Australian Government
Bureau of Meteorology

A new Ensemble Optimal Interpolation SST Analysis System at the Bureau of Meteorology

Helen Beggs[1], Pavel Sakov[1], Paul Sandery[2] and Gary Brassington[1]

[1]Bureau of Meteorology, Melbourne, Australia

[2]CSIRO Oceans and Atmosphere, Hobart, Australia

19th GHRSST Science Team Meeting, Darmstadt, Germany, 4th – 8th June 2018

Introduction

- The Bureau's existing optimal interpolation (OI) SST analysis systems (Global Weekly, GAMSSA and RAMSSA) are based on legacy Fortran code developed in the 1980's for the BoM Oceanic Sub-surface Thermal Analysis Scheme (Blomley et al, 1989)
- This code base is difficult to maintain
- The Ensemble Kalman Filter data assimilation C code (EnKF-C), developed by the Bureau under the Bluelink Project, is a lightweight, generic parallelised framework that is currently used for data assimilation into the Bureau's OceanMAPS v3.1 ocean model
- Based on EnKF-C, an Ensemble Optimal Interpolation (EnOI) Global SST analysis system ("GSAS") has been developed
- GSAS is being assessed for its suitability to eventually replace the Bureau's operational OI SST analyses

EnKF-C EnOI

GSAS system uses DA software EnKF-C [Sakov, 2014] with EnOI [Evensen, 2003]. The analysis equation and EnOI background covariances can be written as:

$$x^a = x^b + \mathbf{K}[\mathbf{y} - \mathcal{H}(x^b)]$$

$$\mathbf{K} = \mathbf{B}\mathbf{H}^{\mathrm{T}}[\mathbf{H}\mathbf{B}\mathbf{H}^{\mathrm{T}} + \mathbf{R}]^{-1}$$

$$\mathbf{B} \equiv \mathbf{A}\mathbf{A}^{\mathrm{T}}[m - 1]^{-1}$$

Where: x^a = estimate of DA system state, x^b = background state, $\mathbf{K}$ = Kalman gain, $\mathbf{y}$ = an observation vector, $\mathcal{H}$ = observation operator, $\mathbf{B}$ = background error covariance, $\mathbf{R}$ = observation error covariance, $\mathbf{A}$ = EnOI anomalies, m = ensemble size (currently 144).

$\mathbf{A}$ is defined by OFAM3 model spinup, forced by ERA-interim. (OFAM3 is global, 0.1° MOM based model used in BoM OceanMAPS ocean forecasts.)

Through $\mathbf{A}\mathbf{A}^{\mathrm{T}}$ term EnOI uses anisotropic covariance (particularly important in coastal and highly dynamic regions), unlike OI which uses isotropic covariance.

Advantages of EnKF-C

- Uses super-obs to handle different resolution input products and representativeness errors
- Flexible error covariance models including ensemble based methods
- Innovation statistics for each instrument in user-defined regions
- Able to account for observation error
- Able to adaptively QC observations
- Multivariate analysis – able to include other data types (e.g. in situ)
- Easy to install new observations
- Parallelised and computationally efficient (< 24 hours to process 1 year)
- Open source (https://github.com/Sakov/enkf-c)
- Coded in C for GNU/Linux platforms

Daily Global and Regional Multi-Sensor SST analyses (GAMSSA and RAMSSA)

Australian Government
Bureau of Meteorology

http://www.bom.gov.au/marine/sst.shtml

Resolution: Daily, 0.25º global, 0.083º regional

Depth: Foundation SST estimate - by rejecting obs for NWP winds < 6 m/s (day), < 2 m/s (night)

Available: 2007 to real-time (GDS1.6: AO.DAAC; GDS2: AODN)

Method: Optimal interpolation (Beggs et al., 2011)

BG Correlation Length Scales: 50 km (GAMSSA) and 20 km (RAMSSA)

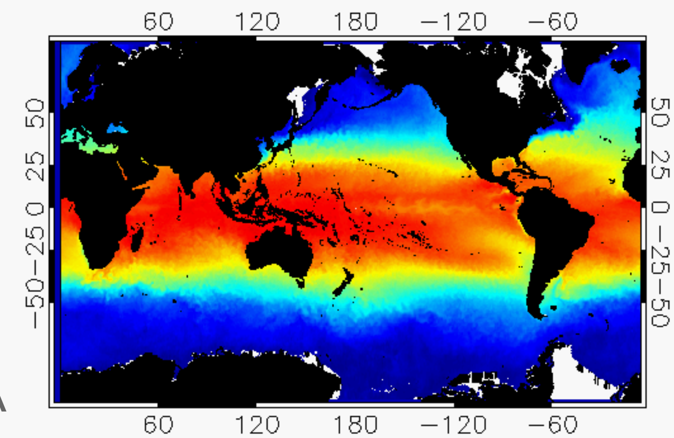
Background: Combination of previous day's RAMSSA/GAMSSA SST and Reynolds and Smith (1994) climatology (1961-1990).

Inputs: (all satellite data bias-corrected except AMSR-2. QL ≥ 4)

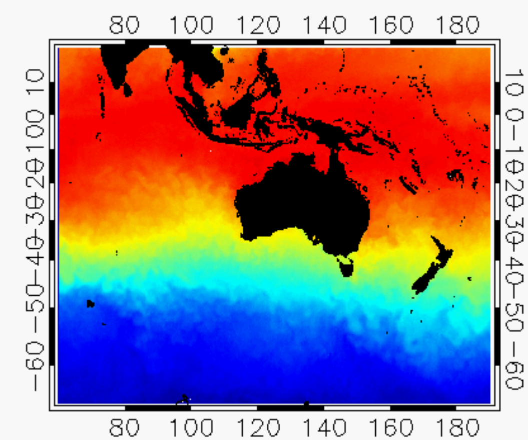
- 1 km IMOS HRPT AVHRR (N-18/19) L2P SST(0.2m)
- 9 km NAVOCEANO GAC AVHRR (N-18/19, METOP-A/B) L2P SST1m
- Night-time ACSPO VIIRS L3U SST(0.2m) (in RAMSSA test system)
- ~50 km JAXA AMSR-2 (GCOM-W) L2P SSTsubskin
- Buoy and ship in situ SSTdepth (GTS)
- NCEP 1/12º sea ice analyses

6 Mar 2018

GAMSSA SSTfnd



RAMSSA SSTfnd



Global SST Analysis System (GSAS) EnOI SST analyses

Australian Government
Bureau of Meteorology

Resolution: Daily, 0.1° near global (±75°N)

Depth: Foundation SST estimate - by rejecting obs for NWP winds < 6 m/s (day), < 2 m/s (night)

Available: 2017 to present (on request)

Method: Ensemble optimal interpolation (Sakov, 2014, 2018).

- Uses background model ensemble error covariances formed from OFAM3 ocean model
- Support Localisation Radius: 100 km (initial tests)

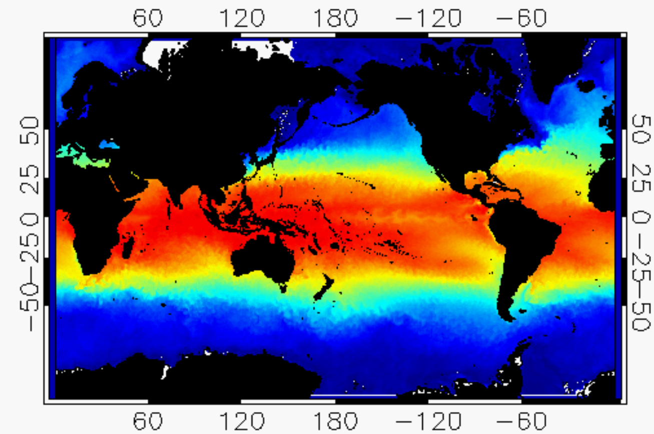
Background: Initially Bluelink Reanalysis (BRAN), followed by previous day's GSAS analysis

Inputs: (all satellite data bias-corrected and QL ≥ 4)

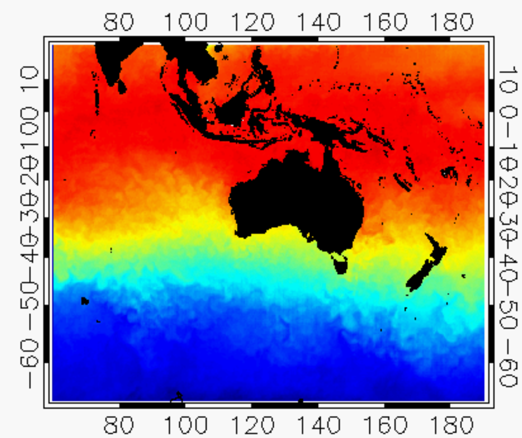
- 9 km NAVOCEANO GAC AVHRR (N-18/19, METOP-A/B) L2P SST1m
- Night-time ACSPO VIIRS L3U SST(0.2m)
- ~50 km JAXA AMSR-2 (GCOM-W) L2P SSTsubskin
- BoM Himawari-8 10 min^{-1} 2 km L2P SST(0.2m)
- No sea ice (considering OSI-SAF 0.05° daily ice analyses)

6 Mar 2018

GSAS SSTfnd



GSAS SSTfnd



GSAS SSTfnd(*t* – 1) – Satellite SSTfnd(*t*)

1 Jan – 31 Dec 2017

Compared previous day's GSAS SSTfnd with super-obbed satellite SSTfnd over Global domain and Australian domain (90ºE–180ºE, 50ºS–5ºN).
Note: Statistics are given for mean daily bias and mean daily RMSD.

