Model-data fusion Workshop: Ocean Data Assimilation Summary

Peter Oke et al.

CAWCR - CSIRO

Talk Outline

- Status of ocean data assimilation internationally
- Current capabilities in Australia
- Aspirations for the Australian community
- Stakeholder needs and requirements
- Gaps in capability and/or capacity
- Potential avenues for addressing gaps
- Known unknowns
- Unknown unknowns
- Workshop goals

Operational ocean data assimilation capabilities

- GODAE short-range prediction

Table 1. Data assimilation methods used by GODAE systems

System Name	Country	Data Assimilation Method	Reference
BODAS	Australia	Ensemble Optimal Interpolation	Oke et al., 2008
ECCO-JPL	USA	Kalman filter and smoother	Fukumori, 2002
FOAM	UK	Analysis Correction	Martin et al., 2007
Mercator	France	Static SEEK filter	Brasseur et al., 2005
MOVE/MRI.COM	Japan	Multivariate 3DVAR	Fujii and Kamachi, 2003
NCODA	USA	Multivariate Optimal Interpolation	Cummings, 2005
NEMOVAR	European Union	Multivariate Incremental 3DVAR	Weaver et al., 2005
TOPAZ	Norway	Ensemble Kalman filter	Evensen, 2006

Cummings et al. 2009: Ocean Data Assimilation systems for GODAE, *Oceanography*, **22**, 80-97.

Operational oc … es

- ➢ GODAE short-ra
- ➢ Seasonal predict

Balmaseda et al. 2010, Ocean Obs Proceedings

MRI-JMA http://ds.data.jma.go.jp/tcc/tcc/products/elnino/index.html		
• **Operational** • MOVE/MRI.COM-G (1x1 +0.3eq) .50 vertical levels • Multi-variate 3DVAR • JRA-25(1979-2003)+JMA ops fluxes • 10 days assimilation cycle+IAU	• COBE-SST gridded product • Subsurface T&S (GTS+α) • SLA along track from AVISO • MDT analyzed with historical T, S	• Weighted mean of clim. (1%) and model fields is used for FG.. • From 1979 onwards • Both Delayed (34-38 days) and NRT (3-7 days) • Lagged ensemble
ORA-S3 (ECMWF) http://ds.data.jma.go.jp/tcc/tcc/products/elnino/ index.html **ECMWF System 3** http://www.ecmwf.int/products/forecasts/d/charts/seasonal/		
• **Operational** • HOPE (1x1+0.3 eq). 29 vertical levels • Multivariate OI • ERA40 (1959-2002)+ ECMWFops fluxes • 10 day assim cycle+IAU	• HadISST+ Reynolds OI v2 SST • Subsurface T&S (ENACT/ENSEMBLES+GTS) • SLA maps from AVISO • MDT by assimilating T,S	• Bias correction (T,S and Pressure) • 10-year relaxation to clim • From 1959 onwards • Both Delayed (12 days) and RT • 5-analyses ensemble
POAMA – PEODAS (CAWCR, Melbourne)		
• **In transition to Operations** • ACOM-2 Ocean Model Based on MOM2. • ERA-40 (1980-2001)+NCEP2 (2002 onwards) fluxes • 3 Day assimilation cycle • Multi-variate ensemble OI	• ENACT observational data set T&S • SST from NCEP re-analysis • Time evolving covariances from ensemble perturbed about main analysis using forcing perturbations	• T&S 3D relaxation to Levitus with 2year time scale • Ensemble initial conditions from ensemble of states used for covariance calculation
GODAS (NCEP) http://www.cpc.ncep.noaa.gov/products/GODAS/		
• **Operational** • MOMv3 (1x1 + 1/3 at eq). 40 vertical levels, 3DVar • NCEP/DOE R2 atmospheric fluxes • 12 hour assimilation cycle+IAU	• Temperature from NODC,GTSPP and GTS. • Along Track SLA from Jason-1 • SST from Reynolds OIv2. • MDT by assimilation of T,S	• From 1979 onwards • Both 14 days and 1 day lags relative to RT • No relaxation to climate
MERCATOR (Meteo France) http://bulletin.mercator-ocean.fr/html/welcome_en.jsp		
• **Operational** • OPA8.2 ORCA2 (2cosϕ x 2° + 0.5° eq.) reduced order Kalman Filter (SEEK) • ERA-40 (1979-2001) + ops fluxes • 7-day assimilation cycle	• Reynolds OI v2 SST • Subsurface T&S (ENSEMBLES+CORIOLIS) • SLA along track from AVISO • Model MDT	• 10-year relaxation to clim • From 1979 onwards • 7 days behind RT
MO (MetOffice) http://www.metoffice.gov.uk/research/seasonal/		
• **Operational** • HadOM3/OI (1x1+0.3 eq) • ERA40 (1985-2002)+ ECMWFops fluxes • 7 days assim cycle+IAU	• HadISST+ Reynolds OI v2 SST • Subsurface T&S (ENACT/ENSEMBLES+GTS)	• Bias correction (Pressure) • From 1985 onwards • 3 days behind RT • 5-analyses ensemble
GMAO ODAS-1 http://gmao.gsfc.nasa.gov/research/oceanassim/ODA_vis.php **GMAO Seasonal Forecasts:** http://gmao.gsfc.nasa.gov/cgi-bin/products/climateforecasts/index.cgi		
• **Operational** • Poseidon/OI and EnKF (5/8 x 1/3) • NCEP R1+ SSMI winds GPCP precip • 5 day assim cycle+IAU	• Reynolds OI v2 SST • Subsurface T&S (NCEP GTS + TAO + GDAC Argo) • SLA along-track from JPL (EnKF only) • Online bias correction for MDT (EnKF only)	• Bias correction (SLA) • From 1993 onwards • Delayed (about 7 days) • 3-analyses ensemble

Table1: Summary of different ocean assimilation systems used in the initialization of operational and quasi-operational seasonal forecasts.

Research ocean data assimilation capabilities

- Existing community systems:
  - Regional Ocean Modelling System (ROMS) 4d-Var:
    - Community modelling system used at Rutgers, UCLA, Scripps, UNSW, …
    - Independently developed system used at OSU
  - ECCO:
    - German effort (Stammar et al.)
    - US effort (Lee et al. JPL; Cornelle et al. SCRIPPS)
  - ???

Current capabilities in Australia

- Research and operational:
  - Mesoscale Open Ocean → Bluelink Ensemble OI @ CSIRO/BoM
  - Seasonal → Seasonal ensemble prediction @ CSIRO/BoM
  - Coastal → CSIRO, UNSW, …
- Research:
  - ROMS 4d-Var @ UNSW

Mesoscale Open Ocean: Bluelink

- EnOI is based on the Kalman Filter equations:

$$\mathbf{w}^{\mathrm{a}} = \mathbf{w}^{\mathrm{b}} + \mathbf{K}(\mathbf{w}^{\mathrm{o}} - \mathbf{H}\mathbf{w}^{\mathrm{b}}),$$

$$\mathbf{K} = (\rho \circ \mathbf{P})\mathbf{H}^{*}(\mathbf{H}(\rho \circ \mathbf{P})\mathbf{H}^{*} + \mathbf{R})^{-1}$$

- where the model state is

$$\mathbf{w} = [\eta \quad T \quad S \quad u \quad v]^{*}$$

$$\mathbf{P} = \mathbf{A}\mathbf{A}^{\mathrm{T}}/(n-1)$$

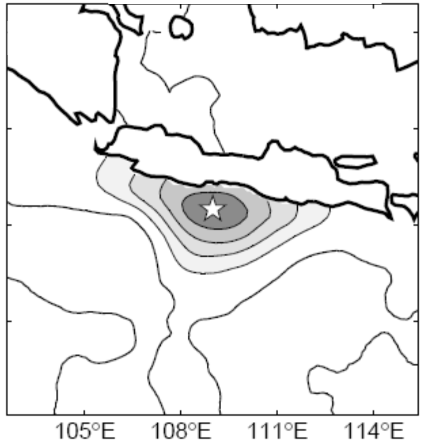
$$\mathbf{A} = \alpha[\mathbf{w}'_1 \quad \mathbf{w}'_2 \quad \cdots \quad \mathbf{w}'_n]$$

- Localisation ρ, is required when the model sub-space >>> ensemble size – and is here implemented as a distance-dependent reduction of P.

