Observation impact in Australia's Western Boundary Current System: from the coherent jet to the eddy field

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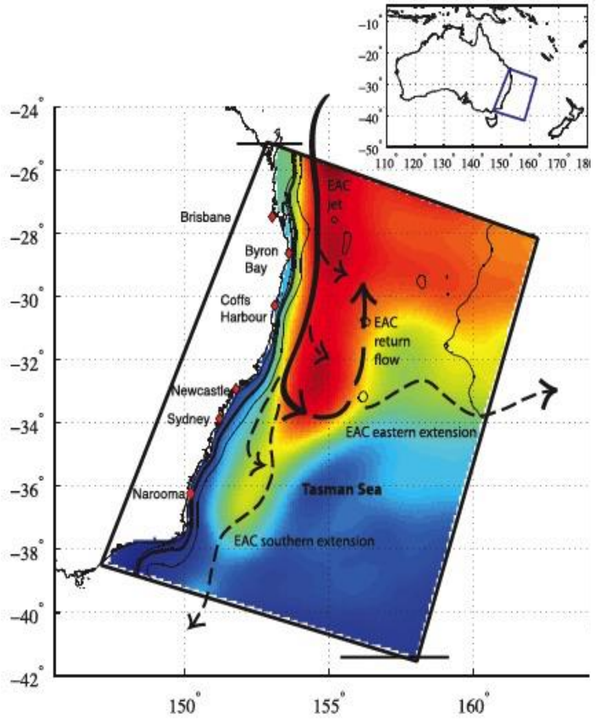
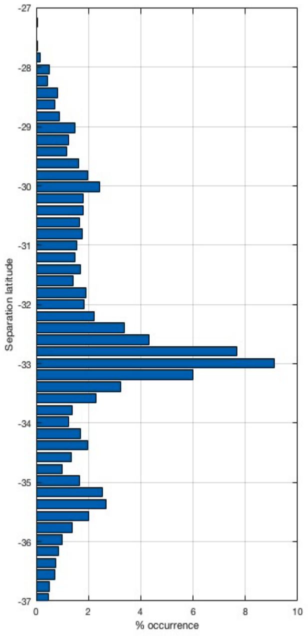
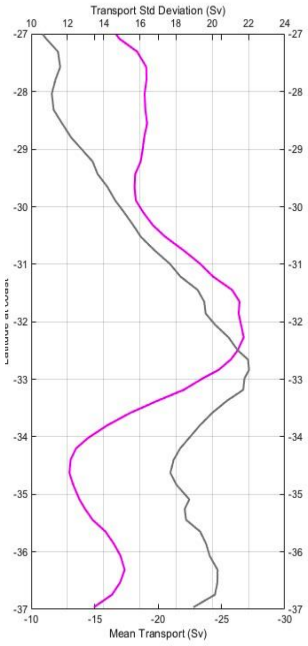
The EAC System

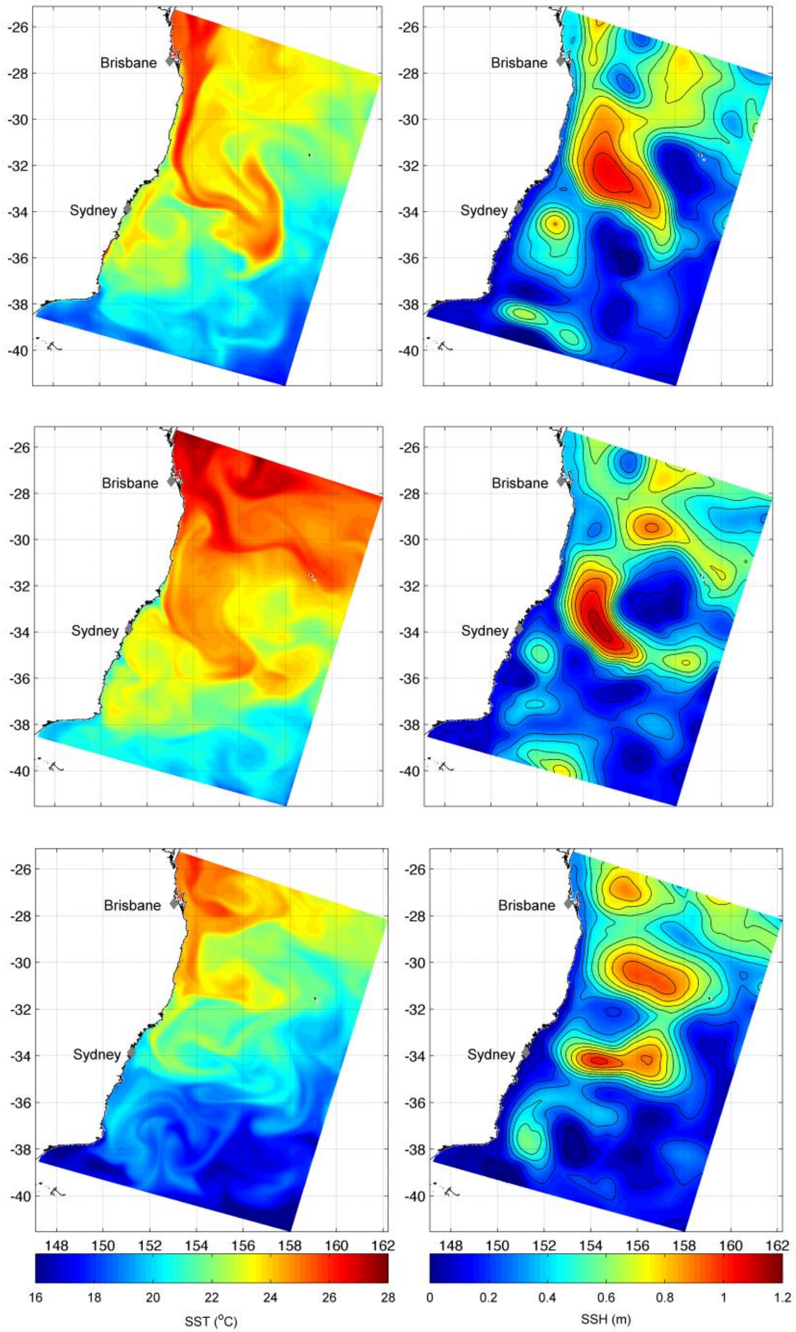
Prediction focused on the

- Strength and structure of the EAC jet upstream of separation
- Separation of the EAC from the coast
- Eddy structure and evolution of the eddy field



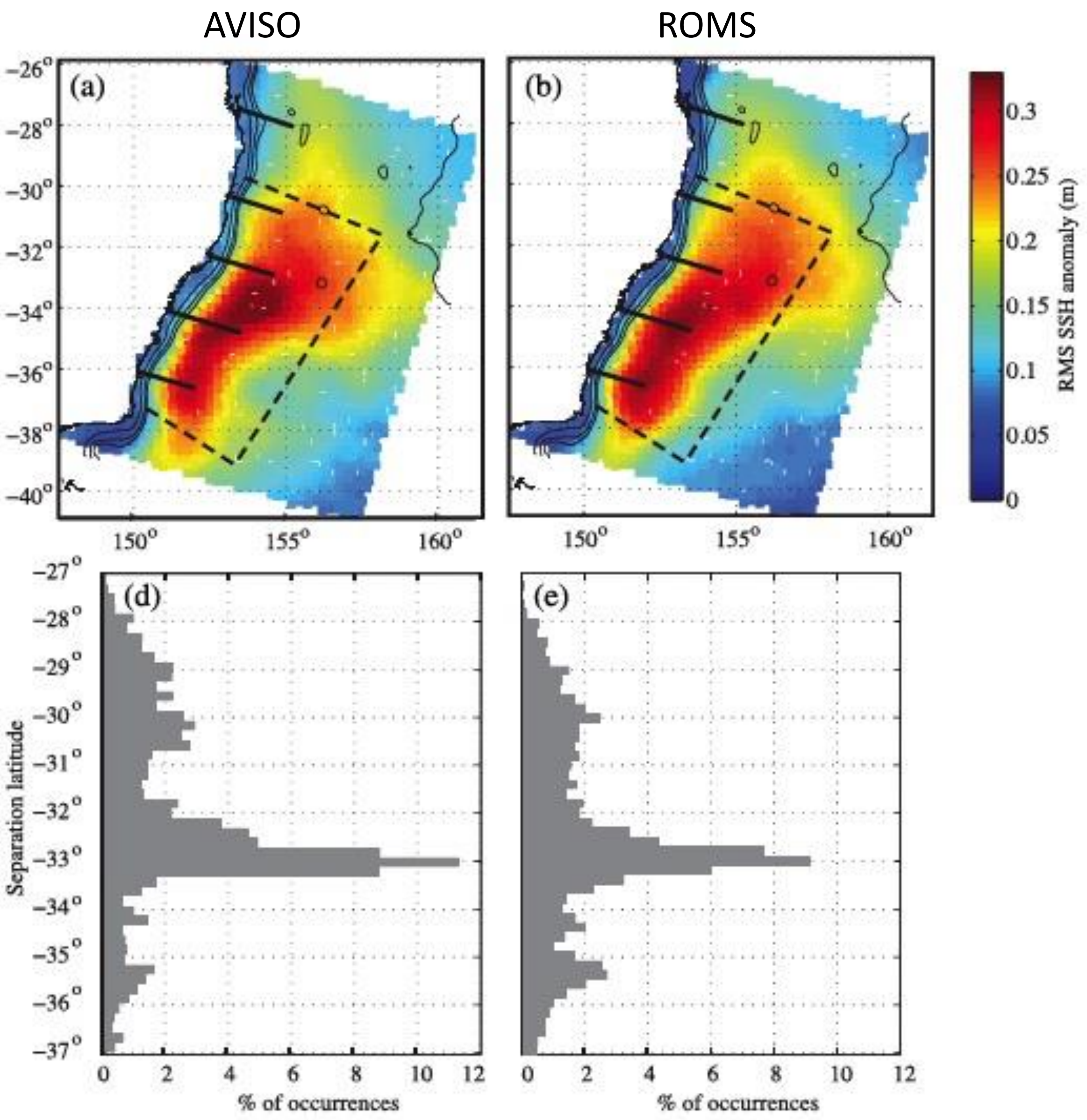






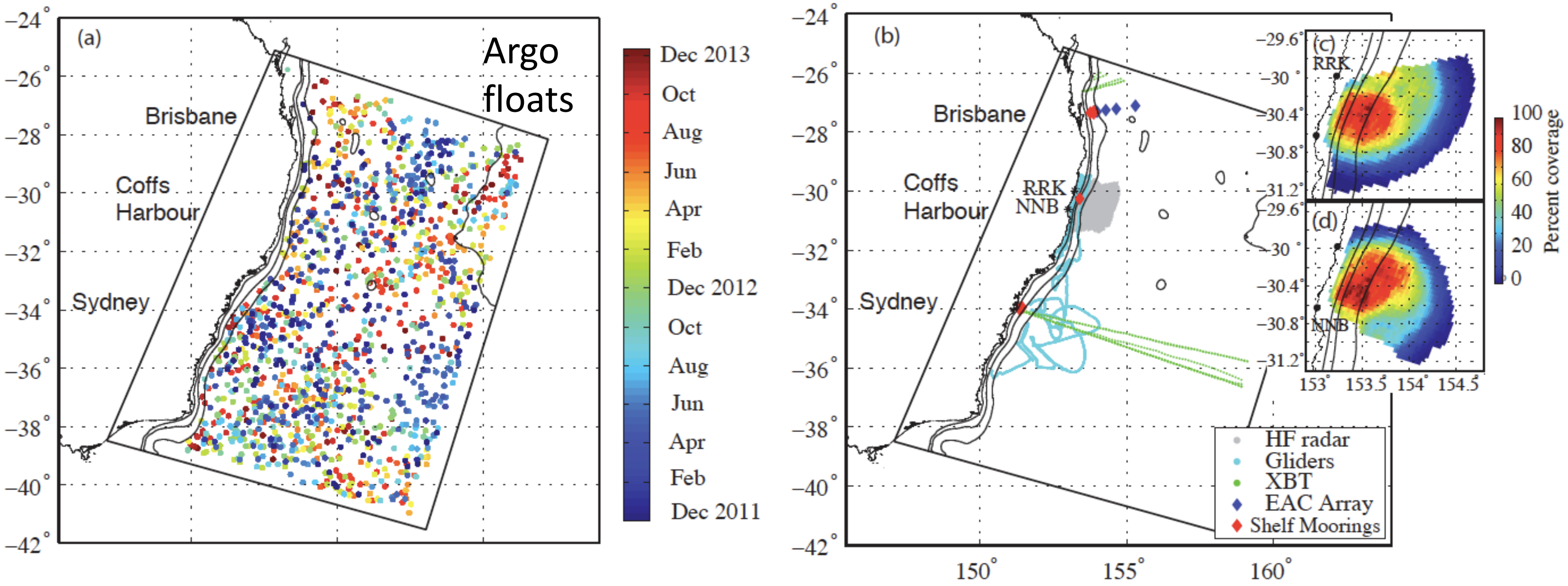
Regional Ocean Modelling System configuration