Analysis	Global Matchups	Global Bias (K)	Global RMSD (K)	Australian Matchups	Australian Bias (K)	Australian RMSD (K)
GSAS (AVHRR, AMSR-2)	679,291,021	-0.004	0.458	75,210,803	-0.007	0.415
GSAS (AVHRR, AMSR-2, VIIRS)	790,599,110	-0.008	0.428	88,323,651	-0.010	0.386
GSAS (AVHRR, AMSR-2, VIIRS, H08)	806,849,907	-0.009	0.459	95,715,601	-0.014	0.458

Ingesting VIIRS results in a reduction of 0.03 K in mean daily innovation RMSD.

Australian Government
Bureau of Meteorology

Analysis SSTfnd(*t* – 1) – Buoy SSTfnd(*t*)

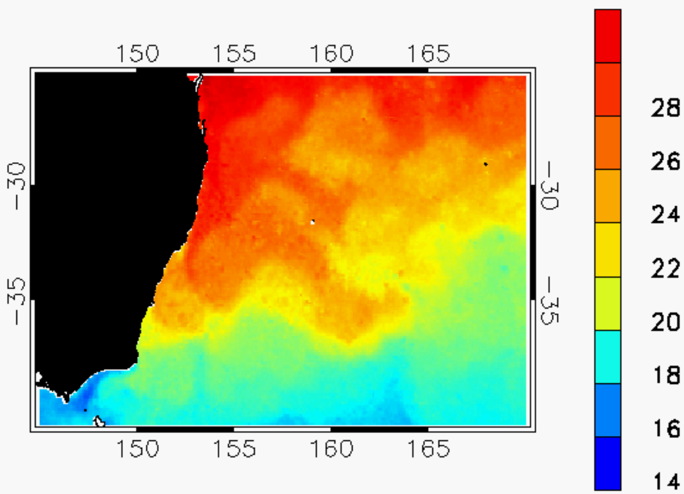
1 Jan – 31 Dec 2017

Compared previous day's SST analysis SSTfnd with drifting and tropical moored buoy SSTfnd over Global domain and RAMSSA Australian domain (60ºE–190ºE, 70ºS–20ºN). Data collocated if within same grid cell, and winds > 6 m/s (day), > 2 m/s (night).

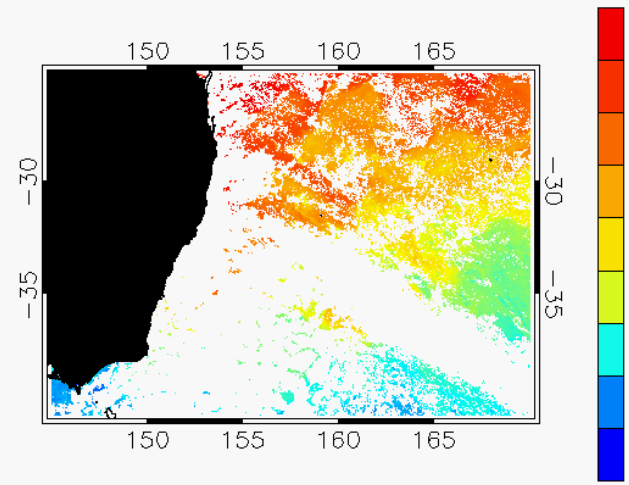
Analysis	Global Matchups	Global Bias (K)	Global RMSD (K)	Australian Matchups	Australian Bias (K)	Australian RMSD (K)
10 km GSAS	355,653	0.056	0.613	206,131	0.045	0.548
10 km GSAS (inc VIIRS)	355,614	0.130	0.604	206,123	0.123	0.541
25 km GAMSSA	502,924	0.030	0.542			
9 km RAMSSA				230,673	0.097	0.536
10 km CMC (inc VIIRS)	844,549	0.061	0.520	206,167	0.080	0.502

GSAS vs RAMSSA
Case Study: East Australian Current 21 March 2018

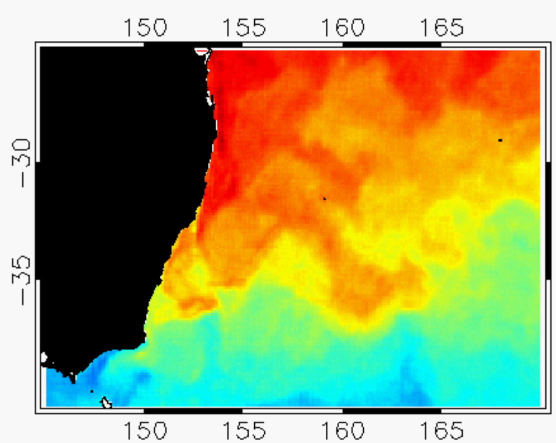
Operational RAMSSA (no VIIRS) (9 km)



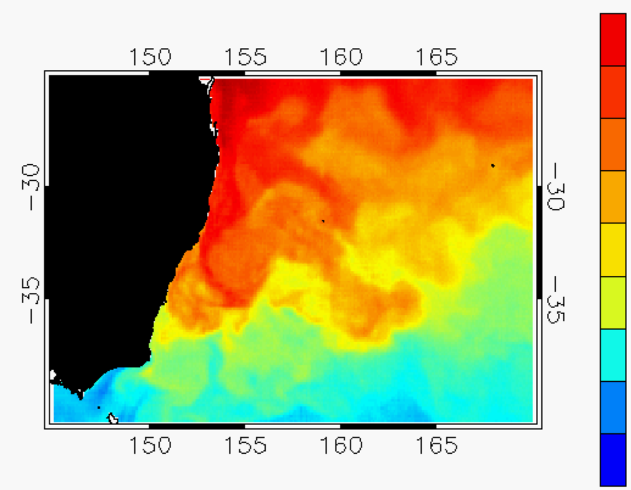
IMOS AVHRR+VIIRS L3S (2 km)



GSAS (no VIIRS) (10 km)



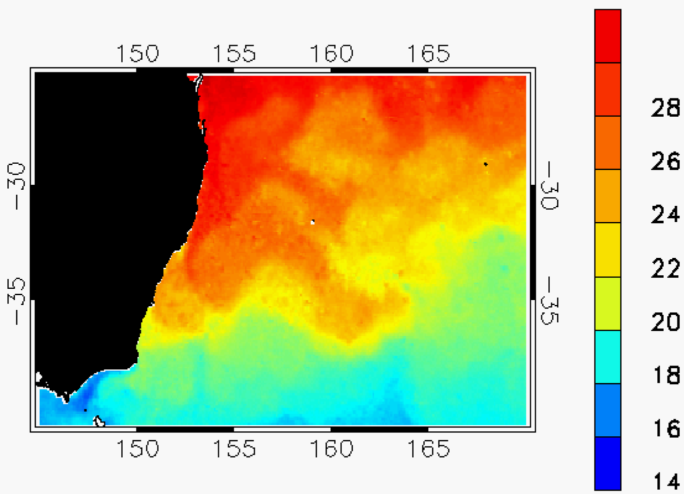
GSAS (VIIRS) (10 km)