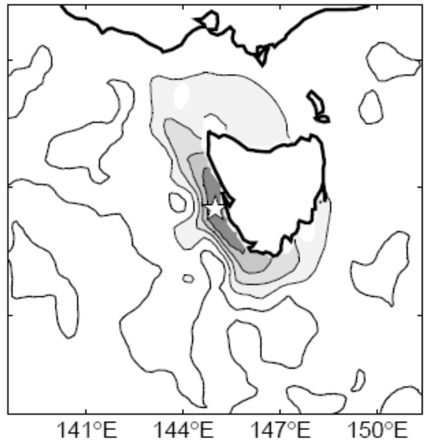
Mesoscale Open Ocean: Bluelink

- Ensemble-based covariances summarise the linear dynamics of the circulation
  - inhomogeneous
  - anisotropic
  - concisely represent length-scales and model variance
  - can easily be seasonally varying (but we haven't exploited this yet)

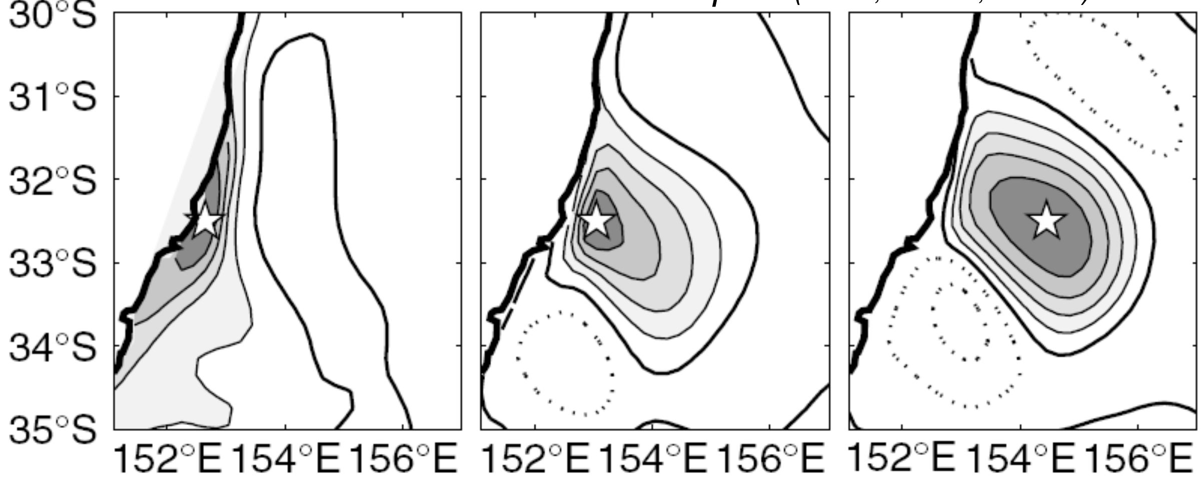
Off Indonesia



Off Tasmania

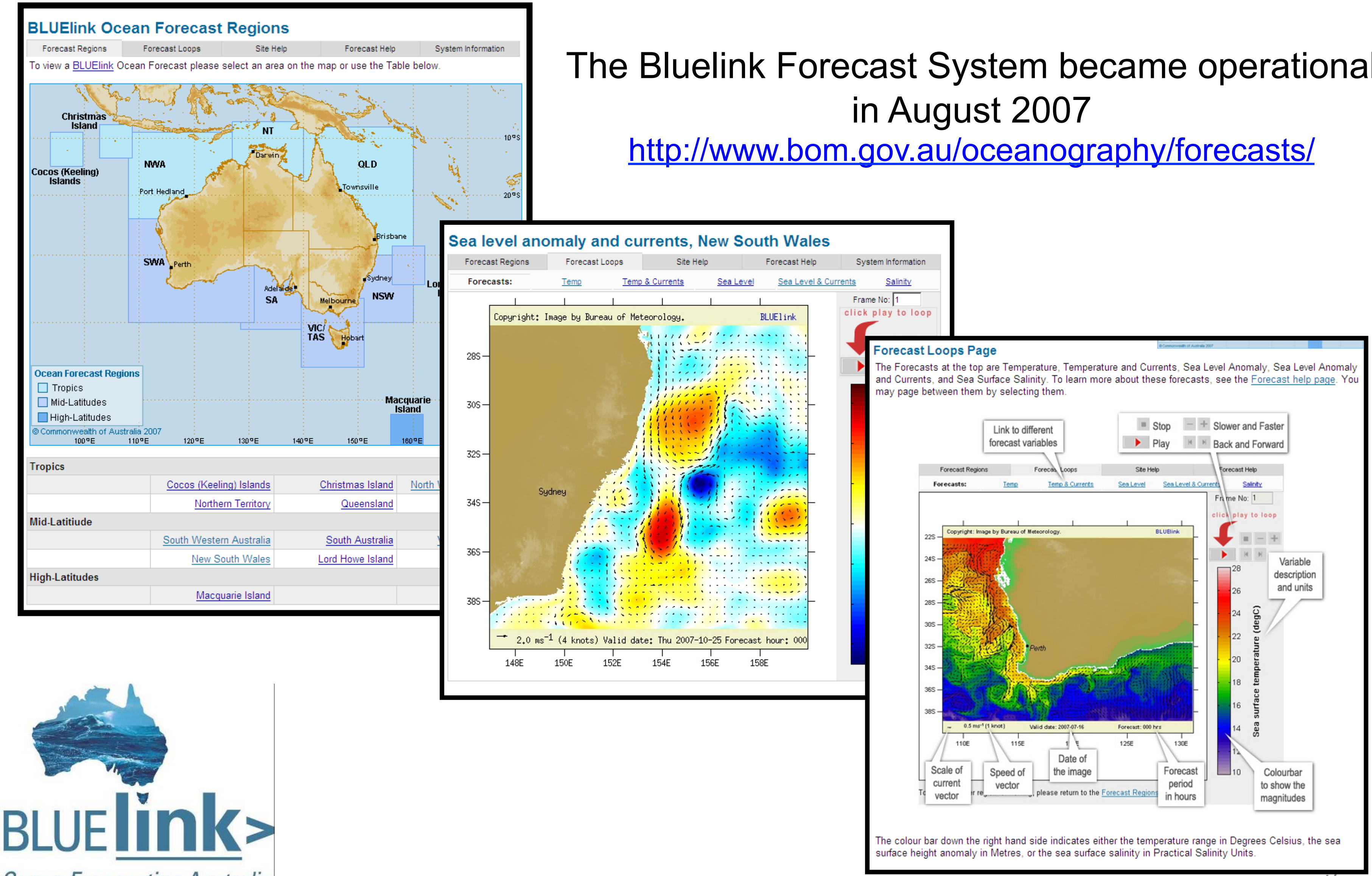


Off SE Australia at different depths *(115 m, 1800 m, 4500 m)*



Mesoscale Open Ocean: Bluelink

The Bluelink Forecast System became operational in August 2007
http://www.bom.gov.au/oceanography/forecasts/



