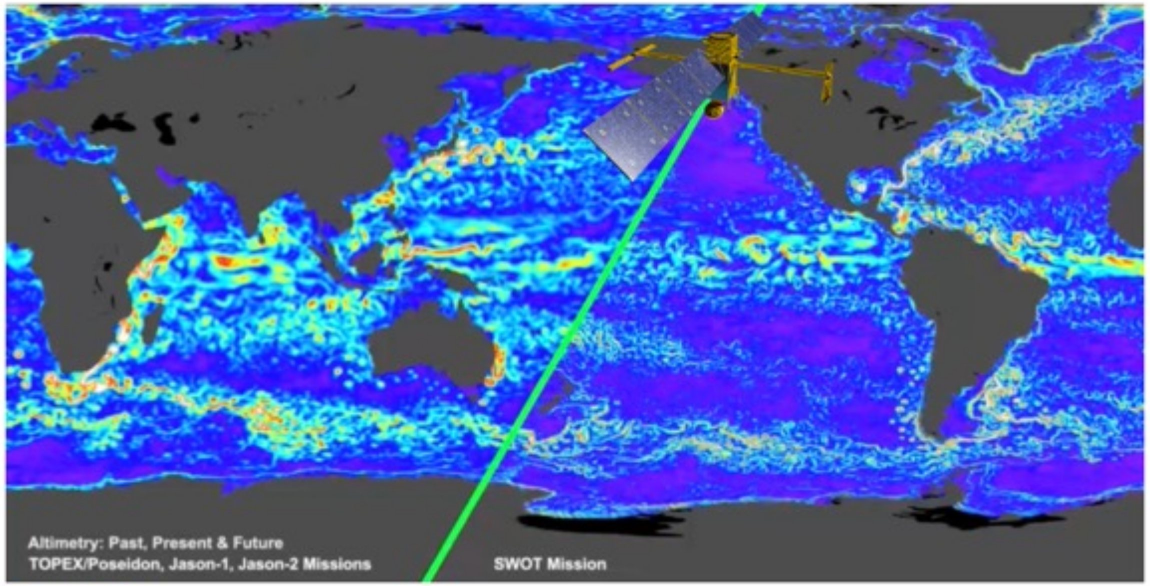
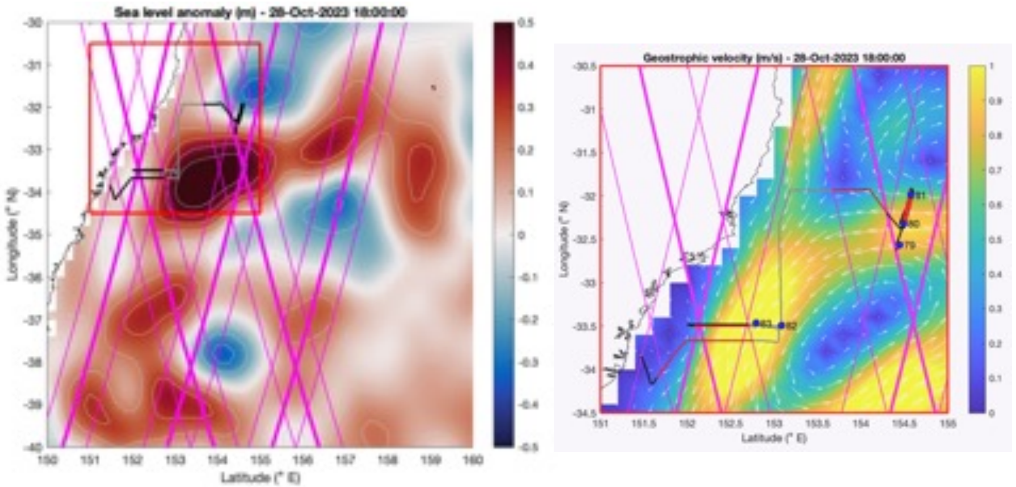


Figure 1: Comparison of the resolution of current-day satellite altimeters (left) with the SWOT mission (right). Source: NASA PO.DAAC. (Full animation at NASA Jet Propulsion Laboratory SWOT mission website.)