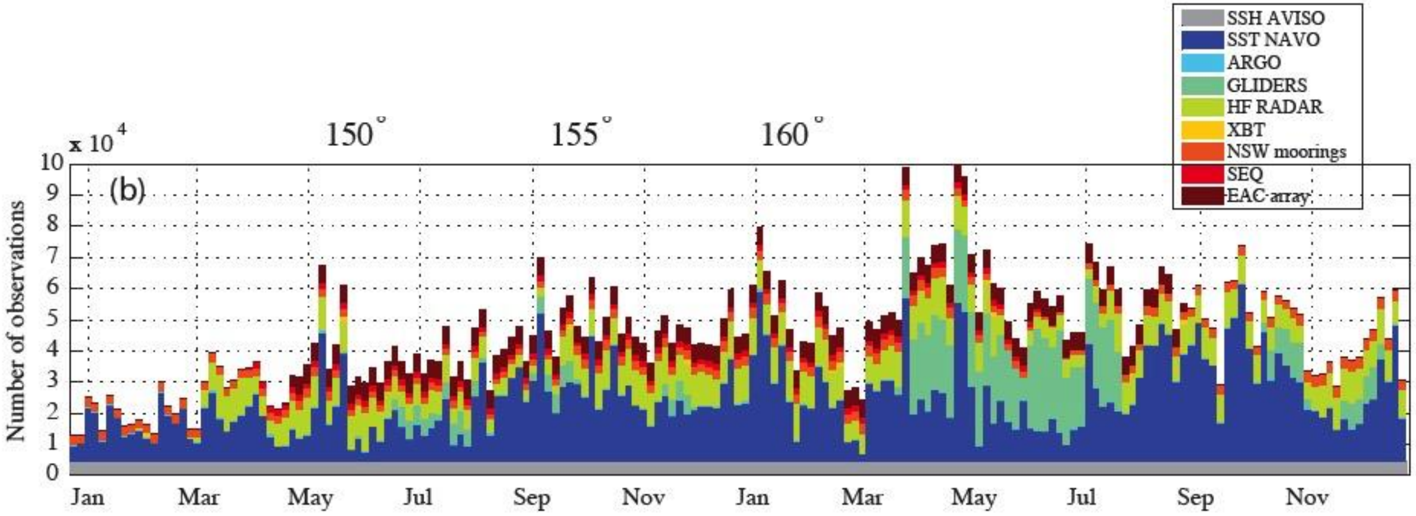
- Variable horizontal resolution
  - 2.5-6km cross shore
  - 5km alongshore
  - 30 s-levels
- Smoothing with emphasis on maintaining shelf width, key to EAC separation
- BRAN initial and boundary conditions
- ACCESS-R 12km for atmospheric forcing



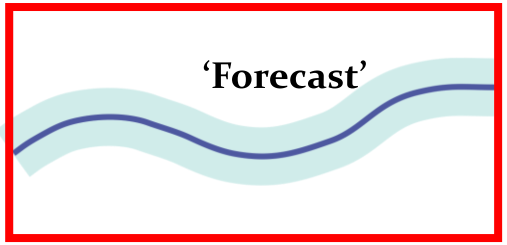
Observations

- AVISO SSH
- NAVO SST
- 1229 Argo profiles
- XBTs
- Shelf moorings
- EAC Array
- Gliders
- HF radar



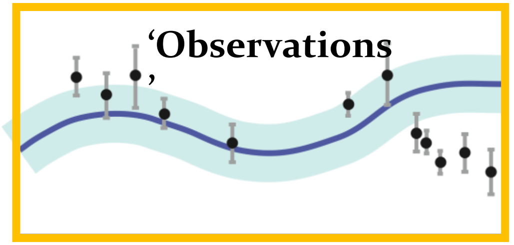


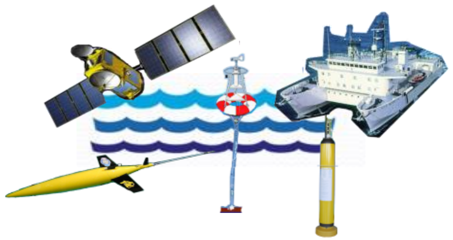
4D-Variational Data Assimilation



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

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





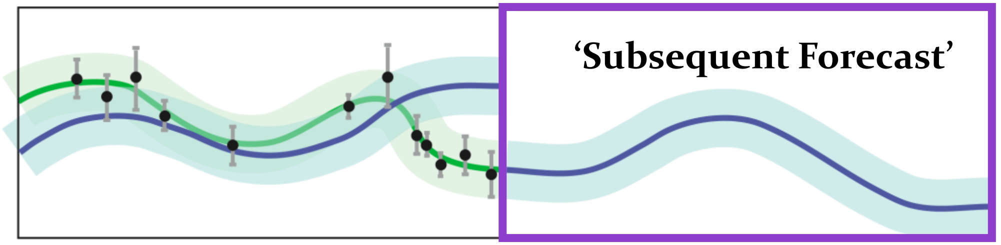
4-D Variational Data Assimilation

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: (δz)
- 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.

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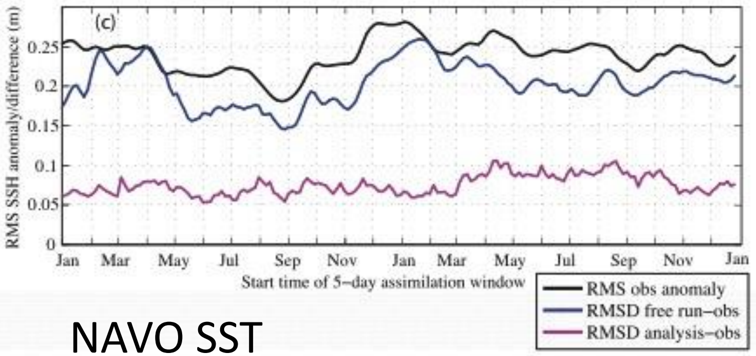
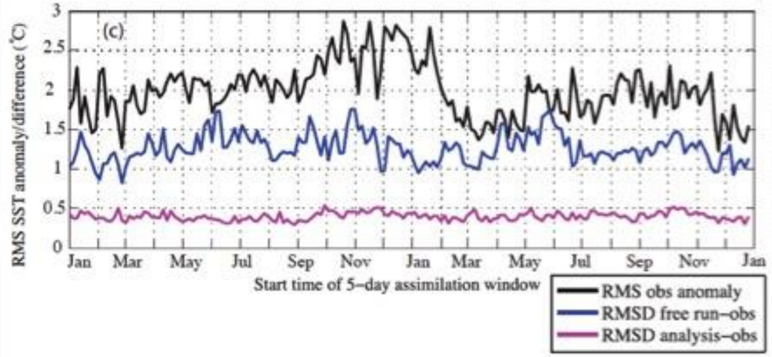
Reanalysis Performance