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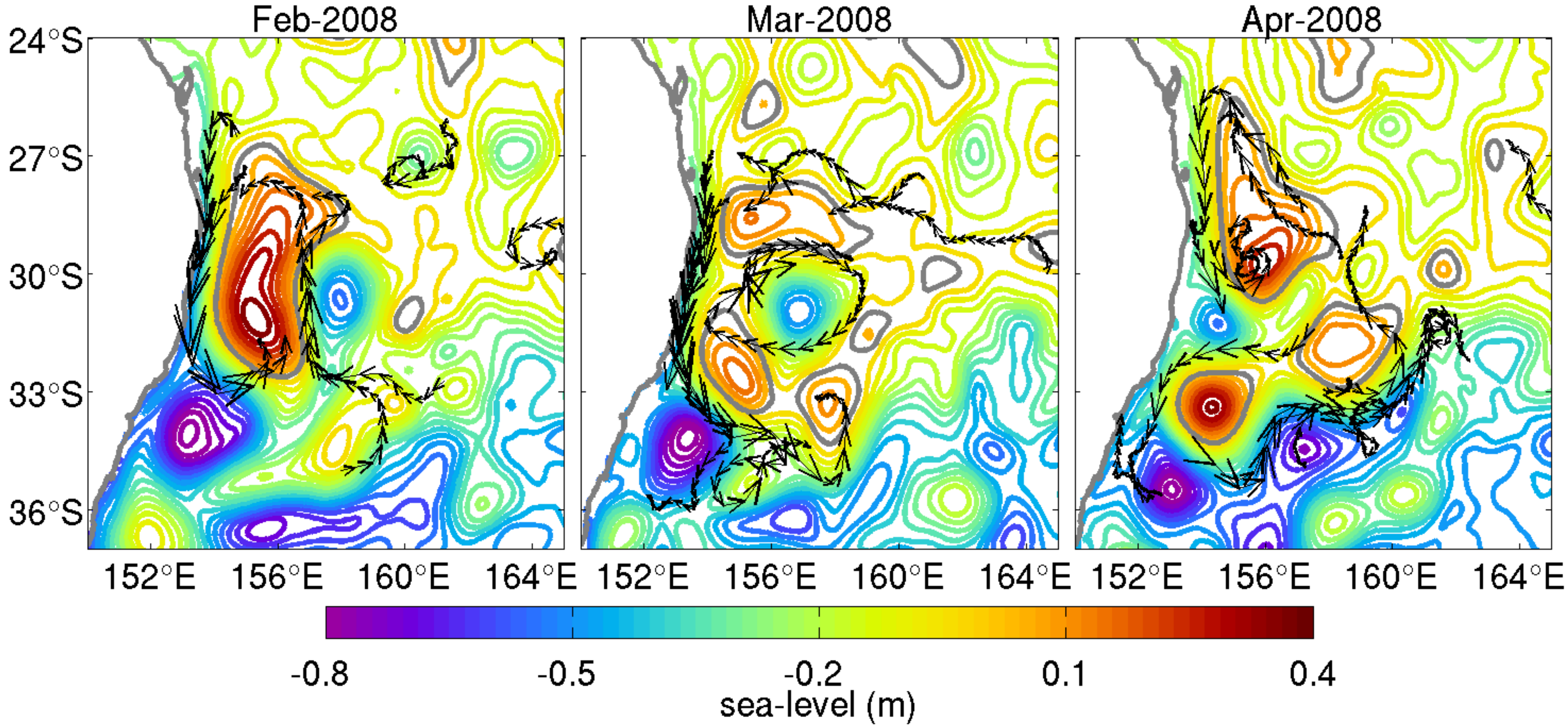
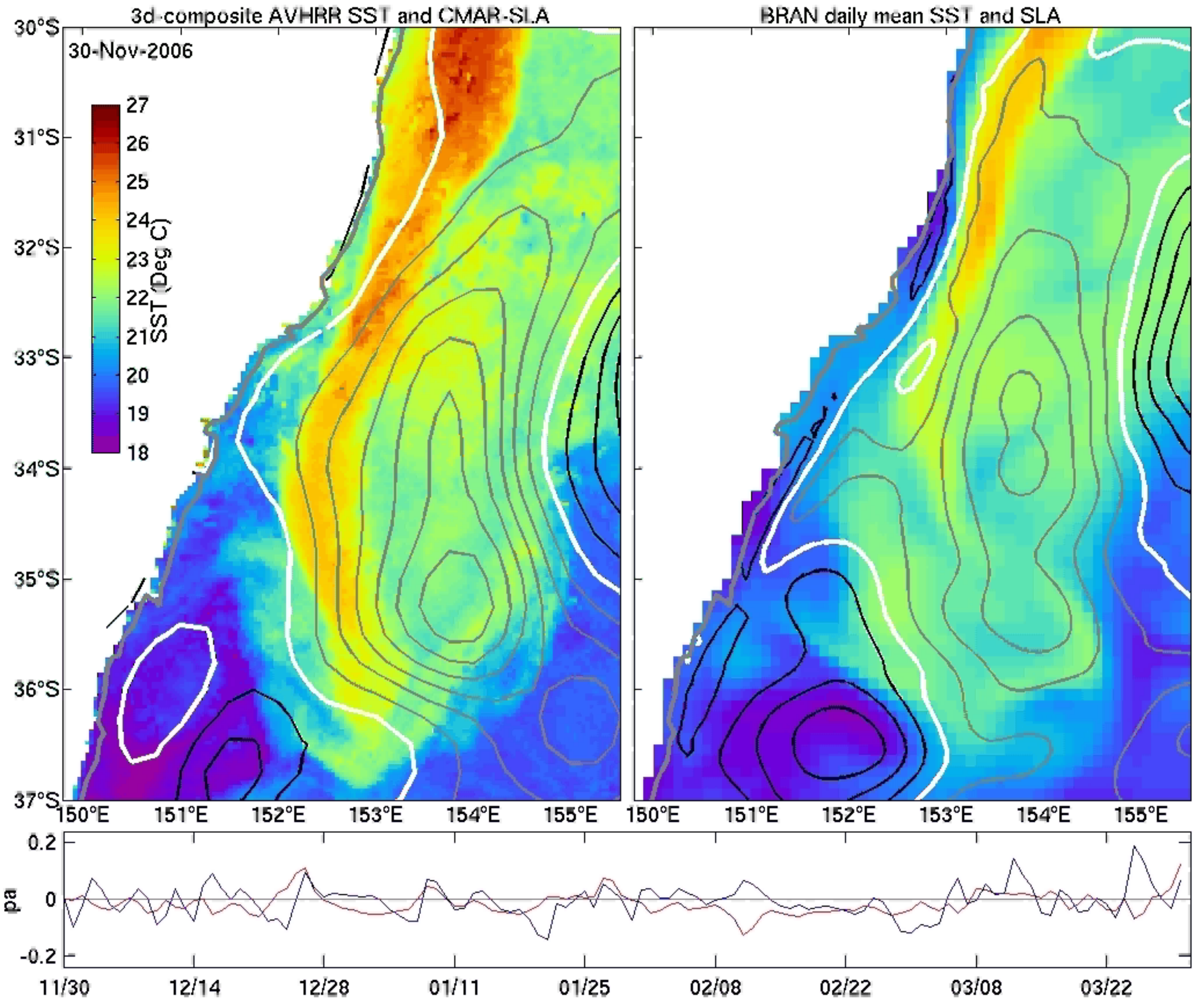
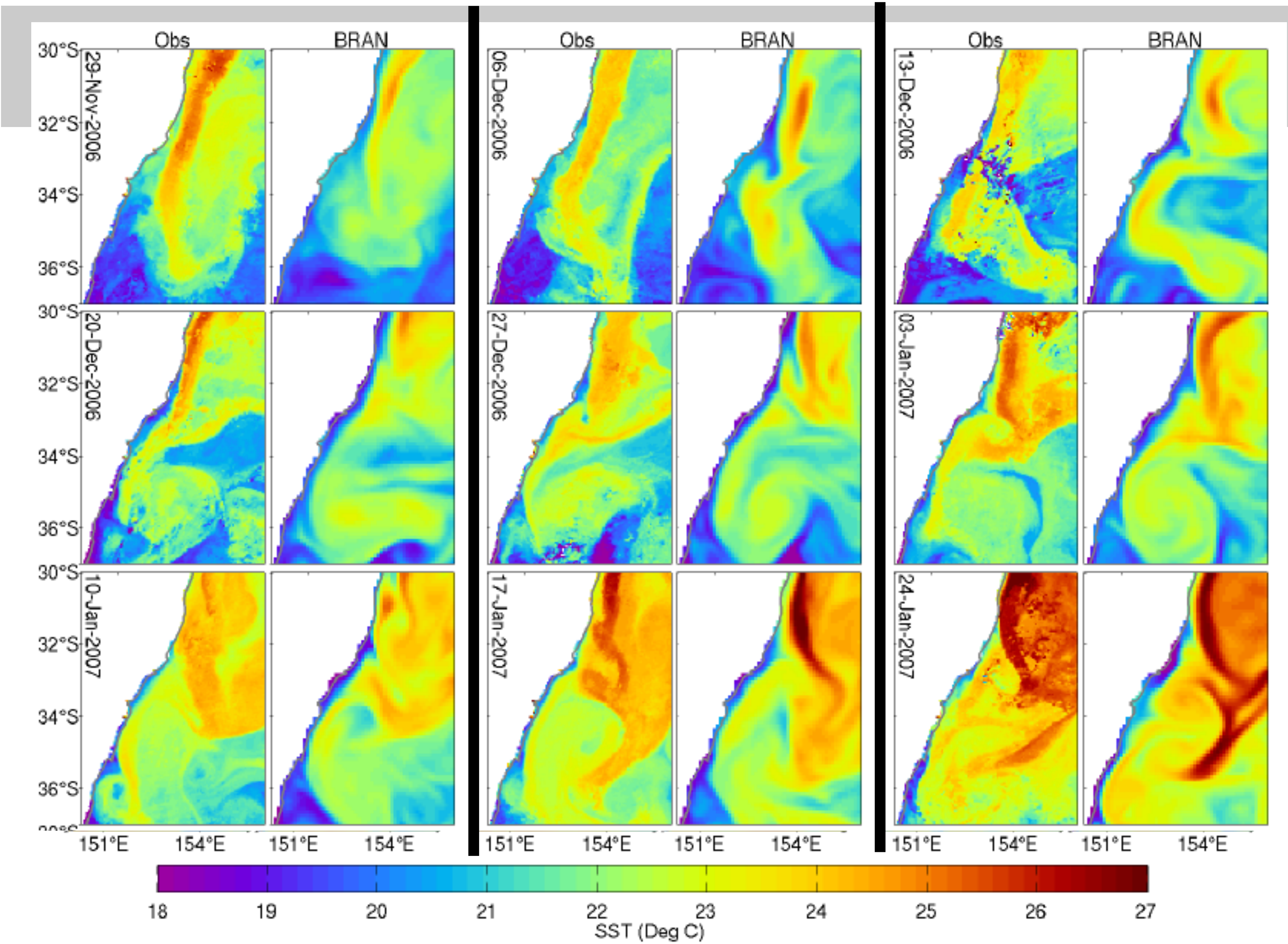
Ocean Forecasting Australia