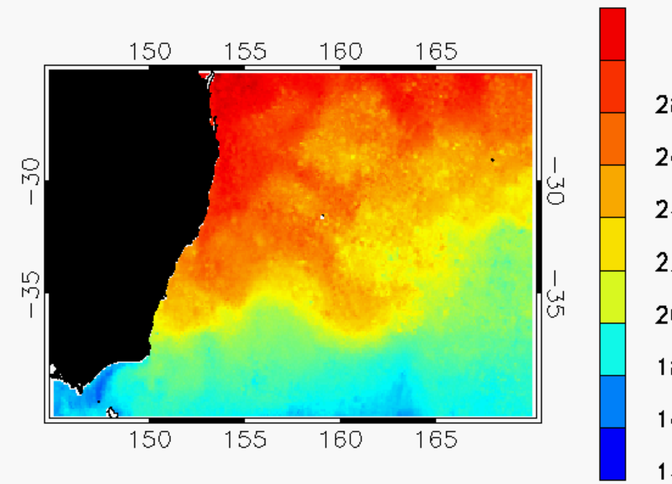
GSAS vs RAMSSA

Case Study: East Australian Current 21 March 2018

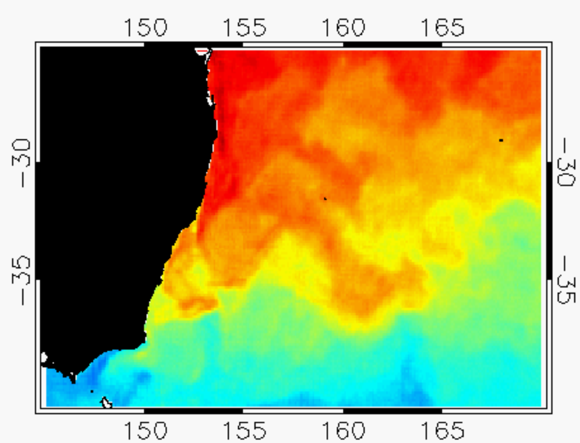
Operational RAMSSA (no VIIRS) (9 km)



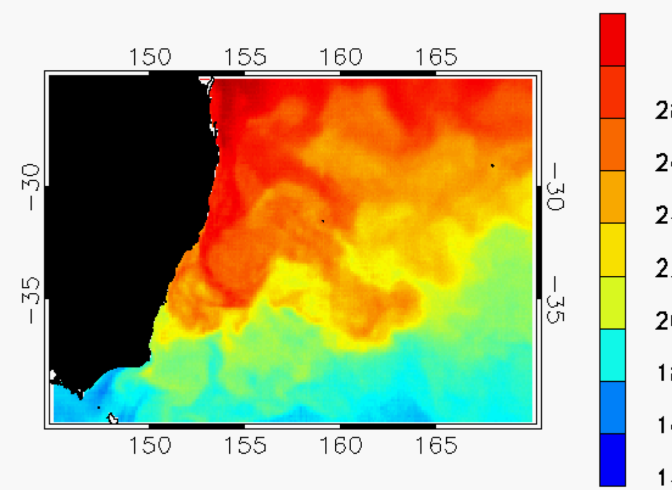
Test RAMSSA (VIIRS) (9 km)



GSAS (no VIIRS) (10 km)

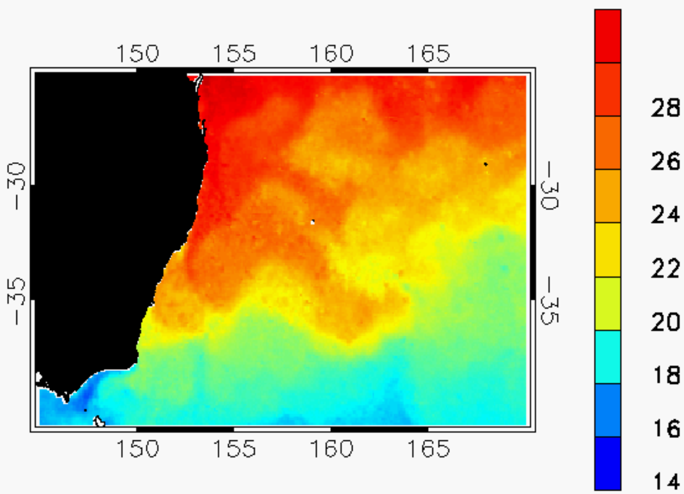


GSAS (VIIRS) (10 km)

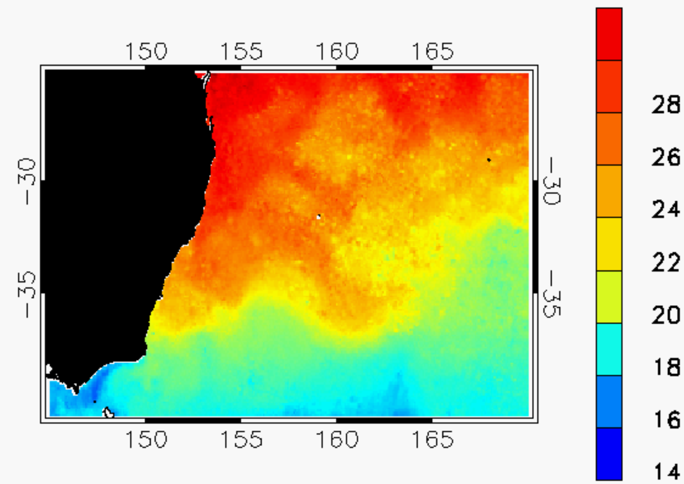


GSAS vs RAMSSA
Case Study: East Australian Current 21 March 2018

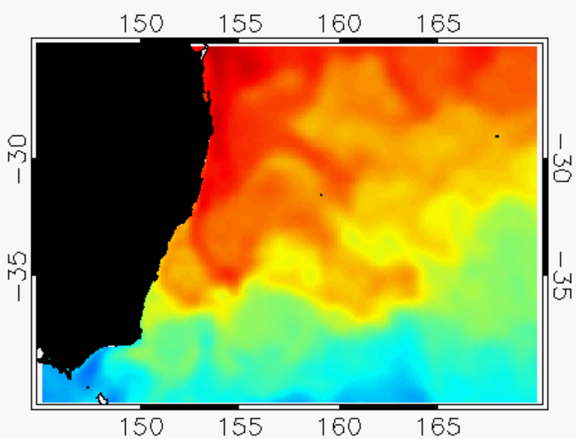
Operational RAMSSA (no VIIRS) (9 km)



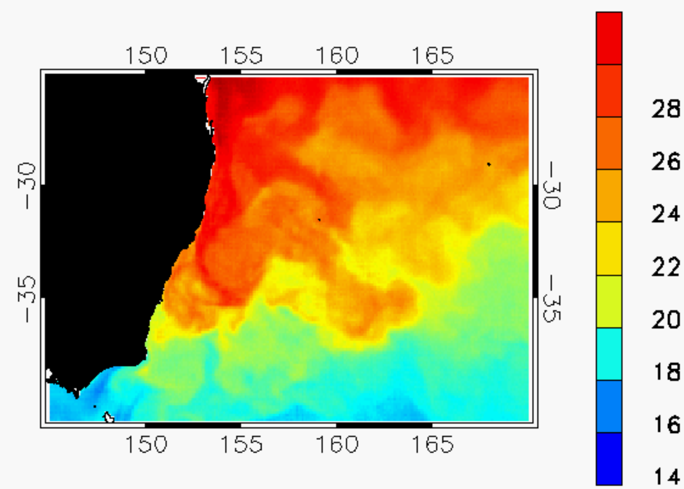
Test RAMSSA (VIIRS) (9 km)



CMC (VIIRS) (10 km)

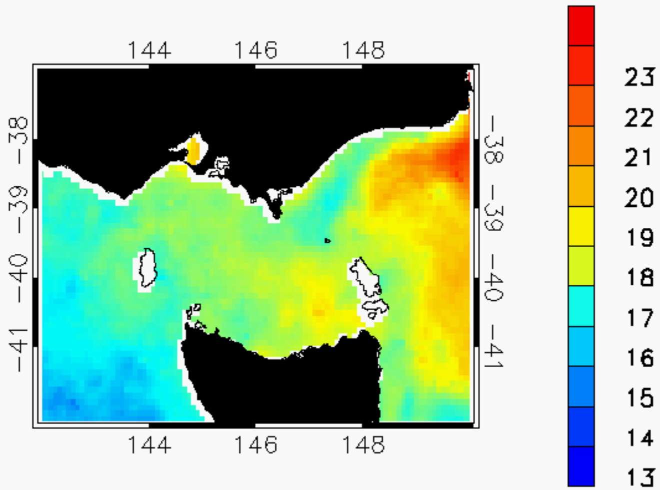


GSAS (VIIRS) (10 km)