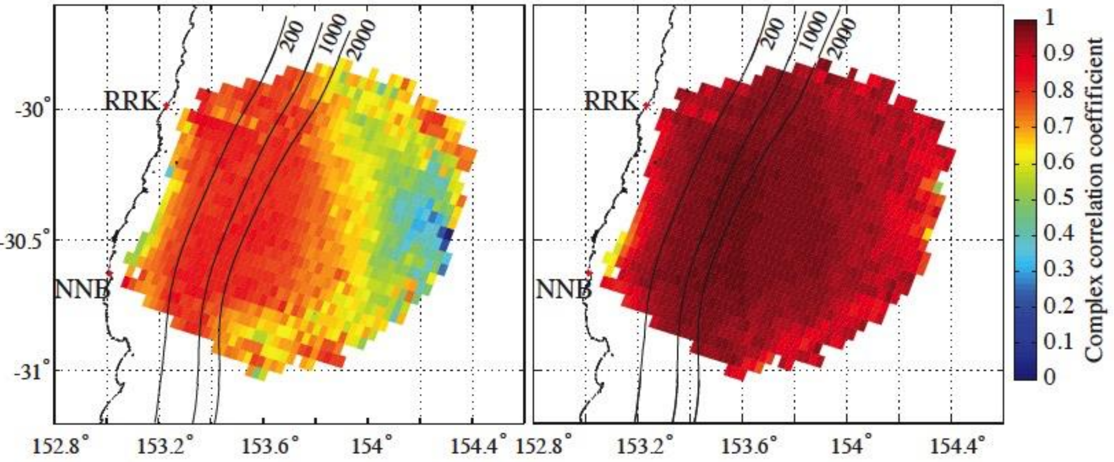
AVISO SSH



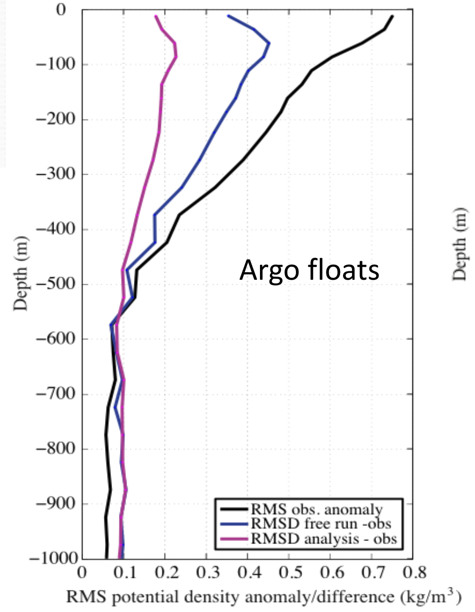
NAVO SST

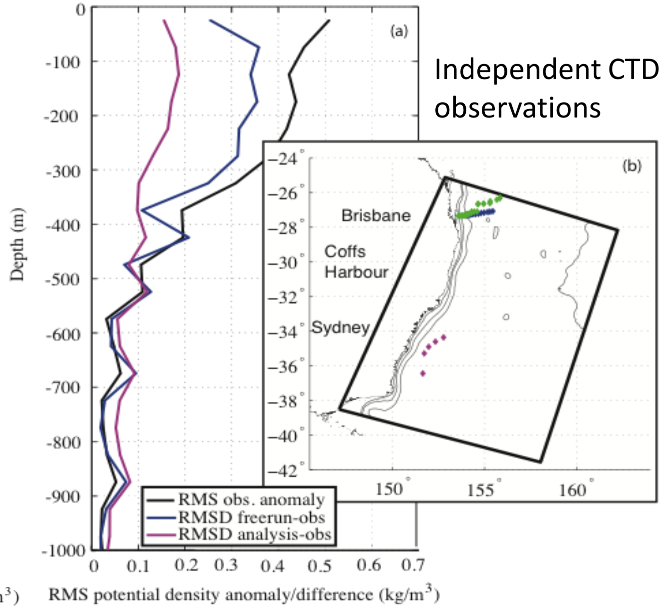


Surface velocities



Potential density



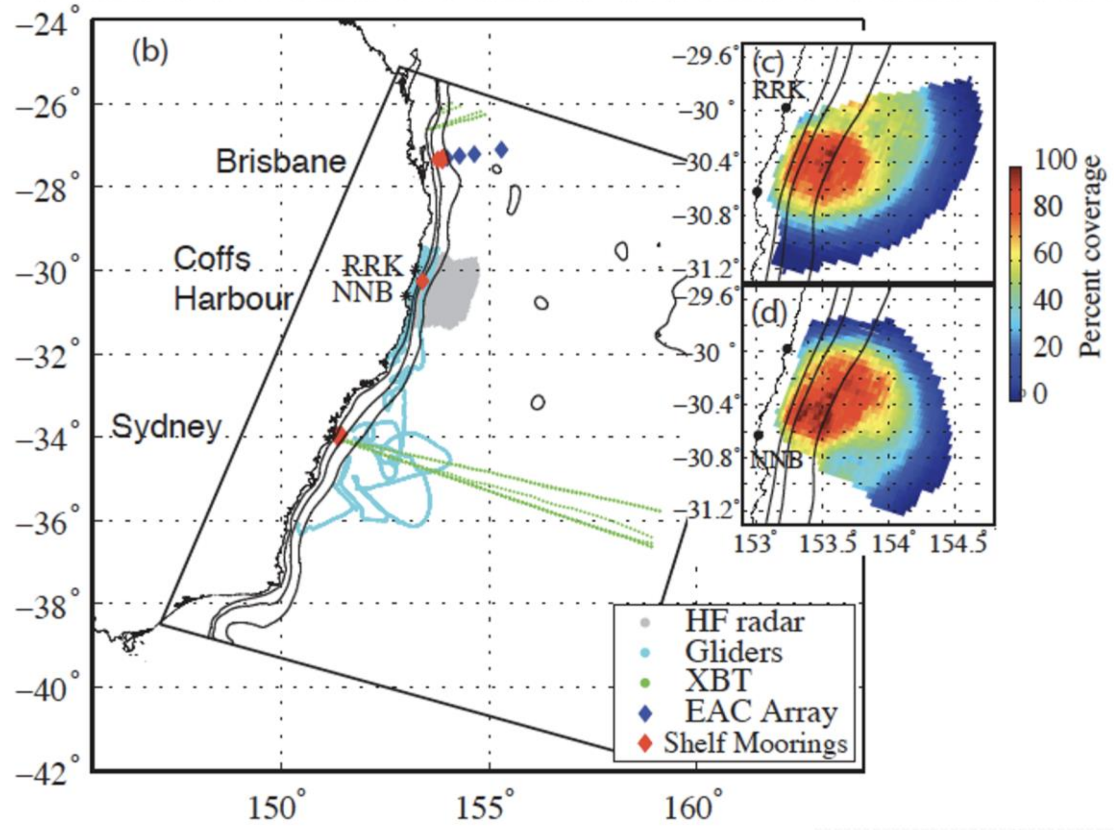


Independent CTD observations

Observation impact 3 ways

We study the impact of novel observations by

1. **Direct quantification of observation impact:** Variational methods allow us to quantify directly how each observation contributes to the state-estimate solution.
2. **Observing System Experiments:** A comparison of experiments with and without the novel observations allows us to assess their value in prediction of current transport and eddy structure.
3. **Observation System Simulation Experiments:** A series of OSSEs are designed to assess the impact of subsurface temperature observations and the impact of sampling the (upstream) coherent jet versus the (downstream) eddy field.



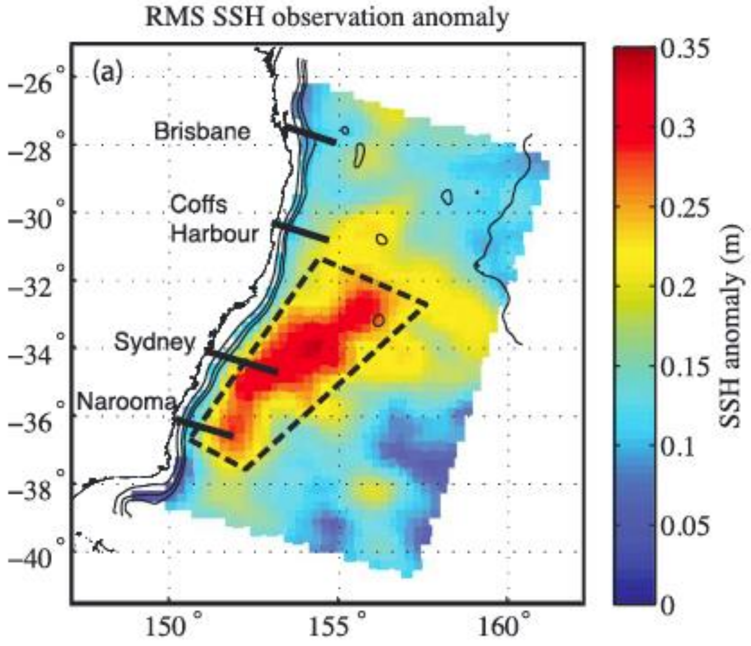
1. Direct quantification of observation impact

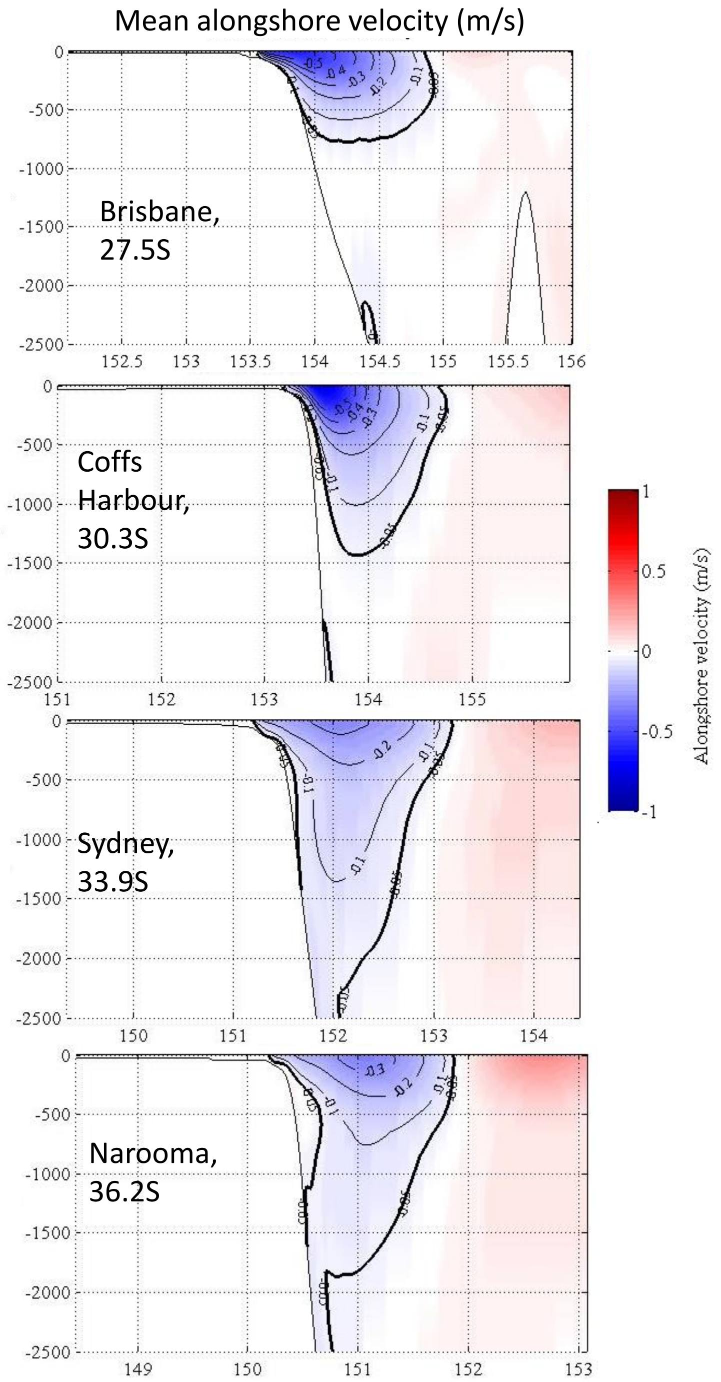
With 4D-Var, we can quantify how individual observations contribute to the changes in estimates of certain circulation metrics.

Alongshore volume transport:

$$S = \frac{1}{T}\int_{t_0}^{t_0+T}\int_{-D}^{0}\int_{x_0}^{x_i}(\mathbf{v})\delta x \delta z \delta t$$

$$\Delta S = S(\mathbf{x}_a) - S(\mathbf{x}_b)$$





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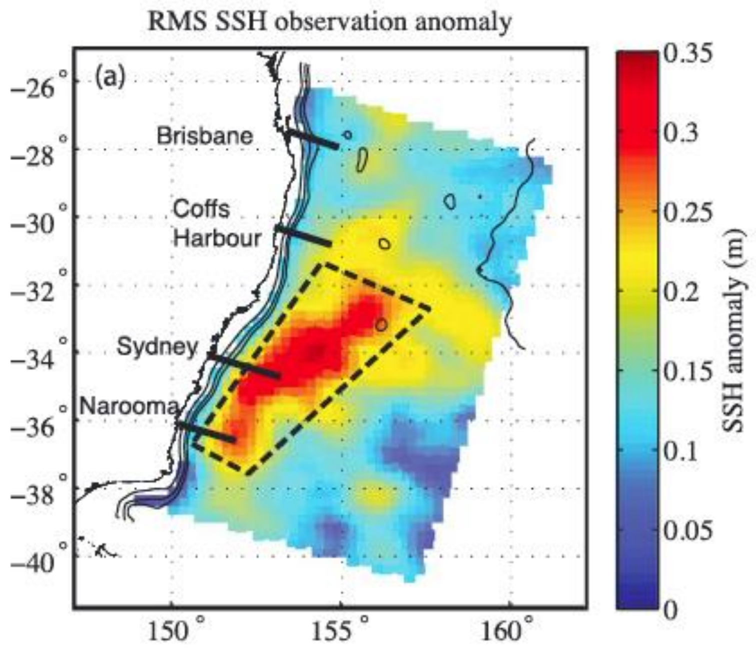


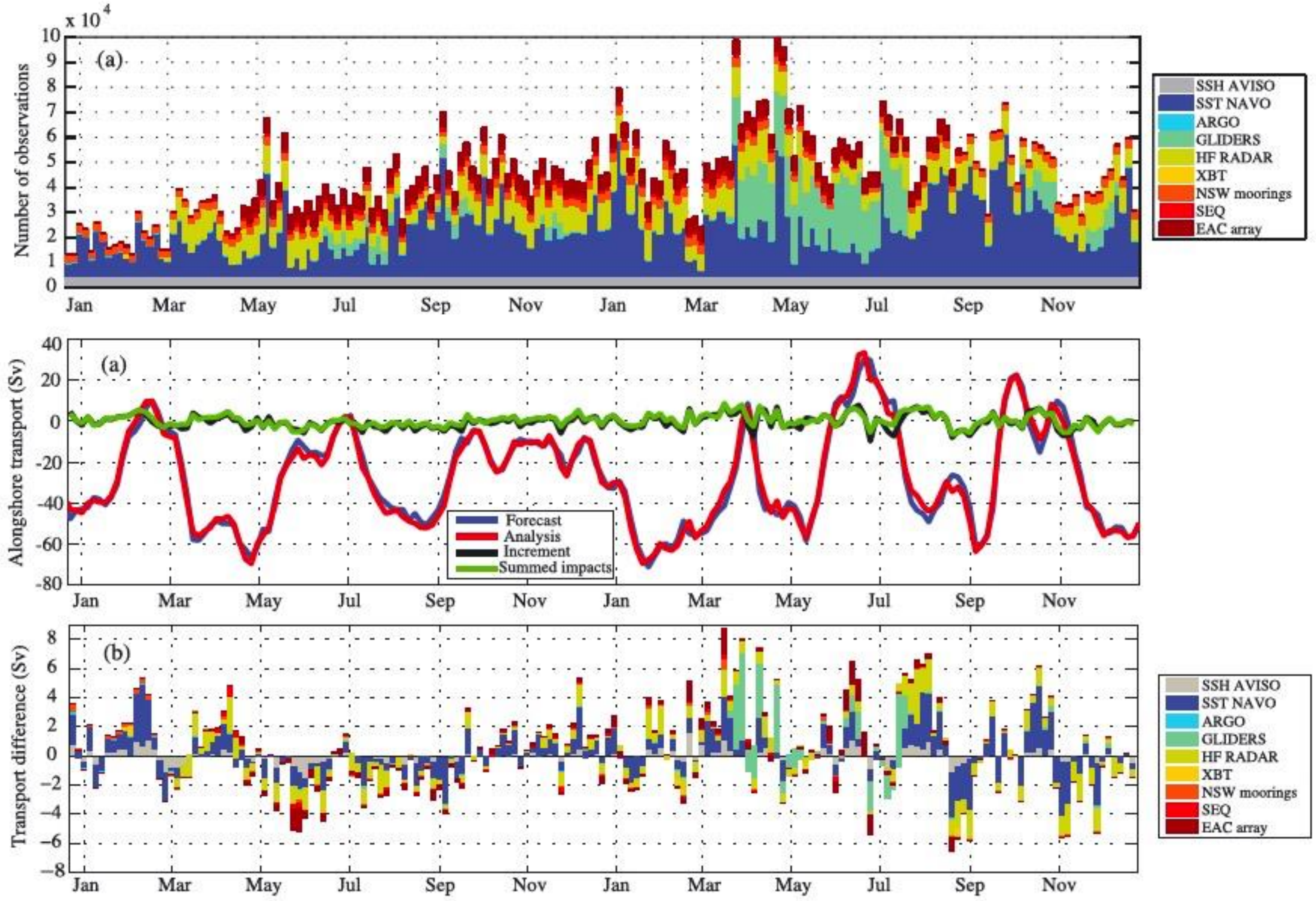
$$\Delta S = S(\mathbf{x}_a) - S(\mathbf{x}_b)$$