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Next Steps – Improving DA below the surface

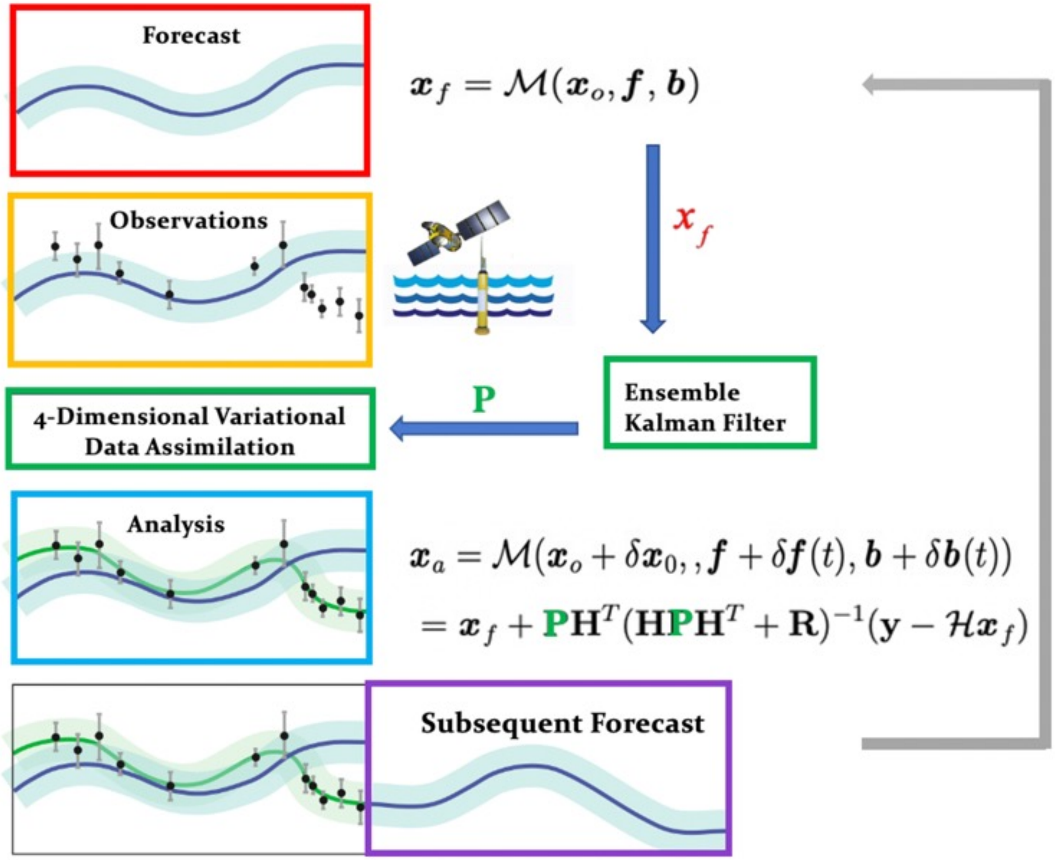
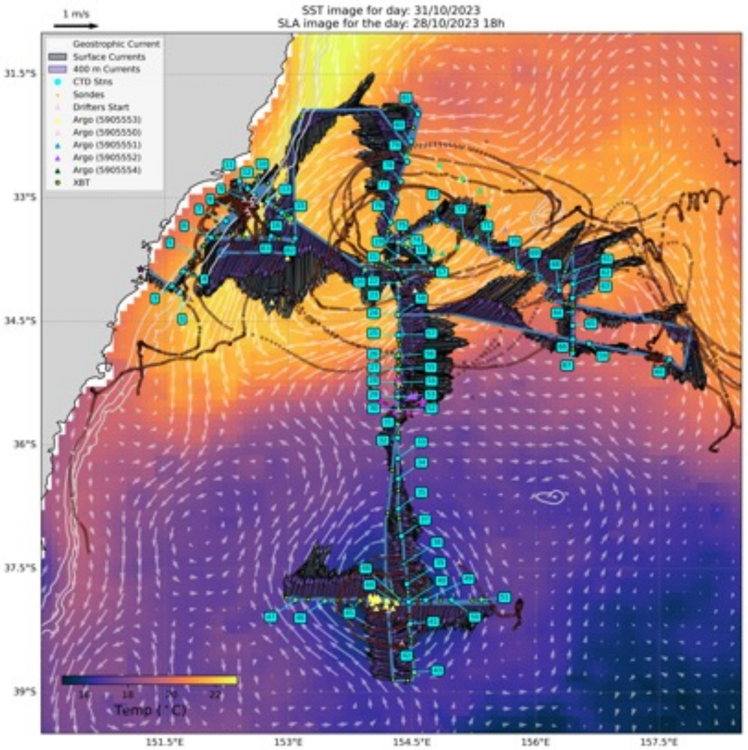
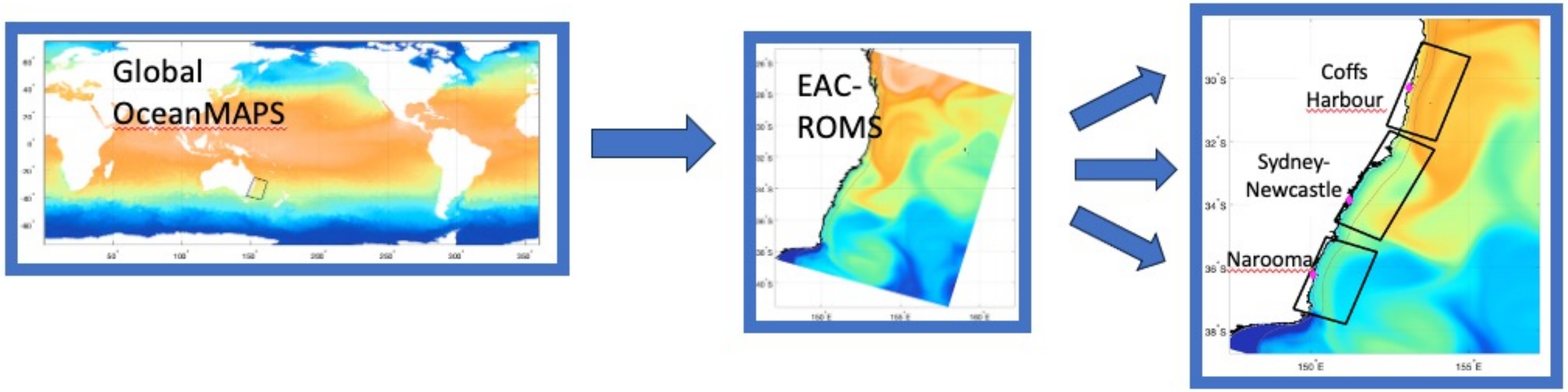