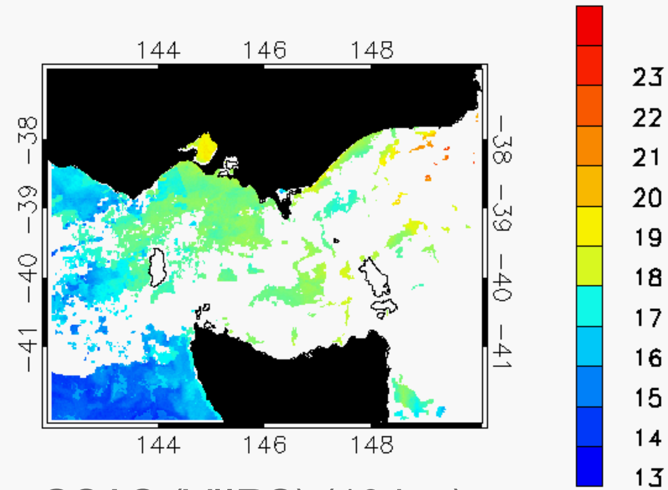


GSAS vs RAMSSA
Case Study: Bass Strait 21 March 2018

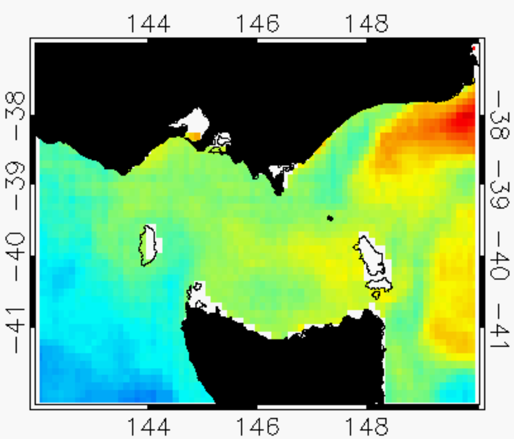
Operational RAMSSA (no VIIRS) (9 km)



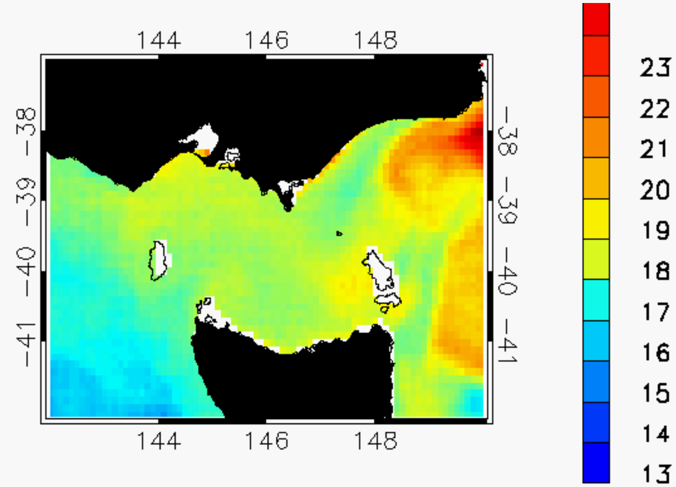
IMOS AVHRR+VIIRS L3S (2 km)



GSAS (no VIIRS) (10 km)

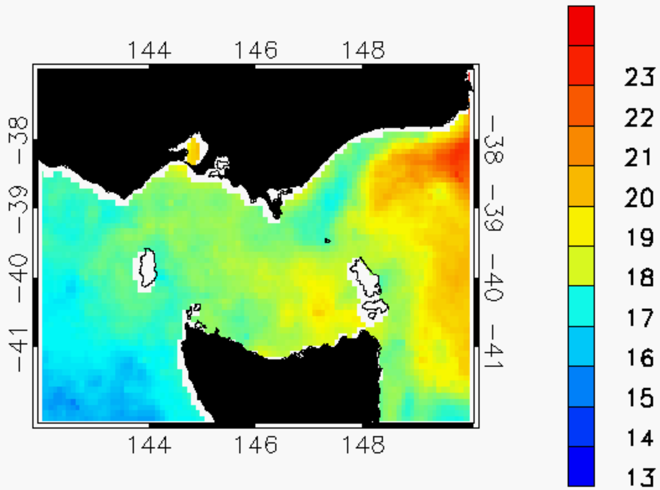


GSAS (VIIRS) (10 km)

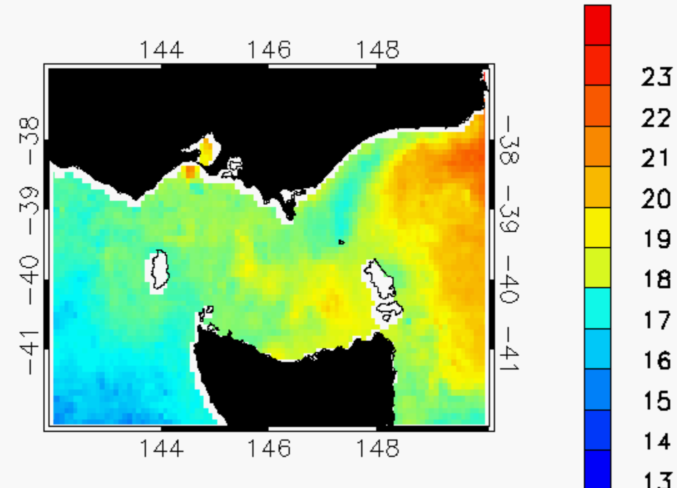


GSAS vs RAMSSA
Case Study: Bass Strait 21 March 2018

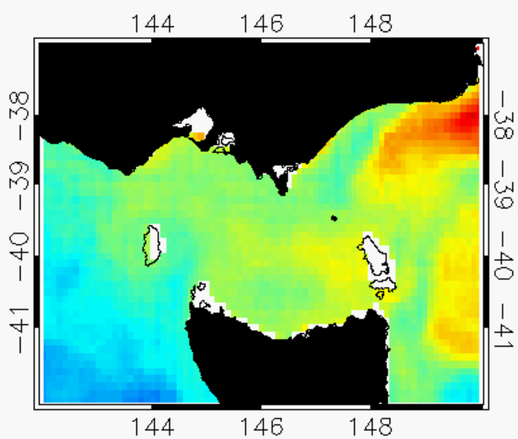
Operational RAMSSA (no VIIRS) (9 km)



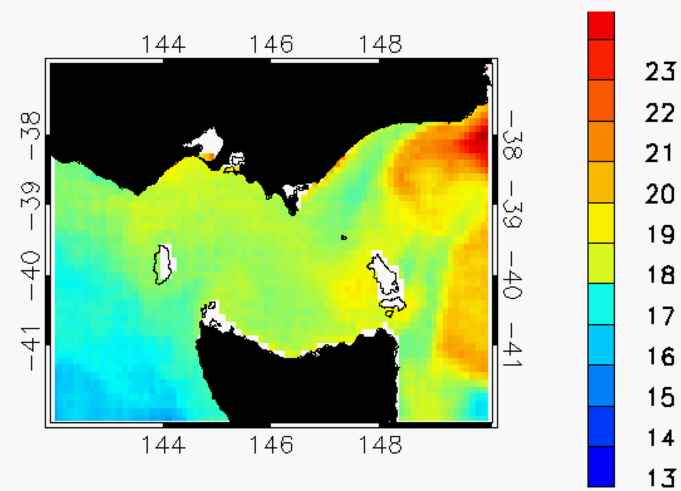
Test RAMSSA (VIIRS) (9 km)



GSAS (no VIIRS) (10 km)

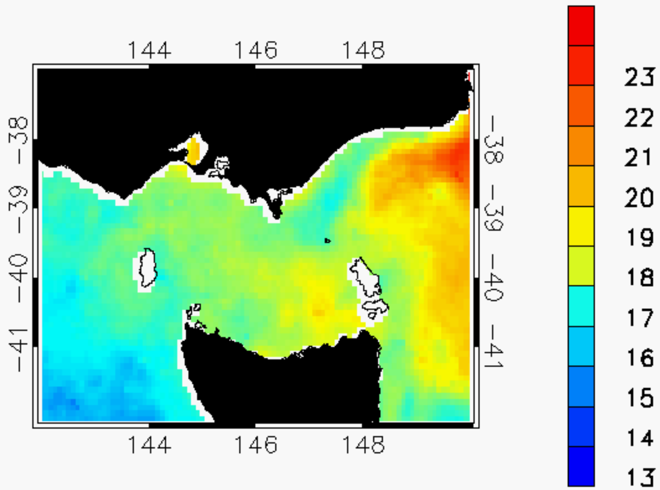


GSAS (VIIRS) (10 km)