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}\mathbf{d}$$

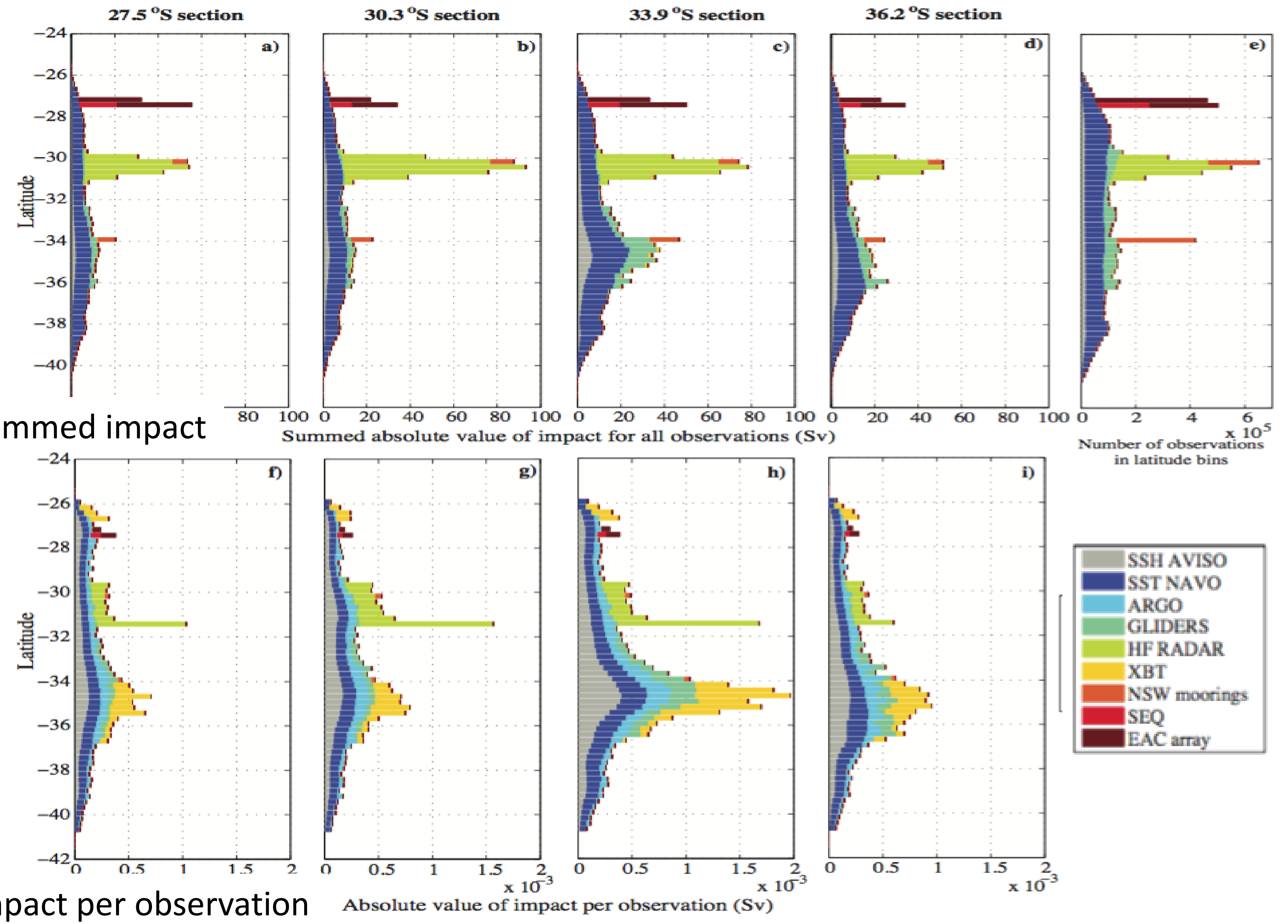
$$\Delta S = S(\mathbf{x}_b + \mathbf{K}\mathbf{d}) - S(\mathbf{x}_b)$$

$$\Delta S = S(\mathbf{x}_b) + \frac{\delta S}{\delta \mathbf{x}_b}\mathbf{K}\mathbf{d} - S(\mathbf{x}_b) = \mathbf{d}^T\mathbf{K}^T\frac{\delta S}{\delta \mathbf{x}_b}$$

Observation impact on volume transport off Sydney (34S)



Alongshore volume transport: Impact with latitude



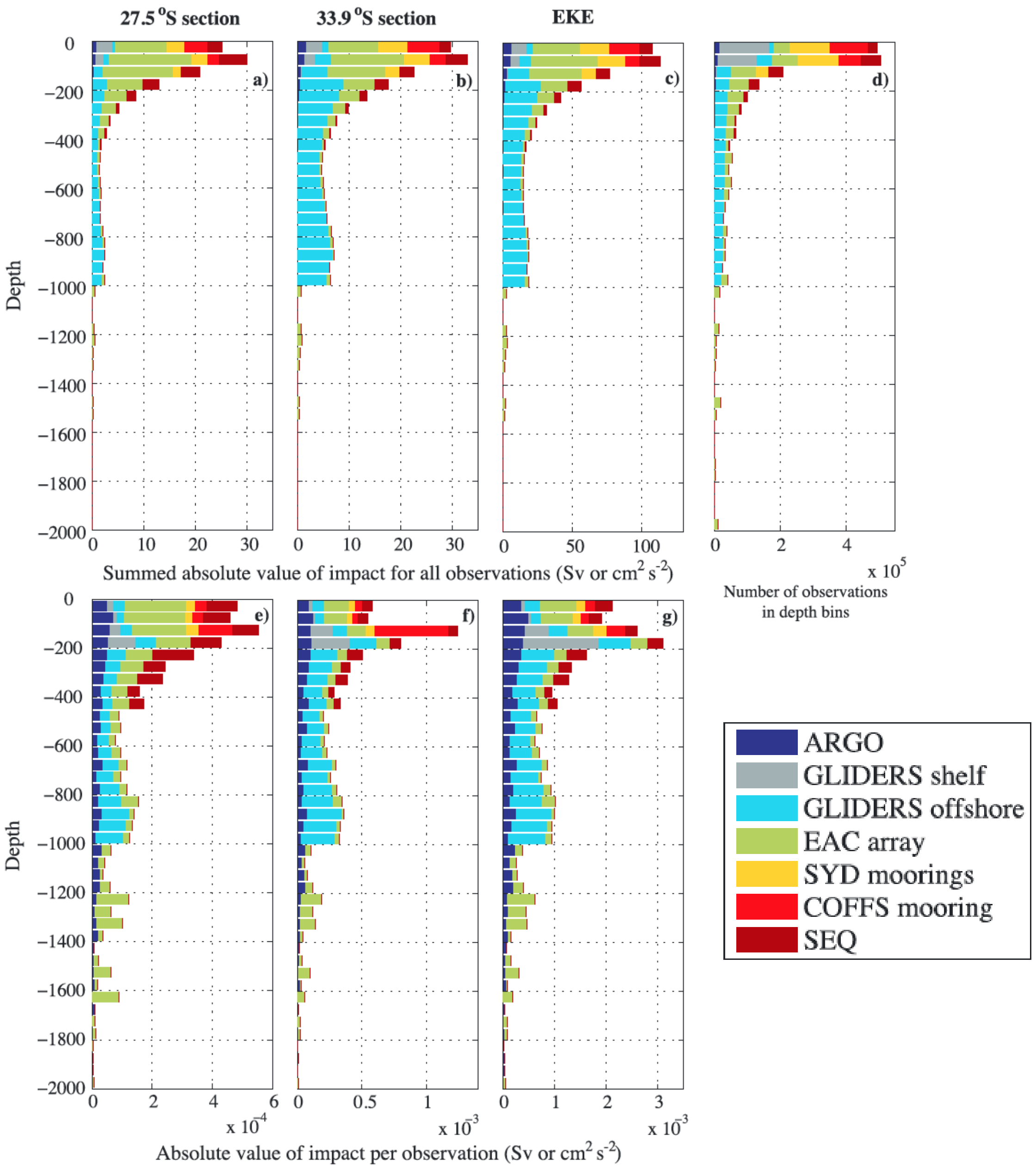
Summed impact

Impact per observation

Alongshore volume transport: Impact with depth

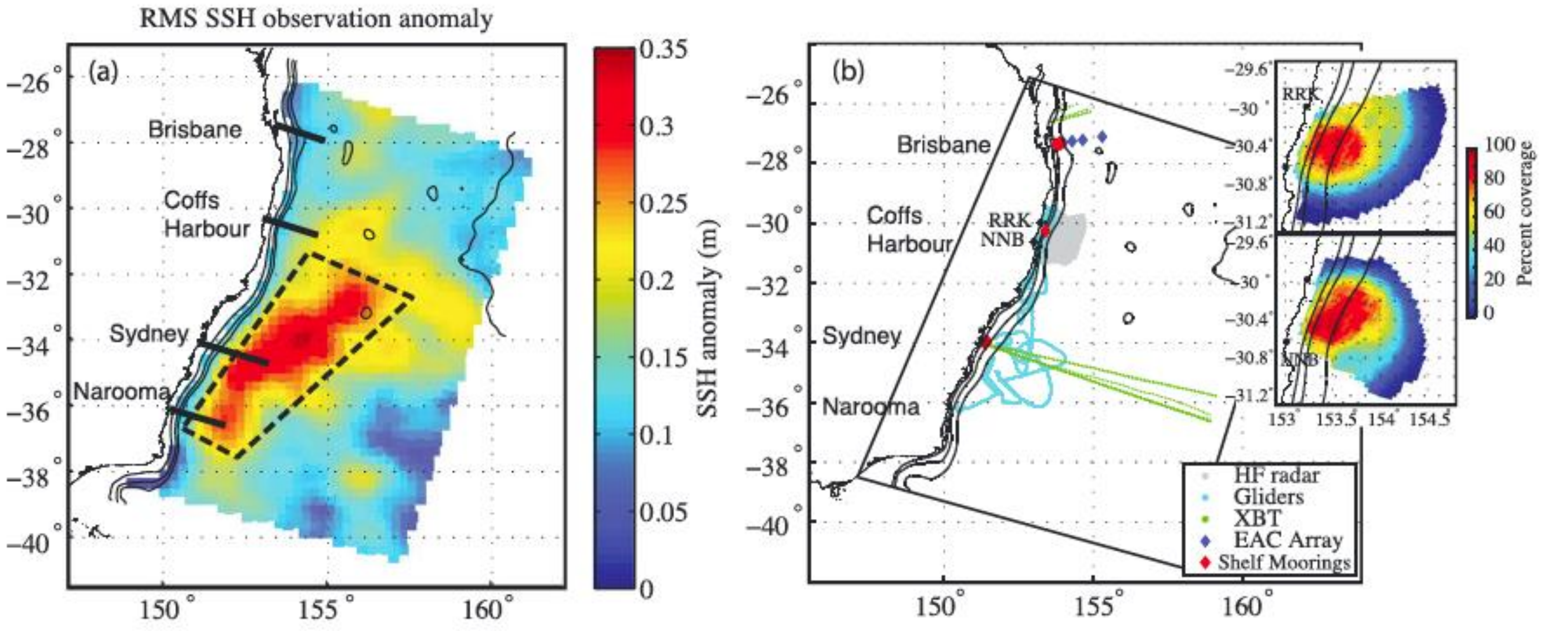
Summed impact

Impact per observation

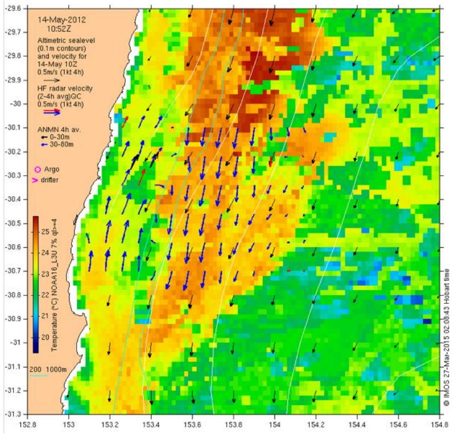


Observation impact on alongshore volume transport

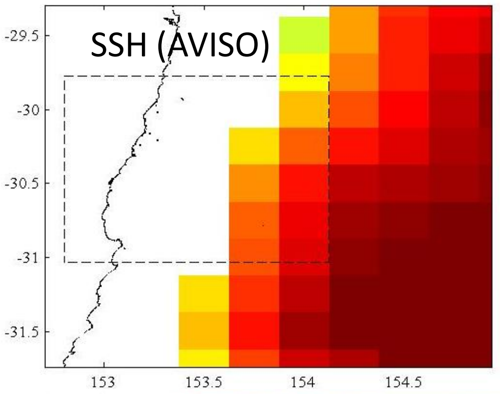
	Mean % of all observations	Mean % impact Brisbane	Mean % impact Coffs Harbour	Mean % impact Sydney	Mean % impact Narooma
AVISO SSH	11.8	9.7	11.2	13.4	14.9
NAVO SST	43.6	42.1	39.1	46.2	46.3
HF radar	17.2	31.3	44.9	25.3	24.3
EAC array	7.8	13.6	6.8	8.3	7.3
Gliders	8.9	6.7	6.0	11.9	9.3
Argo	1.0	0.7	0.8	0.8	0.8
XBT	0.2	0.4	0.4	0.6	0.6