Mesoscale Open Ocean: Bluelink



Mesoscale Open Ocean: Bluelink




Obs
BRAN
Obs
BRAN
Obs
BRAN
29-Nov-2006
06-Dec-2006
13-Dec-2006
20-Dec-2006
27-Dec-2006
03-Jan-2007
10-Jan-2007
17-Jan-2007
24-Jan-2007
30°S
32°S
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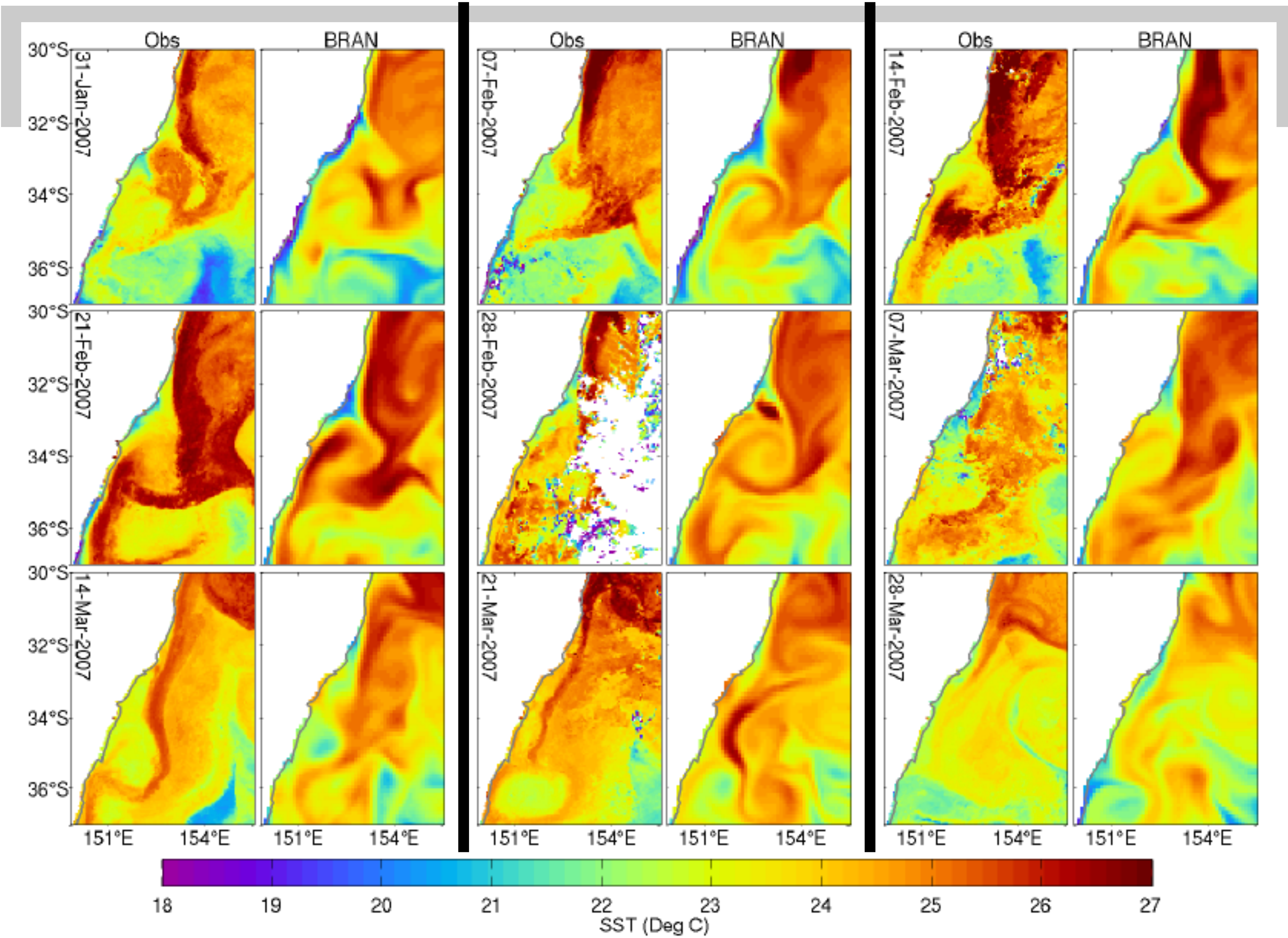
27
SST (Deg C)


Obs
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BRAN
31-Jan-2007
07-Feb-2007
14-Feb-2007
21-Feb-2007
28-Feb-2007
07-Mar-2007
14-Mar-2007
21-Mar-2007
28-Mar-2007
30°S
32°S
34°S
36°S
151°E
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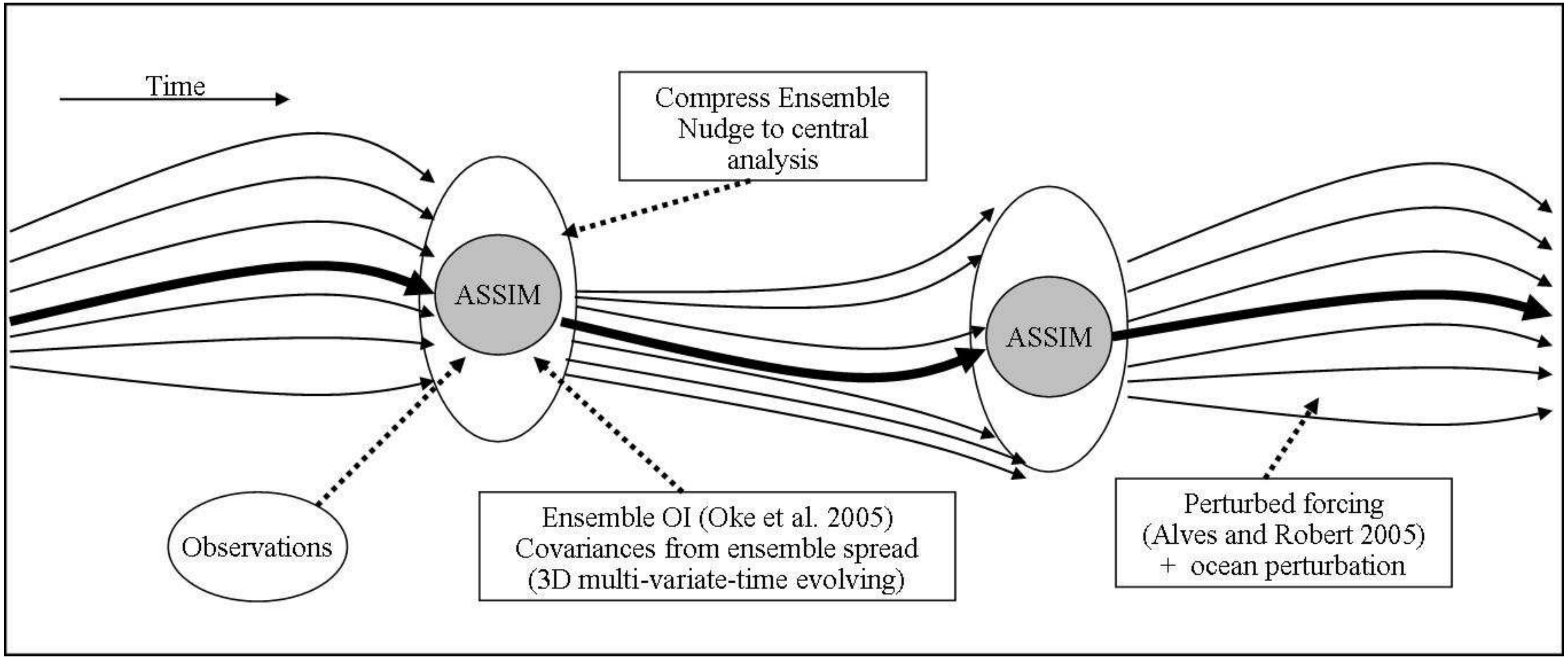
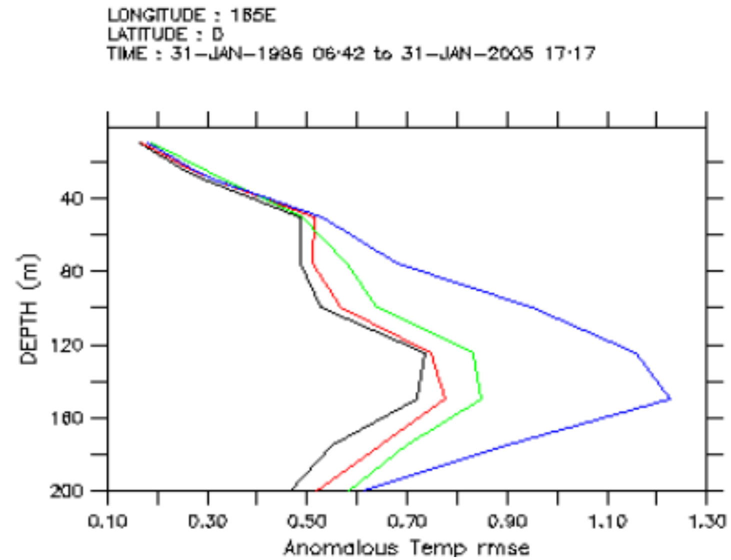
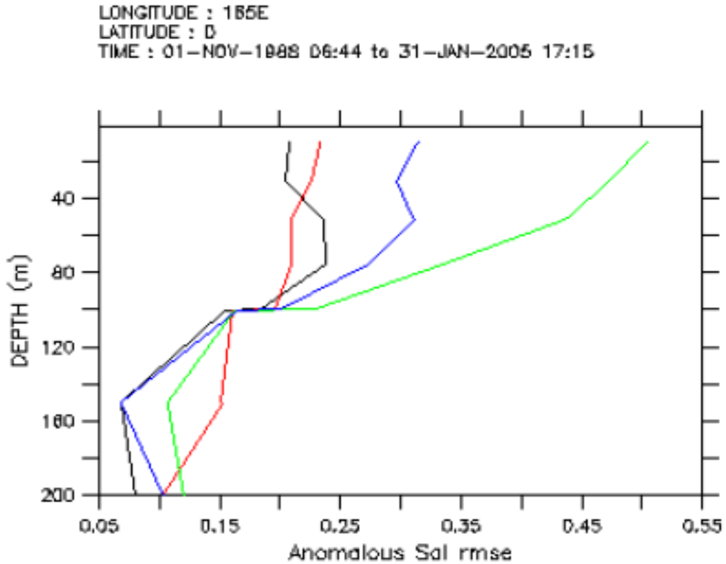
SST (Deg C)