Fig. 2: A schematic representation of the Hybrid Ensemble-4DVar system. The EnKF passes the ensemble-derived covariance P to 4D-Var at the start of each cycle, and 4D-Var passes the control analysis $\overline{x_f}$ to the EnKF which is used to re-centre the ensemble.



Towards a high-resolution south-eastern Australia coastal ocean forecast (SEA-COFS) using advanced data assimilation

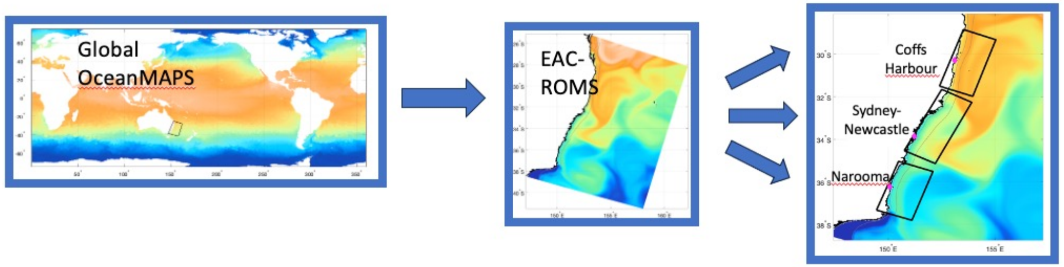


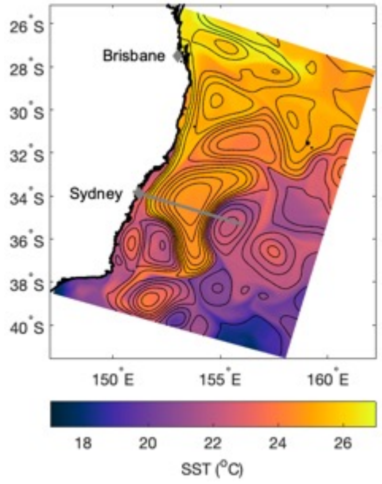
Summary

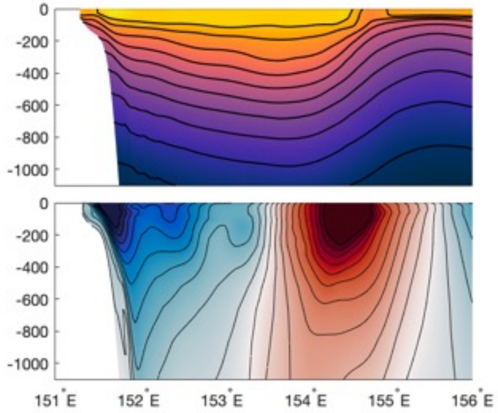
- EAC-ROMS is a crucial downscaling step between the global and coastal scales in this eddy-dominated region
- 4D-Var allows assimilation of observations over a time window for a dynamically consistent state estimate
- Observations have impacts up- and downstream and forwards and backwards in time
- Subsurface observations are crucial, and the DA scheme must be optimised to make use of them

- ***10 year reanalysis from 2010 to present in progress, stay tuned for the data availability***

Towards a high-resolution south-eastern Australia coastal ocean forecast (SEA-COFS) using advanced data assimilation







Next Steps - Operations

- Extending domain to Tasmania
- Operational mode
- Assimilation of novel observations in real-time
- Rivers and BGC

Next Steps - Research

- Assimilation of Surface Water and Ocean Topography
- Hybrid Ensemble-Var DA for improved subsurface representation