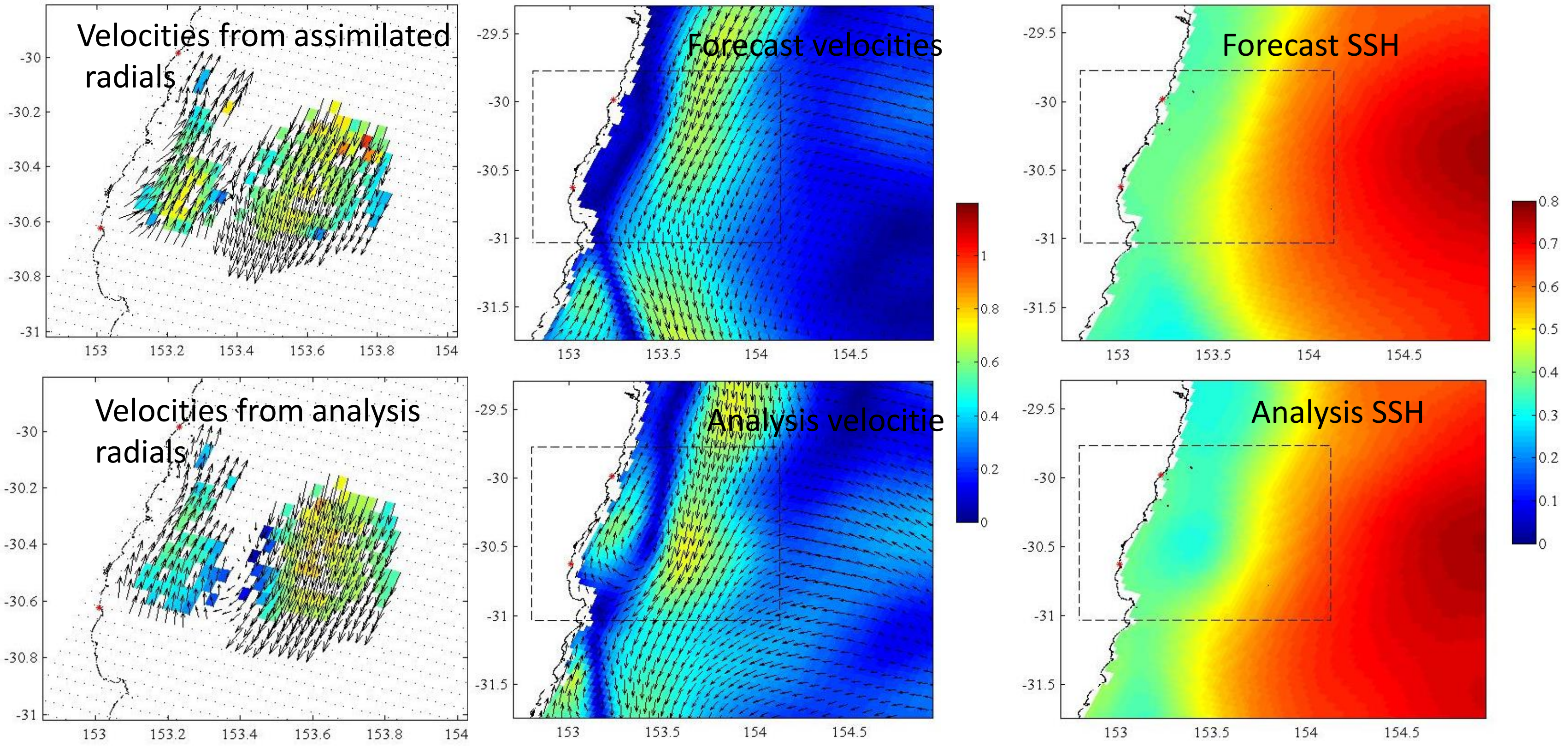


HF radar impact example



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





Key points: Direct quantification of observation impact

- Observations taken in regions with greater natural variability are most impactful
  - SSH and SST observations between 32-37 S have more impact on transport estimates along the coast than the same observations taken elsewhere
  - Observations in the upper 400m are more impactful than deeper observations, as they reveal information about the structure of the mixed layer and thermocline

- Gliders deployed in EAC eddies are particularly impactful

- Observation impact is far-reaching; up and downstream, and forward and backward in time
  - e.g. HF radar, EAC array

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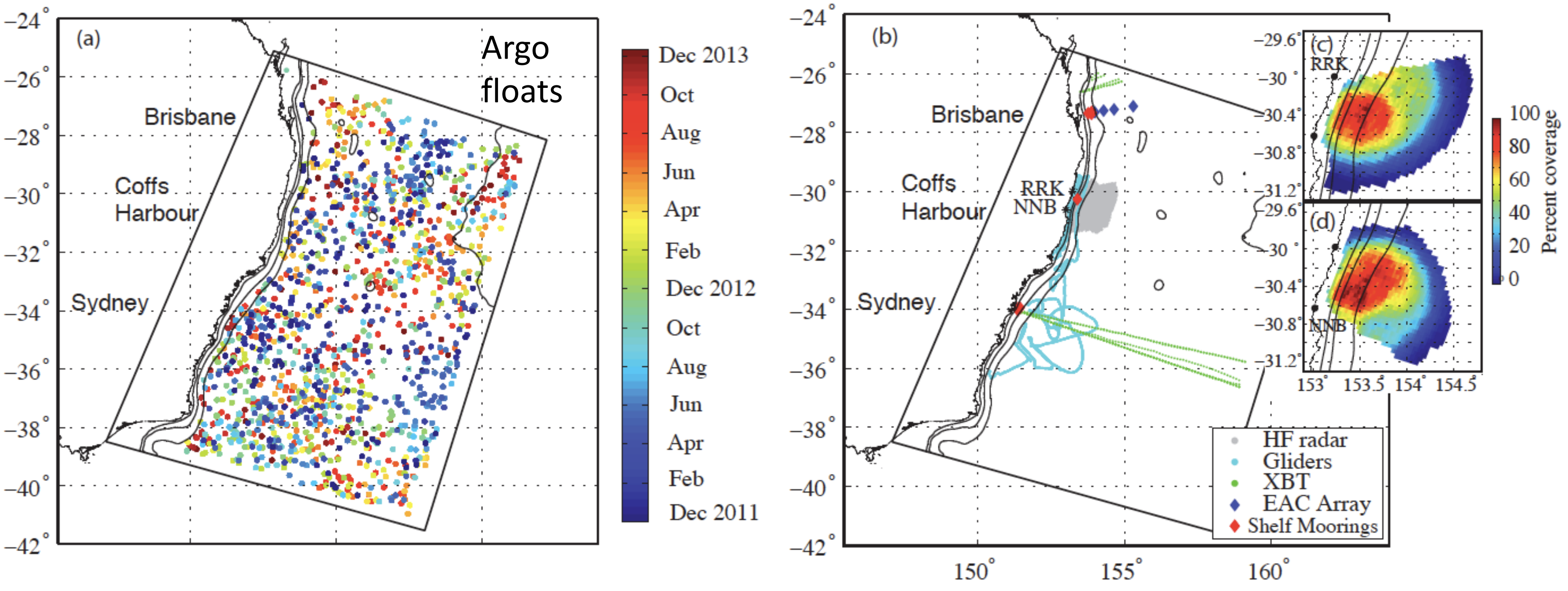
2. Observation System Experiments (withholding the ‘novel’ observations)

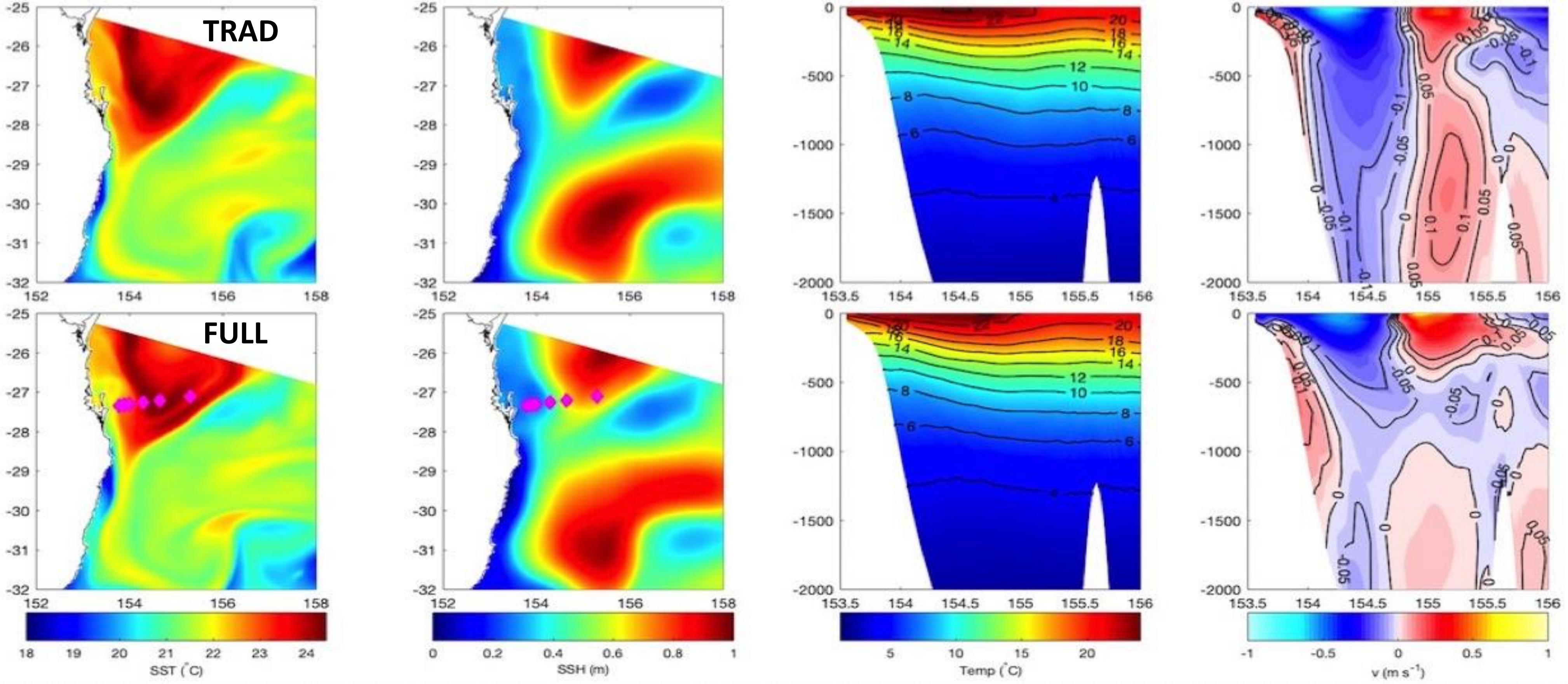


- **FULL:** AVISO SSH, NAVO SST
  1229 Argo profiles, XBTs
  Shelf moorings
  EAC transport array
  Gliders
  HF radar