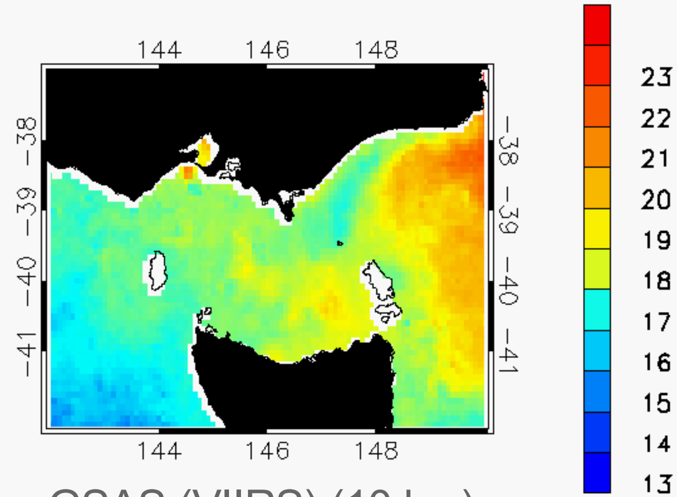


GSAS vs RAMSSA
Case Study: Bass Strait 21 March 2018

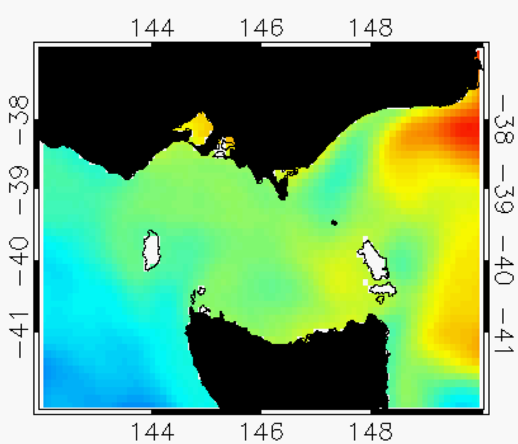
Operational RAMSSA (no VIIRS) (9 km)



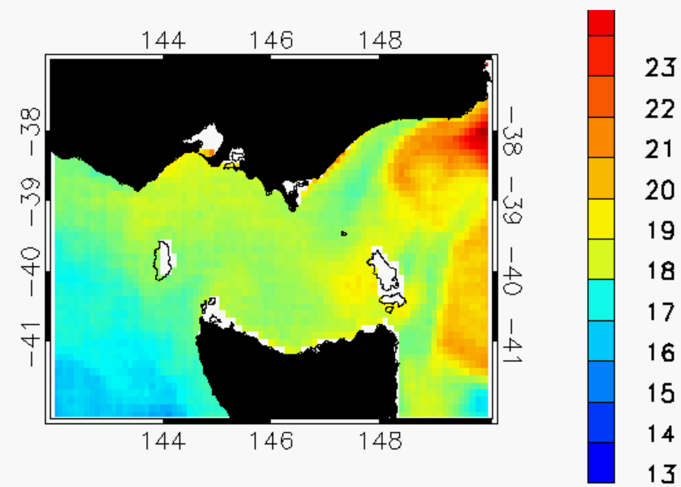
Test RAMSSA (VIIRS) (9 km)



CMC (VIIRS) (10 km)

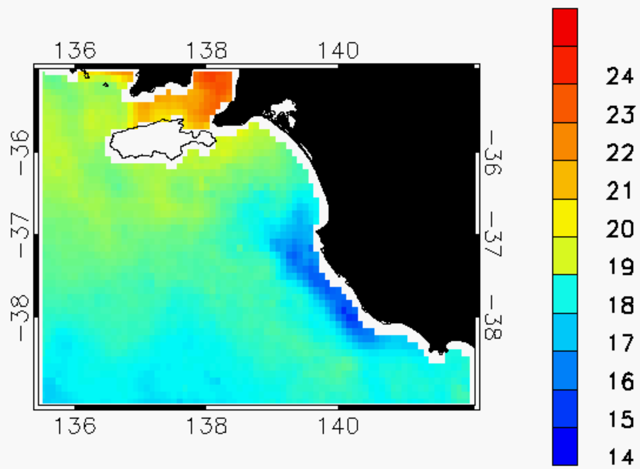


GSAS (VIIRS) (10 km)

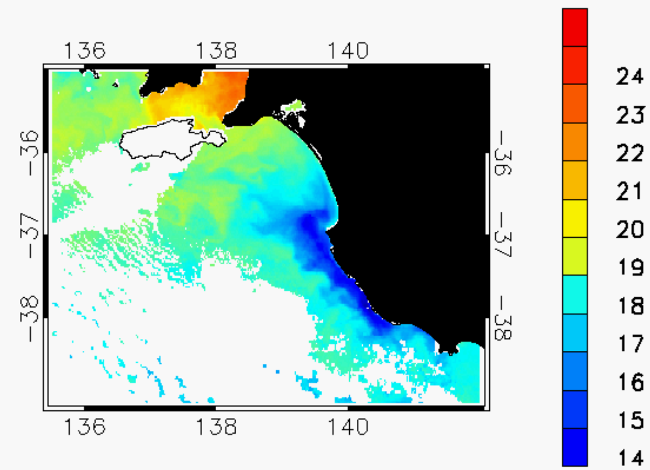


GSAS vs RAMSSA
Case Study: Bonney Coast 6 March 2018

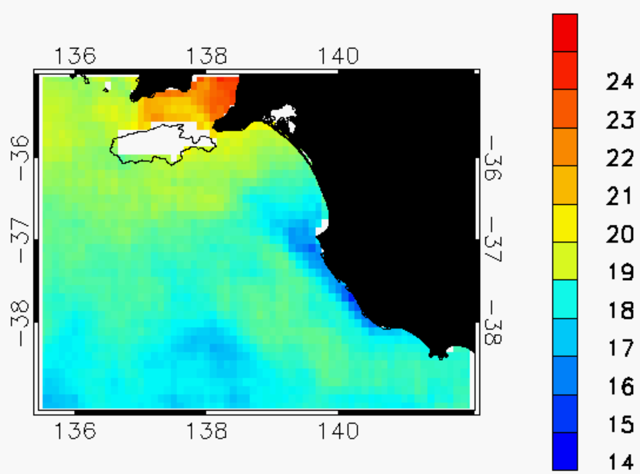
Operational RAMSSA (9 km)



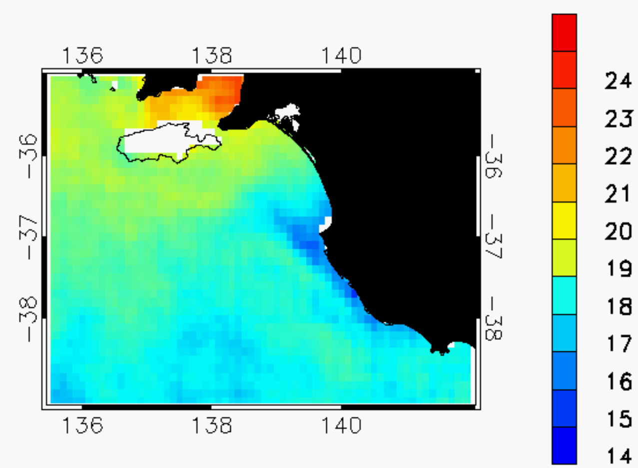
IMOS AVHRR+VIIRS L3S (2 km)



GSAS (No VIIRS) (10 km)

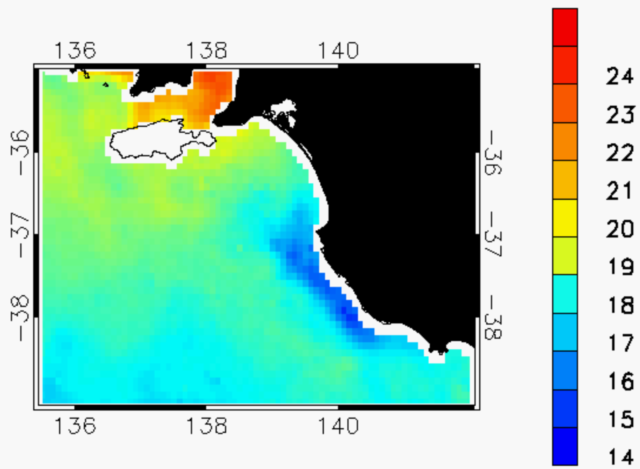


GSAS (VIIRS) (10 km)