Seasonal: POAMA



Seasonal





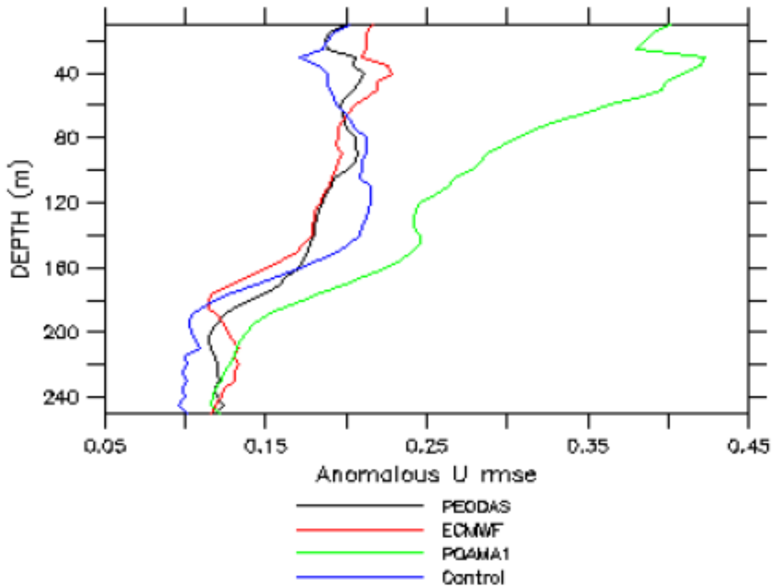
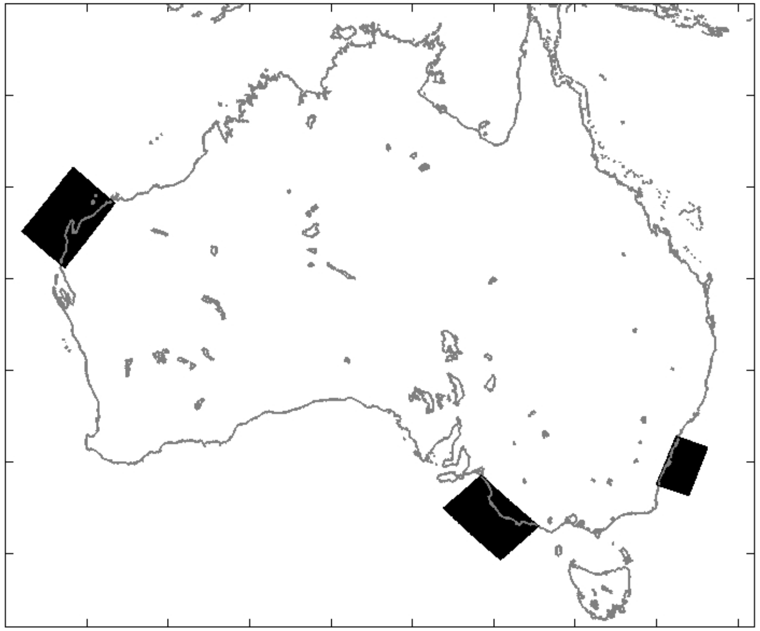
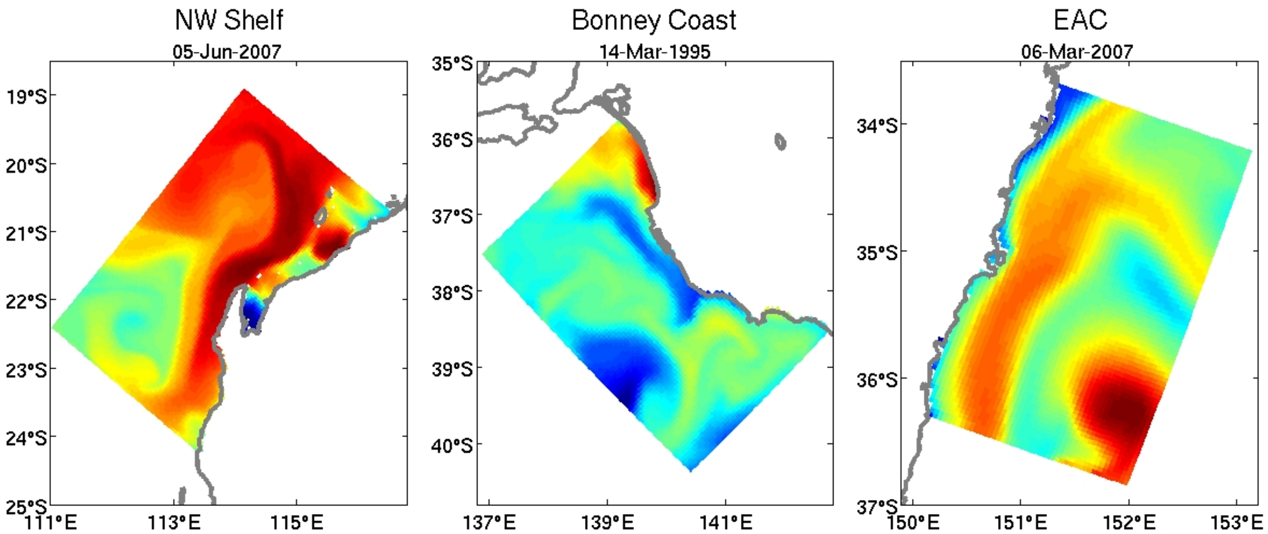


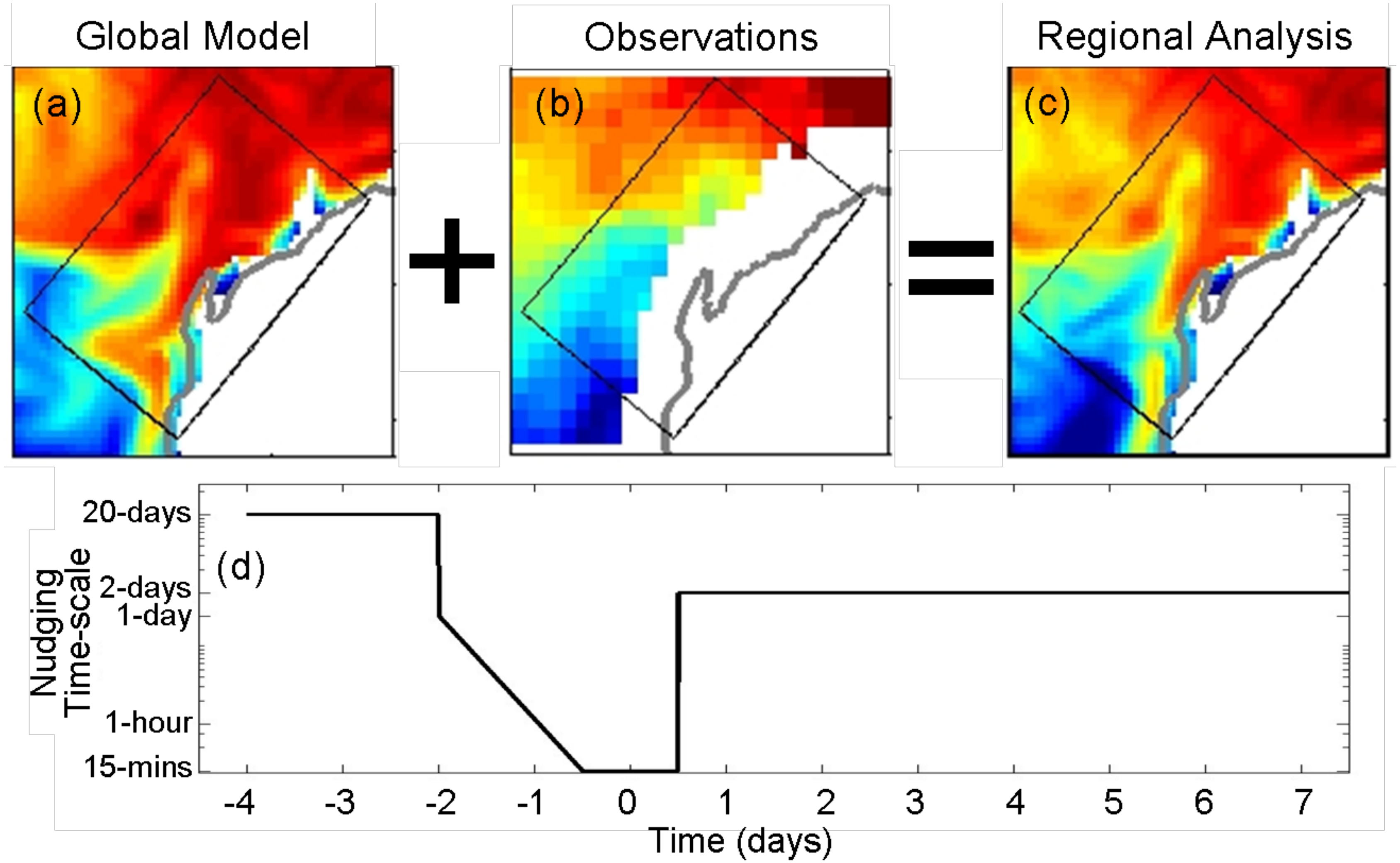
Figure 2. RMS error of interannual anomalies of (a) temperature, (b) salinity and (c) zonal current. Shown are the PEODAS reanalysis (black), the old POAMA re-analysis (green), the ECMWF ORA-S3 (red) and the Control simulation (blue). The verifying observations are from the TAO mooring at location 165°E.