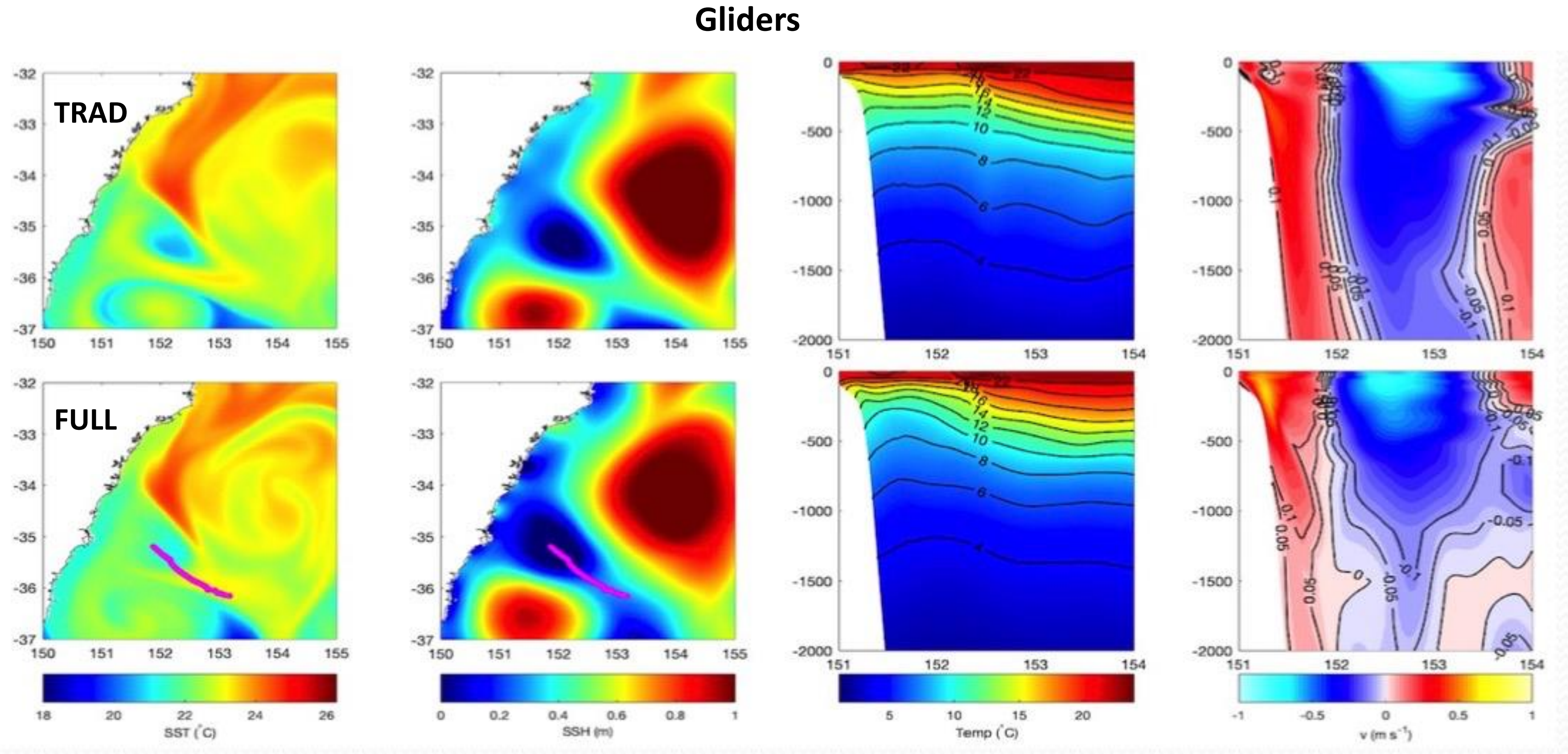
- **TRAD:** AVISO SSH, NAVO SST
  1229 Argo profiles, XBTs