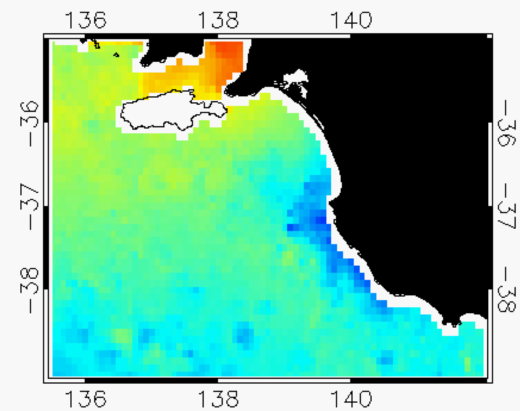


GSAS vs RAMSSA
Case Study: Bonney Coast 6 March 2018

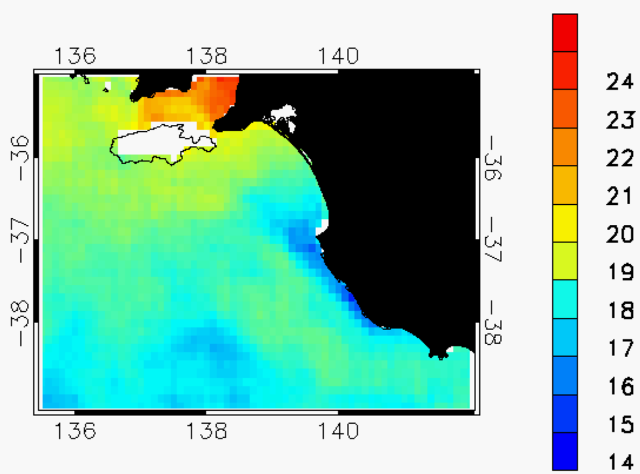
Operational RAMSSA (9 km)



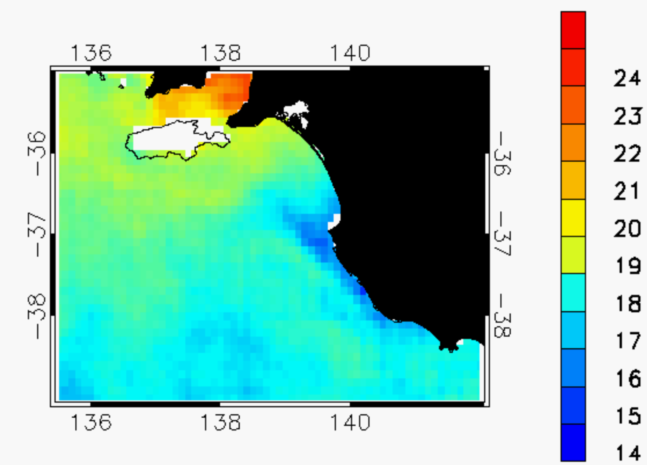
Test RAMSSA (VIIRS) (9 km)



GSAS (No VIIRS) (10 km)

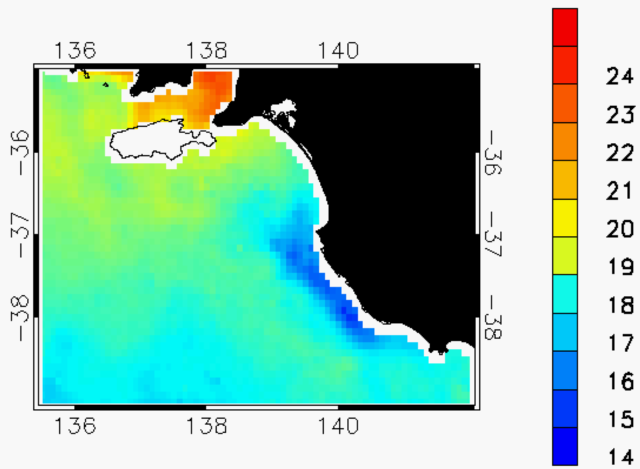


GSAS (VIIRS) (10 km)

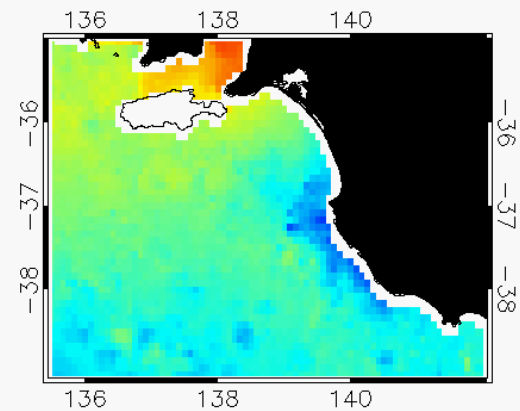


GSAS vs RAMSSA
Case Study: Bonney Coast 6 March 2018

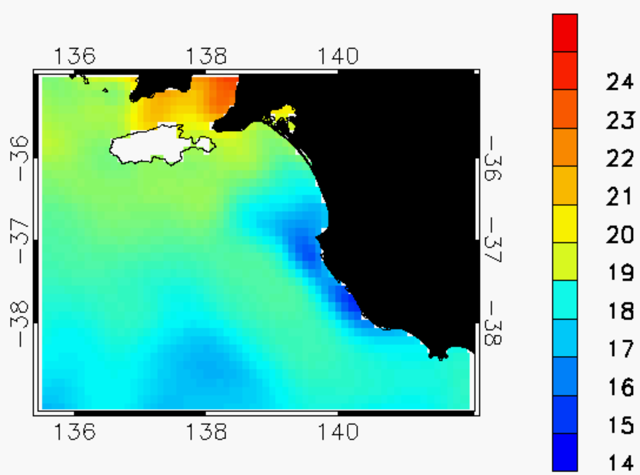
Operational RAMSSA (9 km)



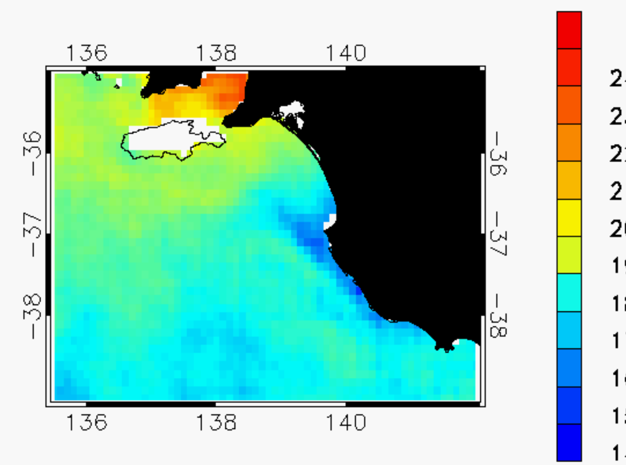
Test RAMSSA (VIIRS) (9 km)



CMC (VIIRS) (10 km)



GSAS (VIIRS) (10 km)



Australian Government
Bureau of Meteorology

Conclusions so far…

- GSAS appears to resolve surface ocean features more effectively than RAMSSA or CMC, and appears smoother than RAMSSA, but does not provide SSTs in semi-enclosed coastal regions (e.g. Port Phillip Bay).
- Without any tuning, the global accuracy of the 10 km GSAS SST analyses appears slightly lower than the 25 km GAMSSA or 10 km CMC analyses, possibly due to lack of tuning the background error covariance. GSAS RMSD 0.07 K higher than for GAMSSA.
- Over the RAMSSA domain, 10 km GSAS RMSD is very close to that of operational 9 km RAMSSA (and only 0.04 K higher than 10 km CMC), even without assimilating in situ data into GSAS.
- Assimilating night-time VIIRS data into GSAS has little effect on the innovation RMSD compared with buoy data, but reduces the GSAS innovation RMSD compared with super-obs by ~0.03 K.