Coastal Ocean DA: EnOI

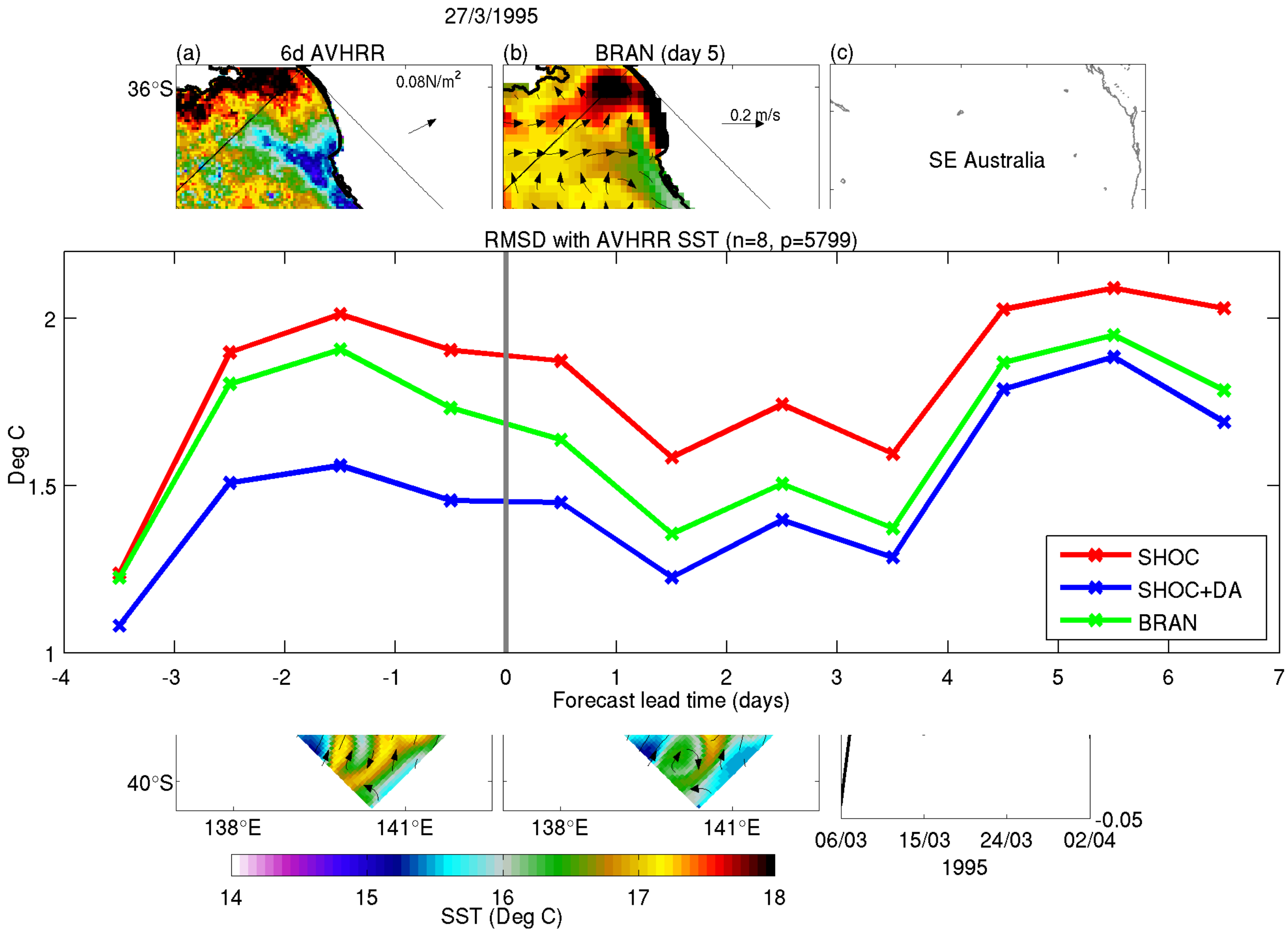




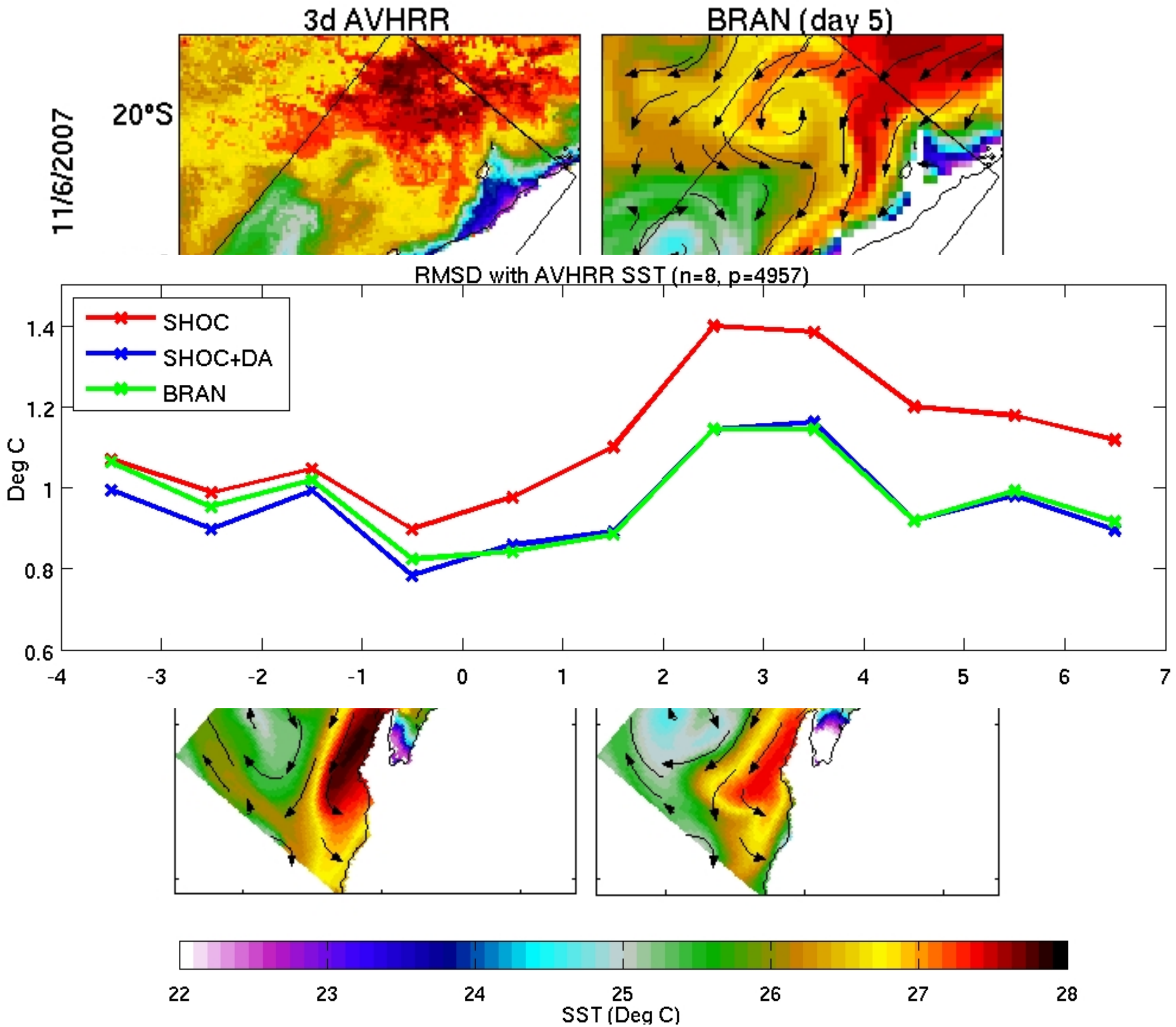
Coastal Ocean DA: EnOI



Coastal Ocean DA: EnOI -- Bonney Coast



Coastal Ocean DA: EnOI -- NW Cape



Coastal / Shelf scale Ocean DA: 4d-Var

- UNSW – MacDonald et al. to advise

Sea-ice DA

- Forecast system exists, but no DA

Ocean BGC DA

- See Parslow et al.
- Plans to develop Ocean BGC DA capability under Bluelink-3 (Lenton & Matear)

Aspirations for the Australian community

- CSIRO/BoM aspirations include:
  - 4d Ensemble DA extension
  - Ensemble-Var development
- University aspirations:
  - ???
- Community aspirations:
  - Method development?
  - Do we want to be research leaders?
  - Or bask in the shadow of other international efforts?

Stakeholder needs and requirements

- Stakeholders:
  - Defence (D)
  - Meteorology (e.g., TC, fog forecasting …) (M)
  - Search and Rescue (S&R)
  - Oil and Gas (O&G)
  - Environmental stakeholders (e.g., EPA, State & Local Authorities) (E)
  - Research (R)
  - Agriculture (A)
- Variables required:
  - Open Ocean
    - T/S → D, EPA, R, M, A U/V → D, S&R, O&G, EPA, R
  - Coastal
    - T/S → D, EPA, R, M U/V → D, S&R, EPA, R
  - Littoral
    - U/V → D, R Waves → D, R

Stakeholder needs and requirements

- Stakeholders:
  - Defence (D)
  - Meteorology (e.g., TC, fog forecasting …) (M)
  - Search and Rescue (S&R)
  - Oil and Gas (O&G)
  - Environmental stakeholders (e.g., EPA, State & Local Authorities) (E)
  - Research (R)
  - Agriculture (A)
- Derived properties:
  - Prediction of trajectories/dispersion (D, S&R, O&G, E, R)
  - Underwater acoustics (D)
  - Uncertainty (all)

Gaps in capability and/or capacity

- See known unknowns …

- Areas where rapid progress is possible
  - Assimilation of all data types … e.g., from IMOS
  - Combining ensemble and Var DA

- Important areas where progress is likely to be limited
  - Oceans are data-sparse (physics, but esp BGC)
  - Extension of systems to BGC …
  - Recruiting researchers with DA experience is difficult

Potential avenues for addressing gaps

- Development of community DA tools:

- Training / proactive at attracting PhD students
  - How … ? Who … ?