Eddy depth

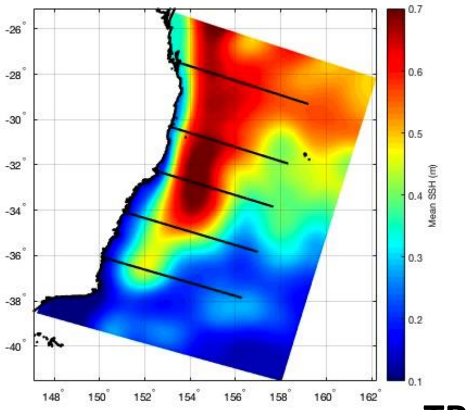
EAC mooring array



Eddy depth

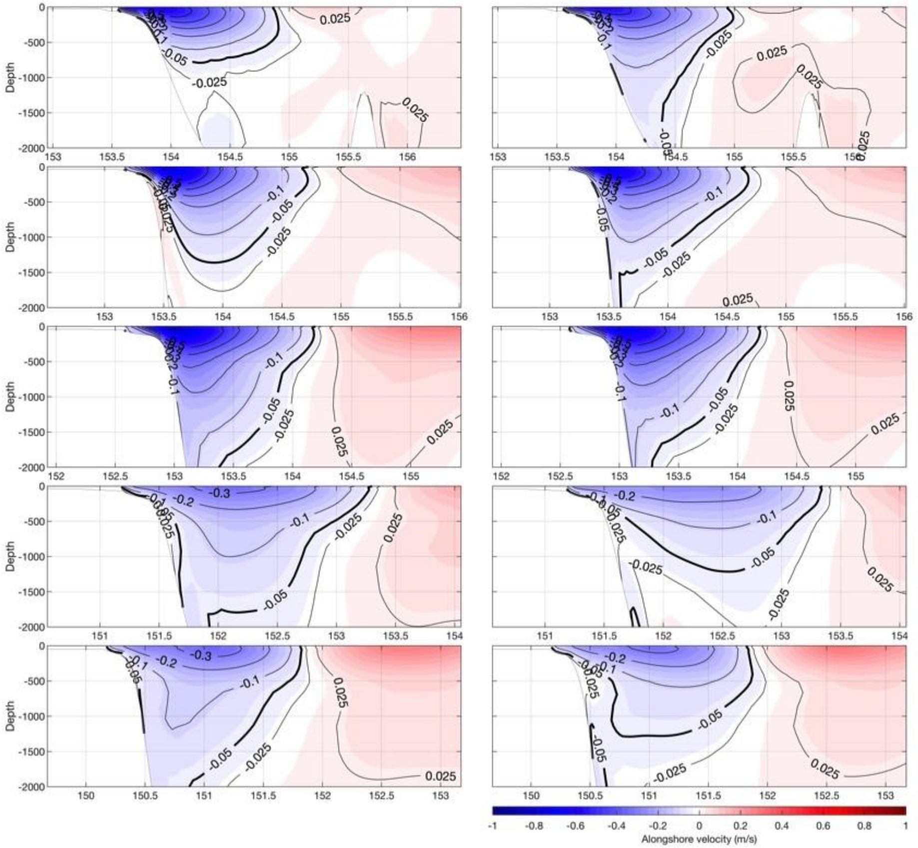


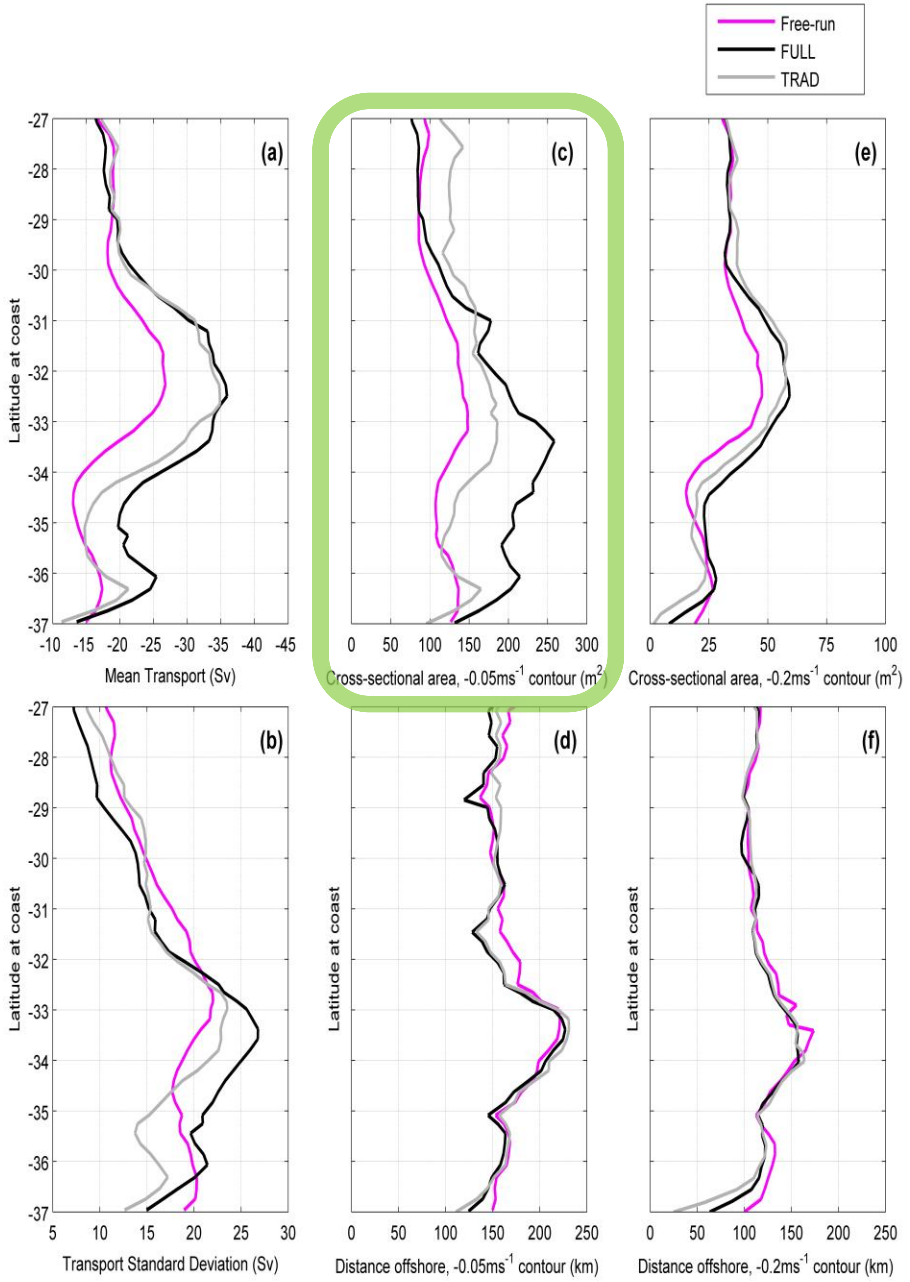
EAC core depth



FULL

TRAD





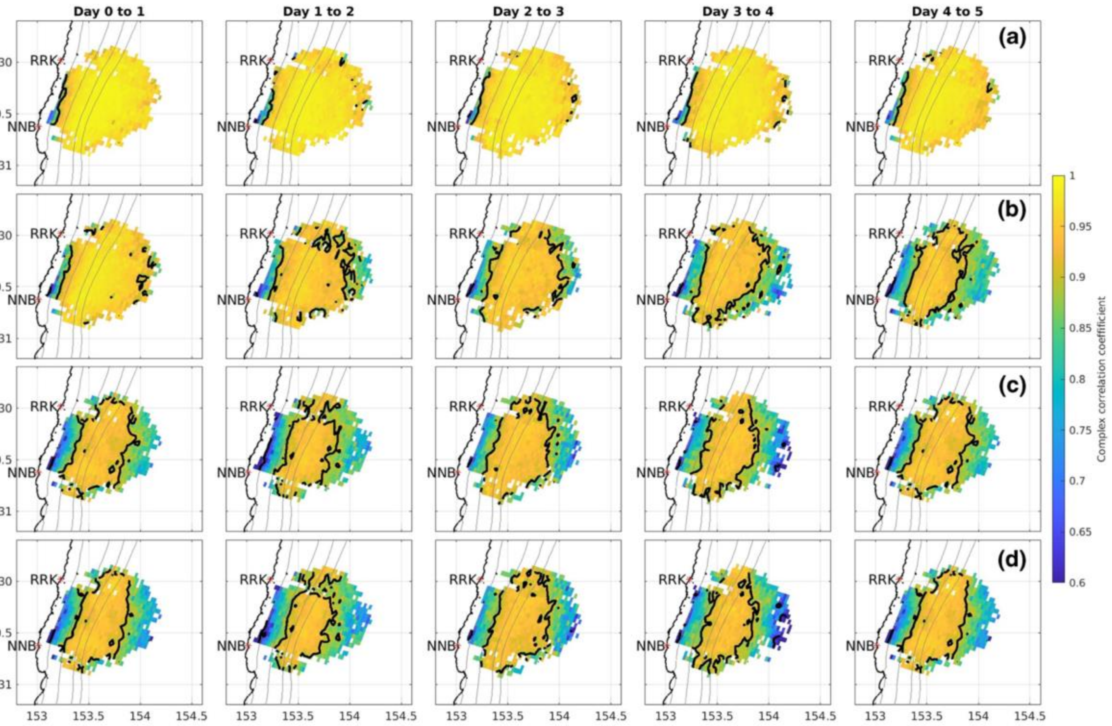
Forecast skill

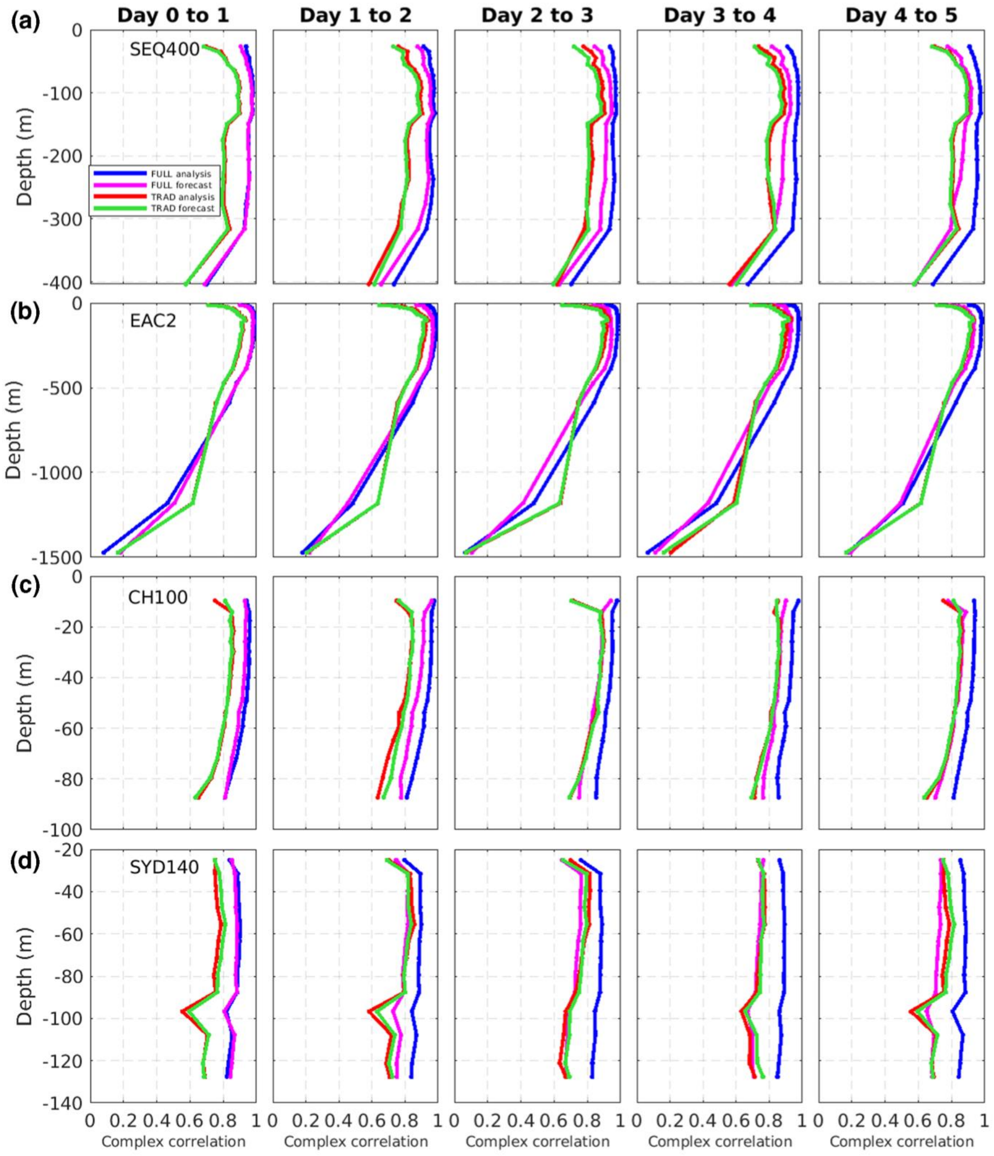
FULL analysis

FULL forecast

TRAD analysis

TRAD forecast





Key points: Observing System Experiments

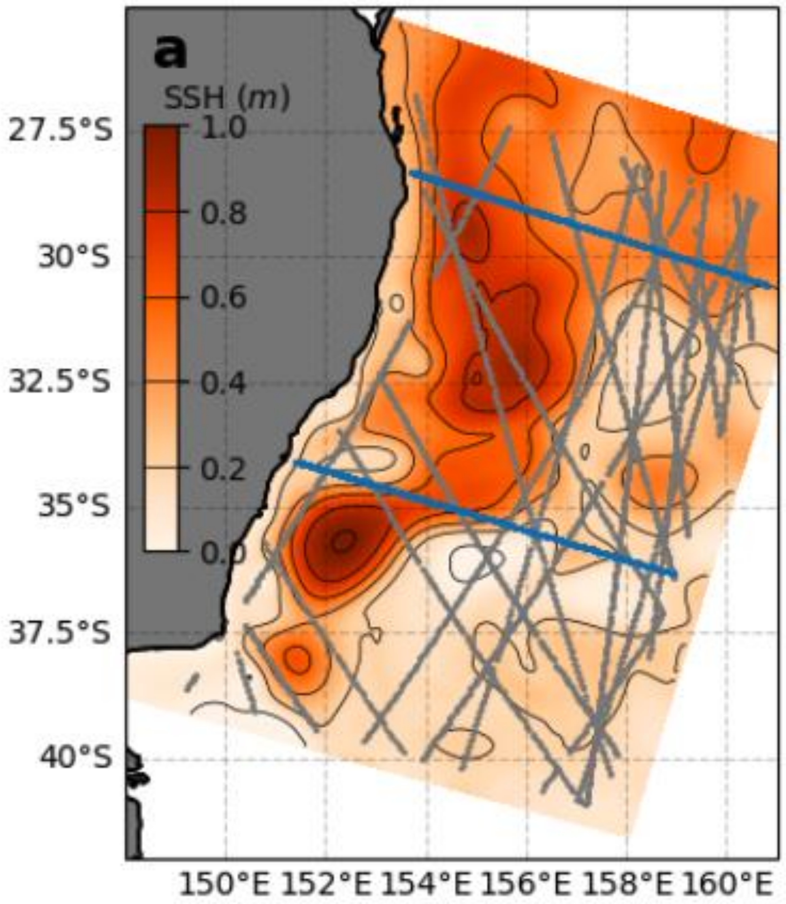
- FULL reanalysis better represents
  - EAC core depth from 27-30^{o}S
  - Eddy depth (in vicinity of the gliders)
  - Surface vorticity inshore of the EAC (and vorticity variance)

- EAC core and eddies are too deep when not constrained with observations (likely need improved background error covariance estimates)

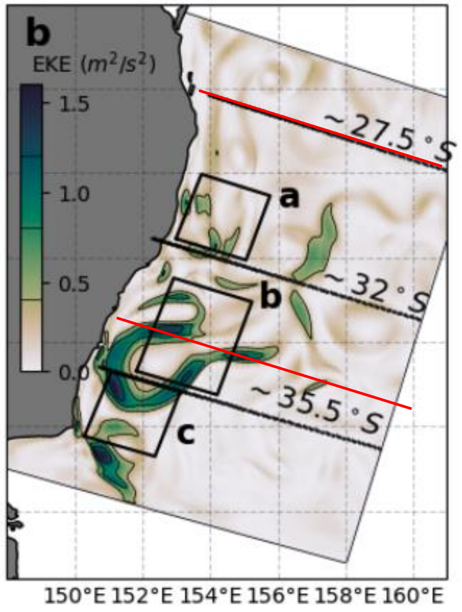
- TRAD displays similar surface and subsurface predictive skill to the FULL after 5 days
- The 'novel' observations introduce scales that cannot be resolved by the forecast model
- The goal is that the impact of the 'novel' observations is more far-reaching in time and space – improved specification of P (flow-dependence)

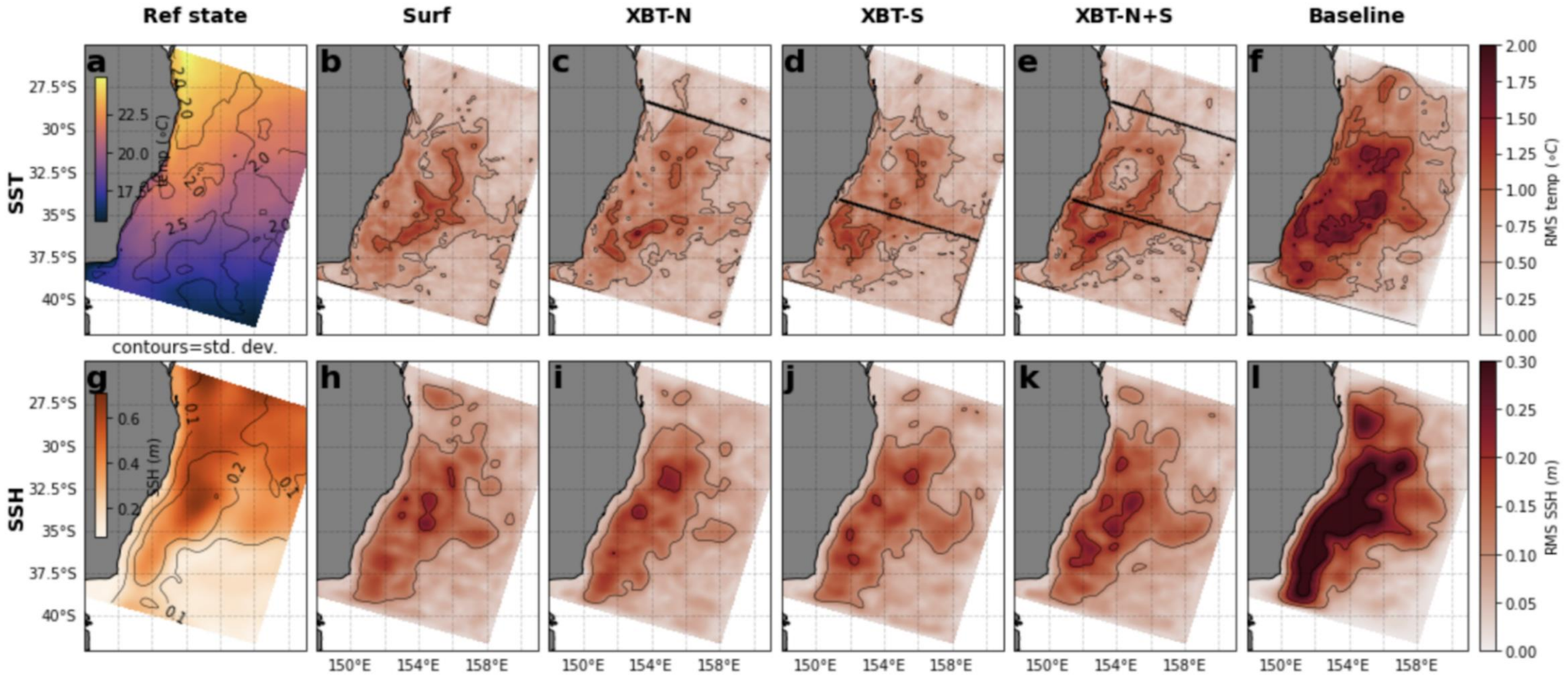
3. Observation System Simulation Experiments

Experiment name	Model configuration details	Synthetic observations
Reference state	Free-running simulation covering period of Nov 2011 - Jan 2013. Observations extracted from this simulation.	
Surf	4DVar simulation covering period of Nov 2011 - Jan 2013; assimilating SSH and SST 'observations' synthesised from Reference state	Along-track satellite-observed sea surface height altimetry and sea surface temperature.
XBT-N	Surface observations plus XBT observations along the northern transect.	XBT temperature profiles to 900 m starting at ∼ 28°S.
XBT-S	Surface observations plus XBT observations along the southern transect.	XBT temperature profiles to 900 m starting at 34°S.
XBT-N+S	Surface observations plus XBT observations along both transects.	XBT temperature profiles to 900 m starting at 28°S and 34°S.