Australian Government
Bureau of Meteorology

Future EnOI SST Work in 2018-2019

- Test setting the localisation radius to be high (> 100 km) but limiting the number of observations to be used closest to the location
- Include a sea ice mask such as OSI-SAF 5 km ice analysis
- Validate the OFAM3 model background ensemble covariances that are used to form GSAS
- Investigate impact of alternative (fully global) background ensemble covariance models so that GSAS can become fully global (currently $\pm 75^{\circ}$N)
- Develop higher resolution, regional EnOI SST analysis products, that can also provide SSTs in semi-enclosed coastal regions

Australian Government
Bureau of Meteorology

Future BoM NWP SST Requirements

- City-coverage 0.015º resolution NWP systems (APS3 ACCESS-C from 2019)
  - Requires regional, daily SSTfnd or 6-hourly SSTskin, L4 with ~0.05º - 0.1º feature resolution
- Global 0.125º resolution NWP systems (APS3 ACCESS-G from late 2018)
  - Requires global, daily SSTfnd or 6-hourly SSTskin, L4 with ~0.1º - 0.2º feature resolution?
- Before end of 2020, under APS4 ACCESS BoM will probably have a single experimental NWP system at ~300 m resolution for fog forecasting at Perth City airport, but SST not required as inland model domain. However, other more coastal regions may follow…
- Could an EnKF-C EnOI SST analysis or EnKF-C Ocean Forecast SST be the solution for higher spatial/temporal resolution SST?

Questions?

Thank You!

Contact: helen.beggs@bom.gov.au

Additional slides for discussion

Analysis SSTfnd(*t*) – Buoy SSTfnd(*t*)
1 Jan – 31 Dec 2017

Australian Government
Bureau of Meteorology

Compared SST analysis SSTfnd with drifting and tropical moored buoy SSTfnd over Global domain and RAMSSA domain (60ºE–190ºE, 70ºS–20ºN). Data collocated if within same grid cell, and winds > 6 m/s (day), > 2 m/s (night).

Analysis	Global Matchups	Global Bias (K)	Global RMSD (K)
10 km GSAS	355,653	0.038	0.582
10 km GSAS (inc VIIRS)	355,614	0.117	0.565

Australian Government
Bureau of Meteorology

Analysis SSTfnd(*t* – 1) – Buoy SSTfnd(*t*)
19 Feb – 25 Mar 2018

To determine effect of assimilating ACSPO VIIRS L3U SSTs into GSAS and RAMSSA, compared previous day's SST analysis SSTfnd with drifting and tropical moored buoy SSTfnd over RAMSSA domain (60ºE – 190ºE, 70ºS – 20ºN). Data collocated if within same grid cell, and winds > 6 m/s (day), > 2 m/s (night).

Analysis	Australian Matchups	Australian Bias (K)	Australian RMSD (K)
10 km GSAS	13,251	0.066	0.425
10 km GSAS (inc. VIIRS)	13,251	0.160	0.419
9 km RAMSSA	14,991	0.115	0.417
9 km RAMSSA (inc VIIRS)	16,257	0.098	0.415
10 km CMC (inc VIIRS)	13,262	0.069	0.378

Daily Regional and Global Multi-Sensor SST analyses (RAMSSA and GAMSSA)

http://www.bom.gov.au/marine/sst.shtml

Australian Government
Bureau of Meteorology

Format: GHRSST v1.6 L4 netCDF3 and GHRSST v2.0 L4 netCDF4

Depth: Foundation SST estimate

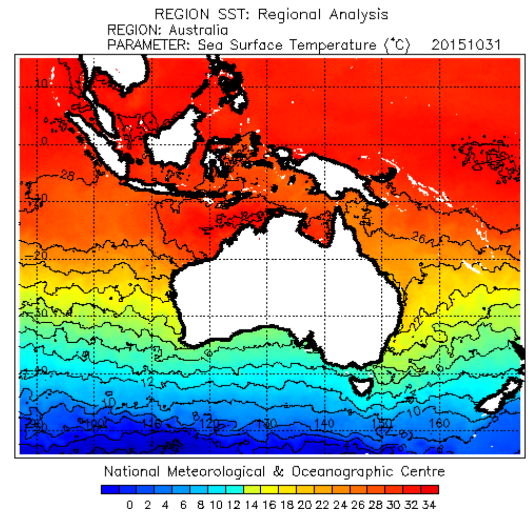
Resolution: Daily, 0.083º regional, 0.25º global

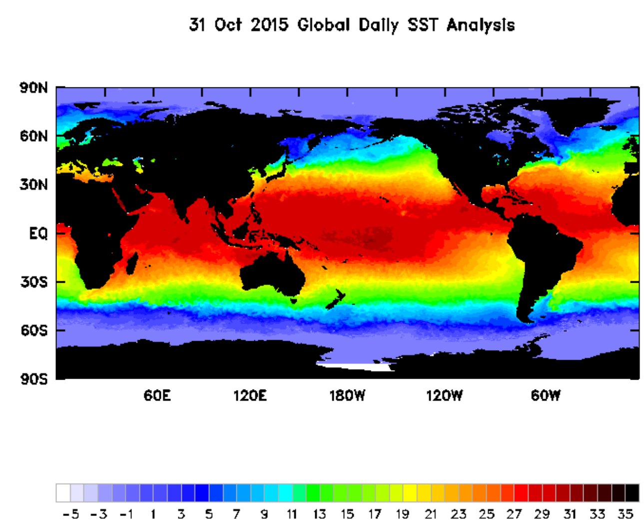
Available: 2006 to real-time (GDS1.6: AO.DAAC; GDS2.0: BoM OPeNDAP server)

Method: Optimal interpolation. Background: Combination of previous day's RAMSSA/GAMSSA SST and Reynolds and Smith (1994) climatology (1961-1990).

Inputs:

- 1-4 km IMOS HRPT AVHRR (NOAA-18/19) L2P SSTskin
- 9 km NAVOCEANO GAC AVHRR (NOAA-18/19, METOP-A/B) L2P SST1m
- ACSPO VIIRS L3U SSTs (in RAMSSA test system)
- ~50 km JAXA AMSR-2 (GCOM-W) L2P SSTsubskin
- Buoy and ship in situ SSTdepth (GTS)
- NCEP 9 km sea ice analyses





Impact of VIIRS on RAMSSA SST analyses

Australian Government
Bureau of Meteorology

- ACSPO VIIRS L3U SST data is being tested for ingestion into the Bureau's operational daily SST analyses (1/12º RAMSSA and 1/4º GAMSSA)

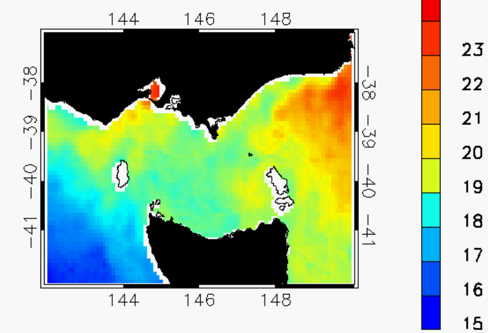
- Night-only ACSPO VIIRS L3U data converted to IMOS VIIRS L3U format (QL changed) then collated to daily 1/12º and 1/4º L3C SSTfnd data

- Optimally interpolated along with HRPT AVHRR, GAC AVHRR, AMSR-2 and in situ SSTfnd data into test RAMSSA SST analyses since 19th Feb 2018

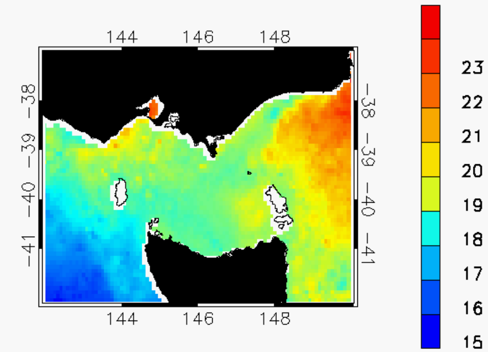
- Mean bias and StDev of RAMSSA (t-1) – Buoy SSTfnd(t) slightly less in test RAMSSA for 19th Feb to 19th Mar 2018 compared to operational system
  - 0.09 ± 0.41 K cf 0.10 ± 0.42 K

- Further tuning needed to optimise correlation length scales (currently 12 km for obs and 20 km for BGF) to reduce "speckliness" of test RAMSSA