- Systems:
  - Implementation on GPU clusters / and on parallel platforms

Known unknowns

… In no particular order

Known unknowns

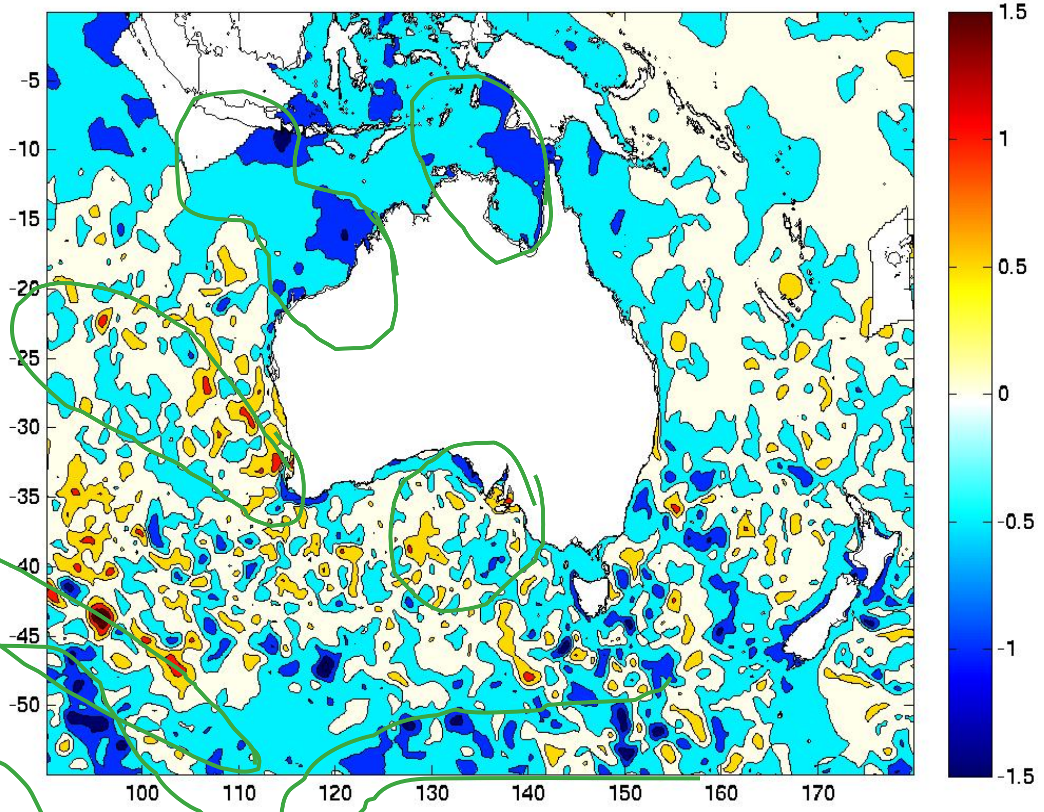
➢ Dealing

Dee, QJRMS

"All data as … y problems with the data, li… e itself. An assimilatio… biases is referred to… mal and can lead to erroneo…

"A sympto… of systematic features in… he form of large persistent…

- First s…
  - Ba…
  - an…
  - an…

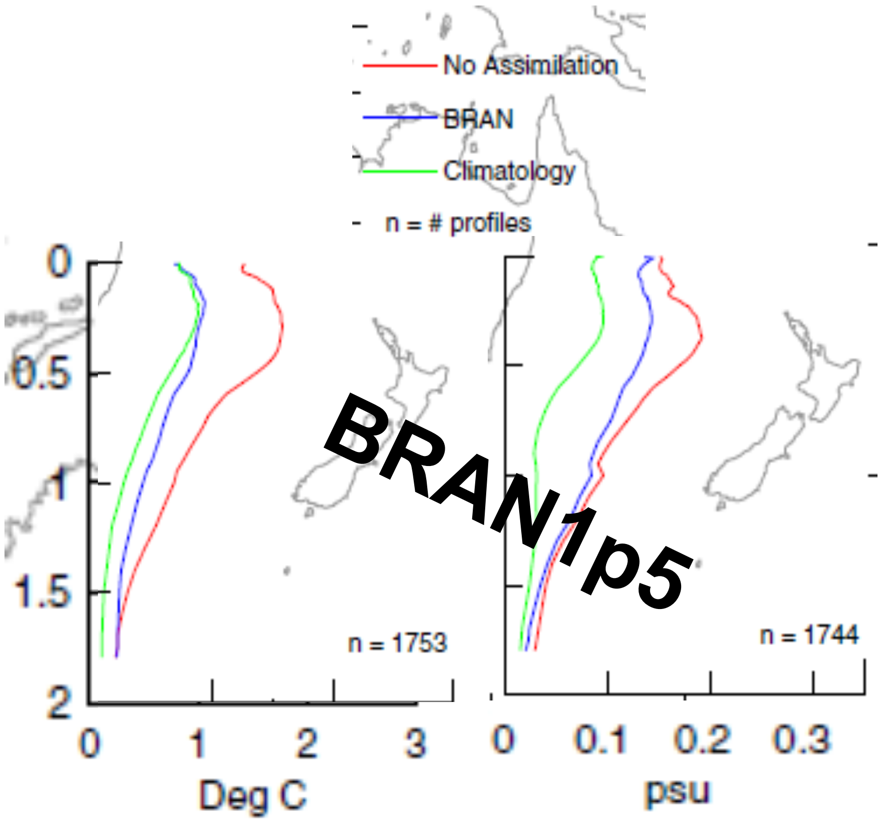


Average of the daily analysis increments of SST induced by assimilation of SST and SLA observations for February 2008.

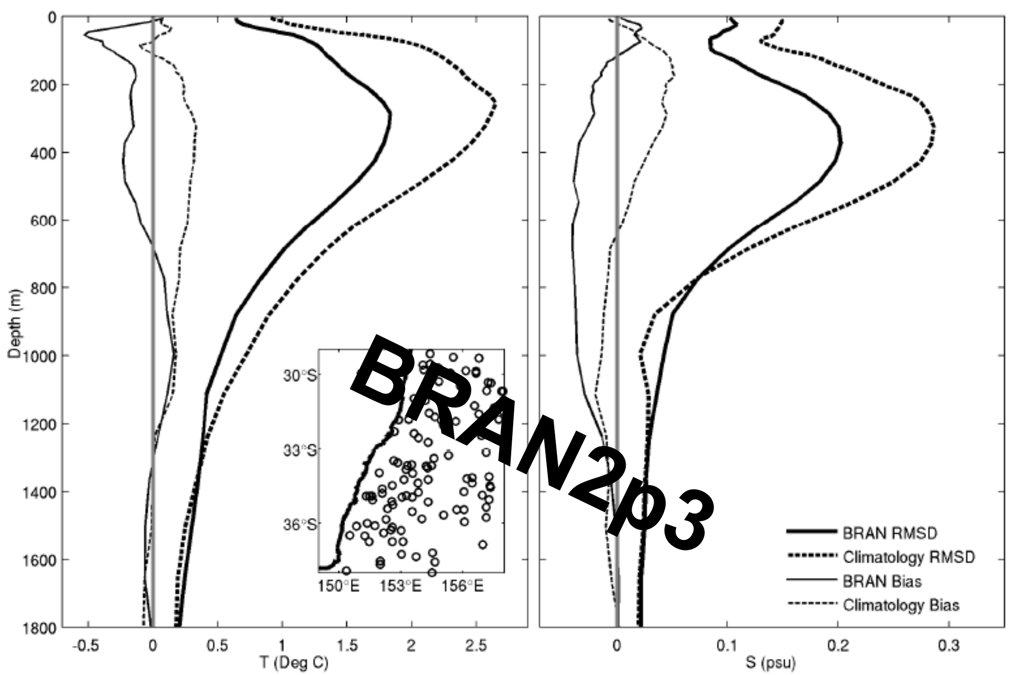
Potential biases

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)



Oke et al. (2008; Oc Mod)



Oke and Griffin (2010; DSR)

BRAN1p5 vs BRAN2p2: main difference is the initialisation: Nudging vs IAU

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
- Mean sea-level … for assimilation of altimetry
  - Several international programs offer “solutions” to this problem ??
  - Some ocean DA systems use obs-products … some still use model estimates

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
- Mean sea-level … for assimilation of altimetry
- Applications to sea-ice
  - CSIRO to work on solution with UTAS
  - Special challenge → sea-ice extent changes, so ensemble approach requires novel treatment

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
- Mean sea-level … for assimilation of altimetry
- Applications to sea-ice
- Applications to BGF … Parslow et al. to offer solution
    - What obs to assimilate?
        - How to relate ocean colour to modelled fields (e.g., NPZ)?
        - ???