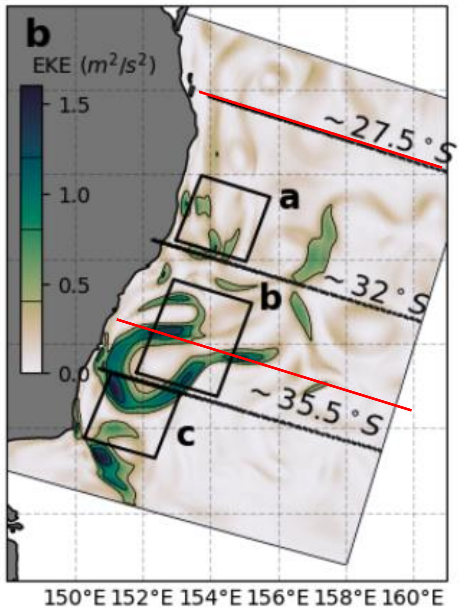


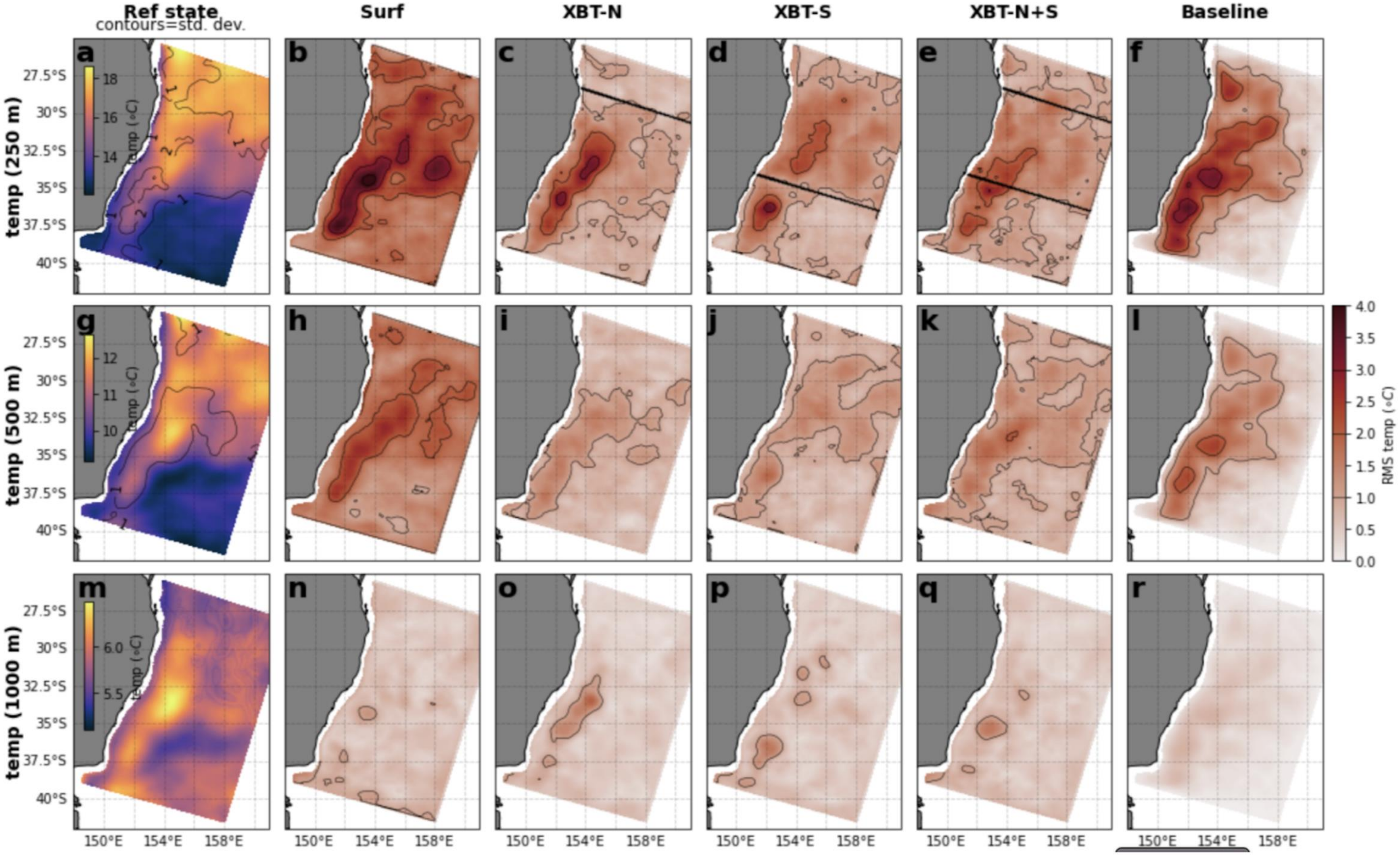
OSSEs: Surface representation





OSSEs: Subsurface temperature representation





Key points: Observation System Simulation Experiments

- Assimilating subsurface temperature observations improves EAC representation (temperature and velocity in the upper 1000m) compared to surface only

- Sub-surface temperature observations across the coherent EAC jet are less effective at improving estimates downstream compared to sub-surface temperature observations through the eddy-dominated region

- Sub-surface temperature observations through the eddy-dominated region in the Tasman Sea improve estimates in the upstream region and the eddying region

Summary: Observation Impact in the EAC

- Observation impact 3 ways gives consistent results
- Observation impact is far-reaching; up and downstream, and forward and backward in time (4D-Var)
- Observations taken in regions with greater natural variability are most impactful
  - ***We need to sample in the eddy-rich region***
  - ***Downstream controls upstream***
  - ***Upstream cannot control downstream due to chaos of separation and eddy shedding***
- EAC core and eddy depth extend too deep when not constrained by observations

- Drawbacks in **vertical** representation likely stem from drawbacks in our estimates of P (isotropic horizontal and vertical decorrelation length scales, time invariant)
- What about **horizontal** projection of ‘information’? ‘Eddy’ scale
- Future work in improving the DA system: Flow dependent background error covariances for 4D-Var

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Future work: Hybrid Ensemble-Var

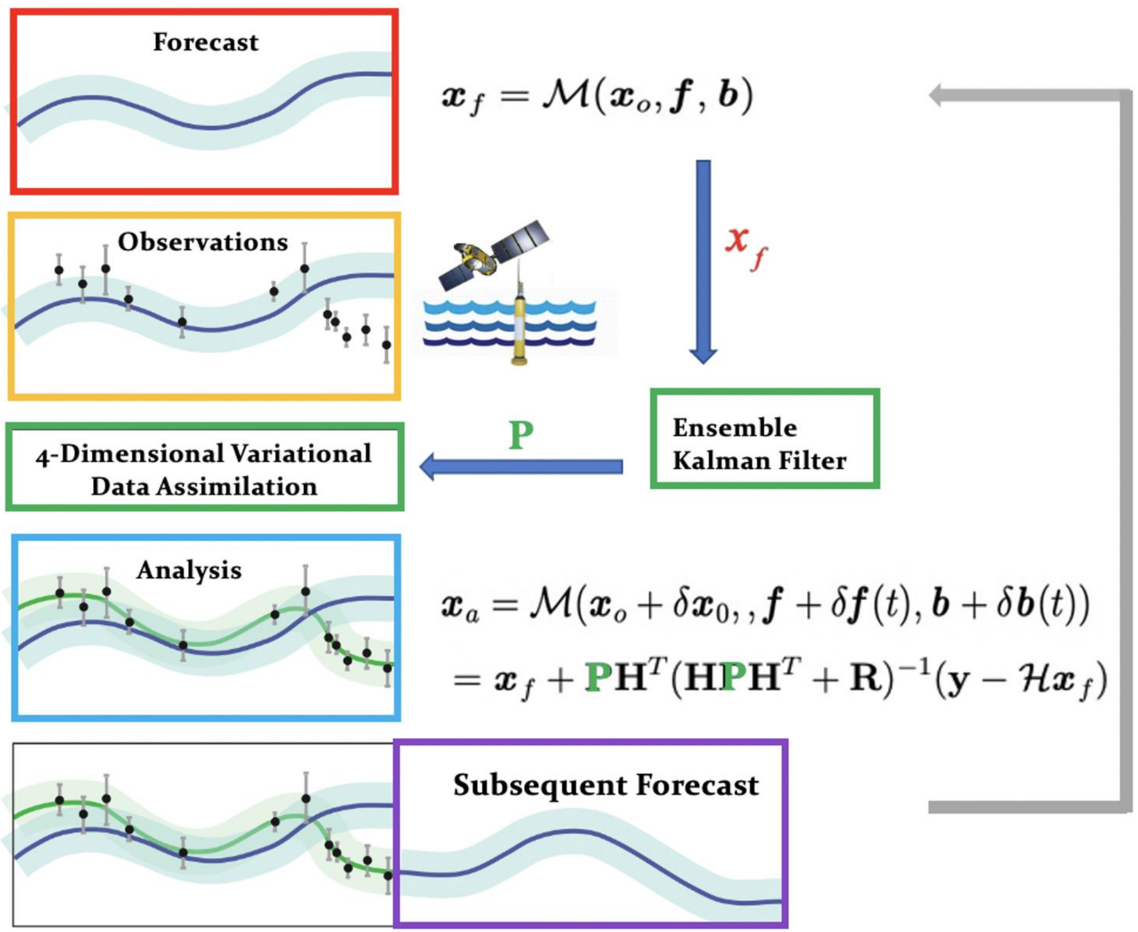
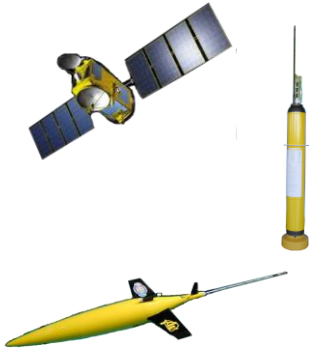


Fig. 2: A schematic representation of the Hybrid Ensemble-4DVar system. The EnKF passes the ensemble-derived covariance P to 4D-Var at the start of each cycle, and 4D-Var passes the control analysis $\overline{x_f}$ to the EnKF which is used to re-centre the ensemble.

- In 4D-Var we use a static background covariance matrix. On the other hand, an EnKF employs an ensemble of nonlinear model states to estimate P and so capture what are commonly referred to in NWP as the "errors of the day."
- Hybrid methods capatilise on the advantages of the two most advanced DA systems, 4D-Var and the EnKF.
- The dynamical interpolation properties of the adjoint, and the explicit flow-dependent error covariances that capture the "errors of the day" that can be provided by ensembles.
- Flow dependence important for highly dynamic regions where climatological covariances don't cut it.
- Also key for under-sampled regions (the ocean compared to the atmosphere!)

Thank you



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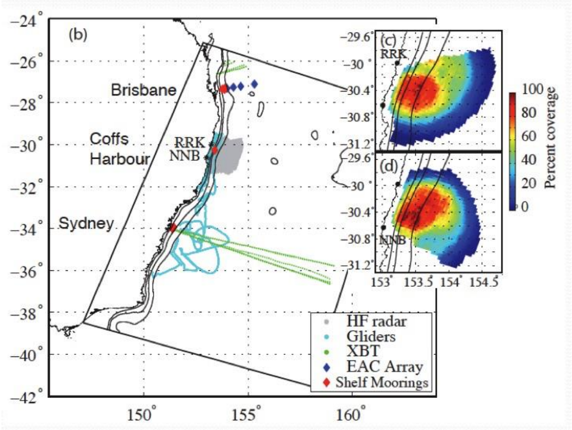

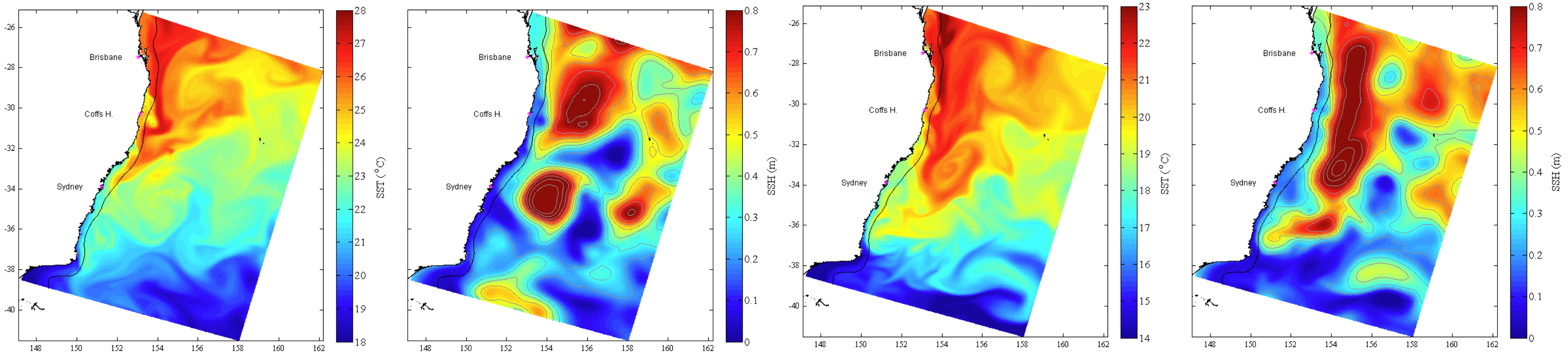

Integrated Marine Observing System