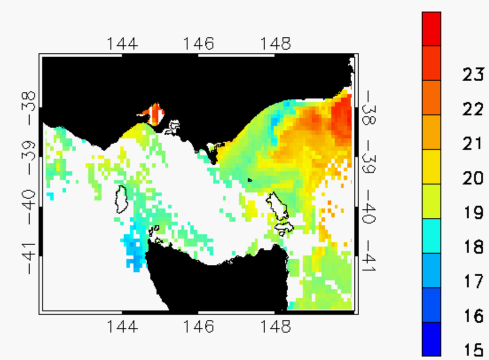
Operational RAMSSA SST



Test RAMSSA SST with VIIRS



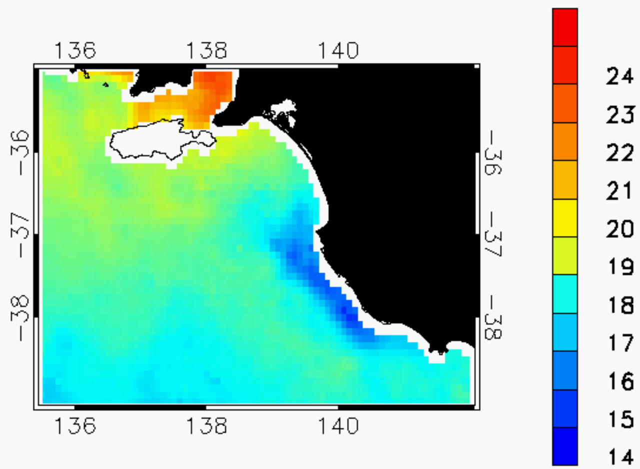
VIIRS SST on RAMSSA grid



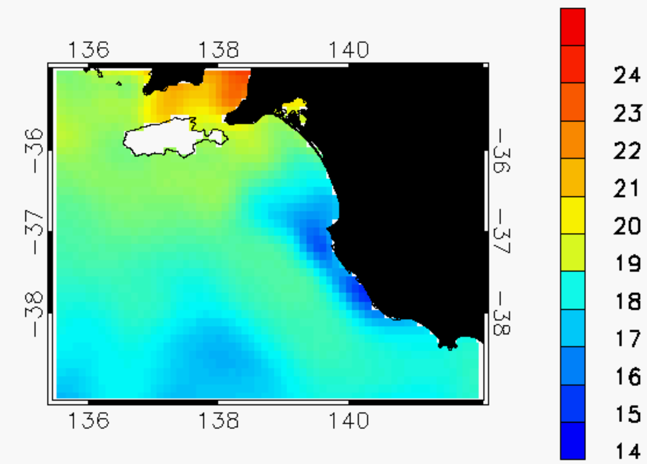
Australian Government
Bureau of Meteorology

GSAS vs RAMSSA
Case Study: Bonney Coast 6 March 2018

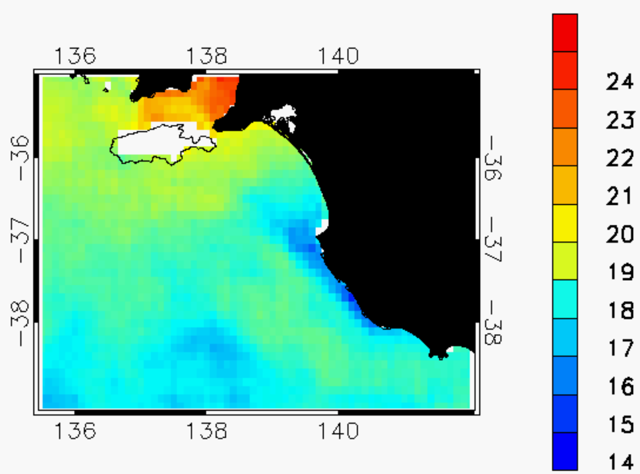
Operational RAMSSA (9 km)



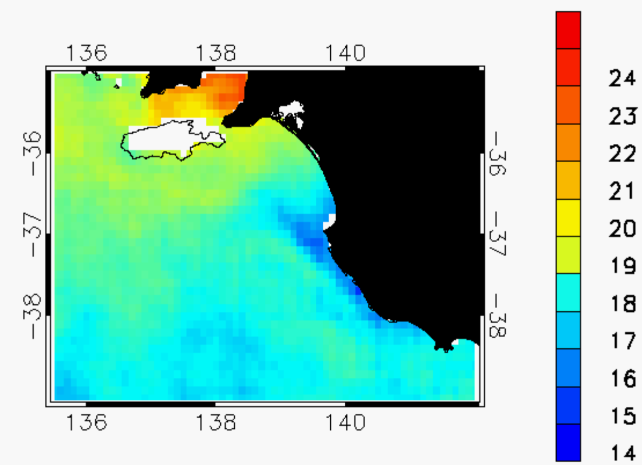
CMC (VIIRS) (10 km)



GSAS (No VIIRS) (10 km)

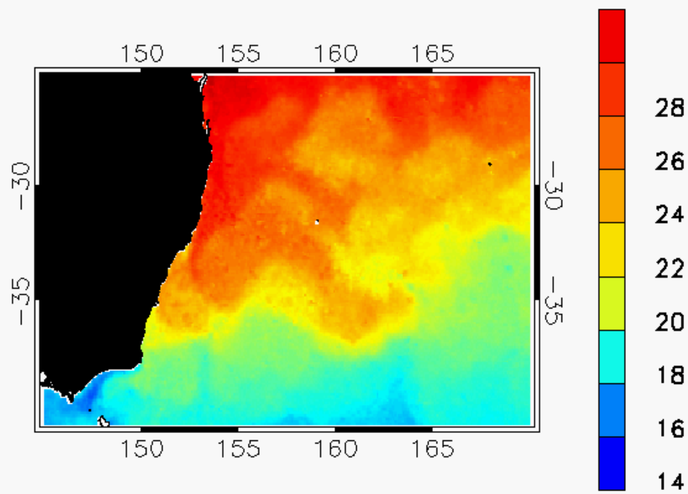


GSAS (VIIRS) (10 km)

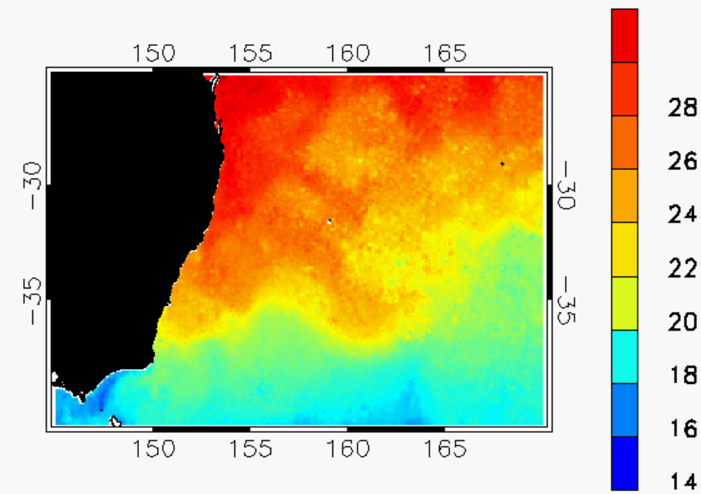


GSAS vs RAMSSA
Case Study: East Australian Current 21 March 2018

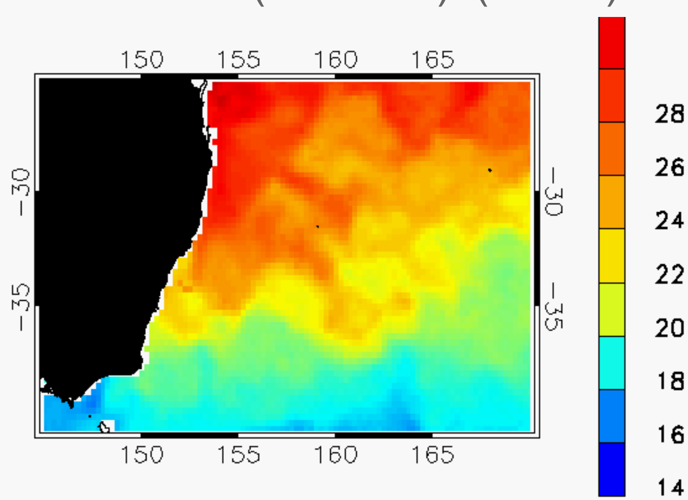
Operational RAMSSA (no VIIRS) (9 km)



Test RAMSSA (VIIRS) (10 km)



GAMSSA (no VIIRS) (25 km)



GSAS (VIIRS) (10 km)