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
- Mean sea-level … for assimilation of altimetry
- Applications to sea-ice
- Applications to BGF … Parslow et al. to offer solution
- Model error
  - DA requires explicit estimates of model error
  - Several studies show that model error is poorly represented (e.g., seasonal prediction)

QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY
Q. J. R. Meteorol. Soc. **135**: 1538–1559 (2009)
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(www.interscience.wiley.com) DOI: 10.1002/qj.464

RMetS
Royal Meteorological Society

Addressing model uncertainty in seasonal and annual dynamical ensemble forecasts

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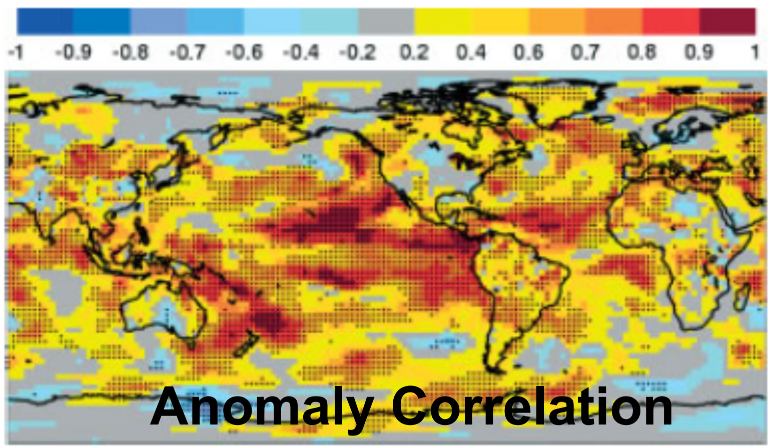
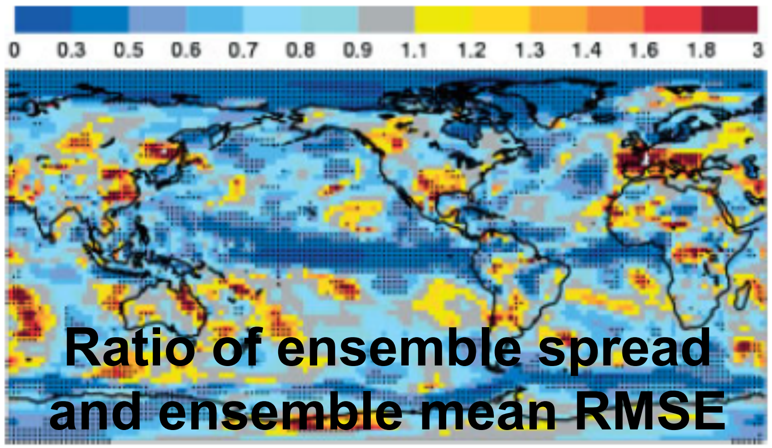
All systems suggest that spread cannot be considered a useful predictor of skill





that spread cannot be considered a useful predictor of skill. Annual-mean predictions showed lower forecast quality than seasonal predictions. Only small differences between the systems were found. The full multi-model ensemble has improved quality with respect to all other systems, mainly from the larger ensemble size for lead times longer than four months and annual predictions.

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
- Mean sea-level … for assimilation of altimetry
- Applications to sea-ice
- Applications to BGF … Parslow et al. to offer solution
- Model error
- How to combine ensemble and variational DA
    - ???

Known unknowns

- Dealing with bias
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- Mean sea-level … for assimilation of altimetry
- Applications to sea-ice
- Applications to BGF … Parslow et al. to offer solution
- Model error
- How to combine ensemble and variational DA
- Coupled ocean/atmosphere DA
    - Different time-scales … lagged coupling
    - BoM committed to 4d-Var, Bluelink/seasonal invested in ensemble
    - BoM exploring for TC applications under Bluelink
    - BoM/CSIRO exploring for seasonal applications under GRDC

Known unknowns

- Dealing with bias
- Forecast skill … beating persistence (getting there)
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- How to combine ensemble and variational DA
- Coupled ocean/atmosphere DA

Unknown unknowns

Workshop Goals

- Obtain an accurate picture of the status of ocean DA
- Identify how we can improve our capability

Breakout session

- Methods:

- Community tools/data
  - What, how, who
- Coupled DA
  - Ocean / atmosphere
  - Ocean / BGC
  - Ocean / sea-ice
  - Sea-ice / atmosphere

Current capabilities in Australia (updated)

- *Ocean data assimilation*
  - Bluelink: Andreu-Burillo, Brassington, Oke, …
    Status: BODAS complete and tested; further developments planned (4d, additional obs types, …)
  - Coastal (e.g., INFORMD): Jones
    Status: developing an EnOI for a coastal model; main challenges are the lack of observations and dealing with tides.
  - ROAM: Oke, Sun
    Status: Preliminary system developed based on Bluelink system
- *Coupled ocean / atmosphere*
  - Regional: Andreu-Burillo, Brassington, Sandery, …
    Status: Preliminary system using MOM4 ocean, TC-LAPS atmosphere, BODAS, and OASIS-3 coupler. Next step to use UM. No coupled DA yet.
  - Seasonal: Alves, Hudsen, O'Kane, Oke, Okely, Webb, Yin
    Status: Operational system running, and a new PEODAS system being transferred to operations. Started work on coupled DA. 50-year reanalysis completed.
- *Biogeochemical data assimilation*
  - Systems to be developed under BL-3.
    Status: Tested various techniques for BGC for toy models. Developed a "good framework" for 4d application.
- *Uncertainty*
  - Ensemble prediction methods using CLAM to estimate forecast errors and adaptive sampling: O'Kane, Oke
    Status: Breeding system developed for MOM4; application to WBC complete

Aspirations for the Australian community (updated) – page 1

Need to include FTEs …

- Perfect forecasts (Nugzar)
- Use assimilation to understand model error (Alves)
- Treatment of (model or obs) bias rigorously (Andreau-Burillo)
- Dynamical downscaling of climate/seasonal forecasts to meet needs of eg aquaculture (Parslow; Sun)

- *Ocean data assimilation*
  - Development of advanced methods (Oke, O'Kane, Sun). Plans to develop an ensemble-Var ocean DA system – funding pending from ONR. Initial applications will be to coastal ocean applications.
  - Developments of methods to optimise BCs, surface forcing, parameters (Jones, Oke, Parslow, Sun, …) for coastal ocean and climate
  - Ocean state estimation capability; decadal prediction (Hirst, Lenton)
  - Model error (O'Kane): apply systematic sub-grid-scale pareterisation theory to realistic applications
  - Optimisation of model configuration using DA tools (Parslow)
  - Implementation of ROMS 4d-Var to UNSW ROMA configuration (MacDonald)
  - Dimension reduction and emulation (explore different options to with uncertainty other than really crass estimates) of fine-scale DA models (Nugzar)

Aspirations for the Australian community (updated) – page 2

- *Coupled ocean/atmos*
  - World leaders in coupled ensemble DA (Brassington, Sandery, …)
  - Develop the assimilating global ocean model to couple to a global NWP (Brassington)
  - POAMA- coupled DA → Including new observing systems (e.g., altim) → Ensemble generation strategy (Alves, Hudsen, O'Kane, Oke, Okely, Webb, Yin)
  - Consider including waves coupled to POAMA (Brassington)
  - Extend skill of POAMA to multi-week forecasting (Hudson; Alves); to match NWP-ocean forecast systems.

- *BGC DA*
  - Capability to run scenarios and understand uncertainty of those scenarios (Parslow)
  - Short-term BGC forecasts from 100m – 10 km scales to predict eg harmful algal blooms)
  - Use BGC DA to constrain BGC <u>and</u> physics – involves algorithm development (Jones, Parslow)
  - Quantify error propagation from uncertainty in phsics to BGC (Nugzar)

- *Uncertainty*
  - Capability to quantify uncertainty of all ocean forecast systems: O'Kane

Stakeholder needs and requirements (updated)

- Stakeholder needs and requirements
  - Stakeholders want to better understand uncertainty of climate forecasts due to parameter choices

Gaps in capability and/or capacity and avenues for addressing gaps (updated)

- Forcing data sets
  - Systems are configured and tuned for certain NWP product that is not always available

- Community tool box:
  - Toy models and toy DA systems
  - Web site with links to DA tools
  - Links to data sets (international sources, eMII, AODN, …)
  - List of papers published and data used

- Outreach:
  - Annual DA summer school (Jeff Walker to organise @ Monash)
    - Lecturer from ocean, atmos, BGC, terrestrial, …
    - CSIRO and maybe Australian mathematics society to fund
    - E.g., Day 1-3 focus on methods (theory and exercises using above-mentioned toolbox); day 4-5 focus on applications
    - Other coutries have run successfully (eg Oxford Uni; MSRI Berkley)

Bluelink open ocean DA

- Applications to OFAM and CLAM
  - EnOI+GOOS provides useful background state for surface T,S,u,v,eta
    - Not sufficient for high precision surface currents
    - Not sufficient for high precision vertical state and currents
  - Achieving higher precision state estimation?
    - More optimal DA methods and initialisation
    - Progress observing system
  - More optimal yet practical options:
    - Hybrid EnKF, Bred vectors, Time-lagged ensemble (FGAT 4dEnOI), …
  - Fully exploit current GOOS:
    - Remote sensing methods to estimate u,v
    - Remote sensing SSS, SMOS and Aquarius
  - Motivate / contribute to enhancements to GOOS:
    - e.g., Adaptive intensive observations

- How should we represent tides? Explicit or parameterised?
  - Motivation: Baroclinic conversion, T/S mixing, Transport, residual flux, non-linear sea level
  - Risk: tide error > mesoscale errors; explicit tides could degrade lower frequency variability
  - Possible strategy:
    - Multi-scale analysis (separation of time-scales, …)
    - BLUElink(global) non tidal => BLUELink(regional) nested + tidal b.c.'s

- Resolution
  - Horizontal resolution – resolved vs constrain variability
  - Vertical resolution – sensitivity, limited validation data

- Closure of flux errors (momentum, heat and mass)
  - tune parameterisations
  - surface currents, waves, SST, mixed layer depth (sound ducts)
  - ABL winds, heat and moisture

- Coupled projection of innovations
  - wave errors => atmos. winds and ocean currents
  - SST errors => atmos. winds, clouds, ocean state and currents

- Opportunity of ACCESS / UM + BLUElink
  - Ocean prediction and GOOS has matured
  - ACCESS supporting coupled infrastructure

Seasonal DA - POAMA

- Ocean DA
- Coupled DA

Coastal DA

- ROAM DA
  - Currently assimilated SST
  - Will soon assimilate altim, T/S
- INFORMD
- ROMS / UNSW