Enhancing ship of opportunity sea surface temperature observations in the Australian region

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As part of the Australian Integrated Marine Observing System (IMOS), hull-contact temperature sensors have been installed on six commercial vessels. Near real-time, quality controlled, sea surface temperature (SST) measurements from these sensors, and thermistors located in water intakes on nine research and commercial vessels traversing waters around Australia, are now available via the Global Telecommunications System. Comparisons with satellite SST observations indicate that the hull-contact temperature sensors and research vessels produce SST data with comparable uncertainties to those available from data buoys in the same region. These IMOS ship SST data will benefit the validation of satellite SST products and analyses, and validation of ocean general circulation models, over regions lacking in buoy observations, such as coastal areas and the Southern Ocean.

LEAD AUTHOR'S BIOGRAPHY

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INTRODUCTION

Remotely sensed sea surface temperature (SST) data are important inputs to ocean, numerical weather prediction, seasonal and climate models. In order to improve validation of satellite SST products and SST analyses and forecasts in the Australian region, there is a need for high quality *in-situ* SST observations with greater spatial coverage than is currently available from moored and drifting data buoys. Regions particularly lacking buoy observations are the Indonesian seas, close to the Australian coast (including Bass Strait) and the Southern Ocean (Fig 1).[1]

Prior to 2008, SST observations from volunteer observing ships in the Australian region, available in near real-time to operational meteorological and oceanographic systems via the Global Telecommunications System (GTS), were significantly noisier than those available via the GTS from moored and drifting buoys.[2,3] Ship SST observations in this region have therefore been viewed as less reliable than data buoys for operational, near real-time validation of satellite SST observations, analyses or ocean models. In order to improve the spatial coverage of validation-quality *in-situ* SST observations, it was considered that SST observations from ships of opportunity should be improved in accuracy/reliability and provided in near real-time to the GTS.

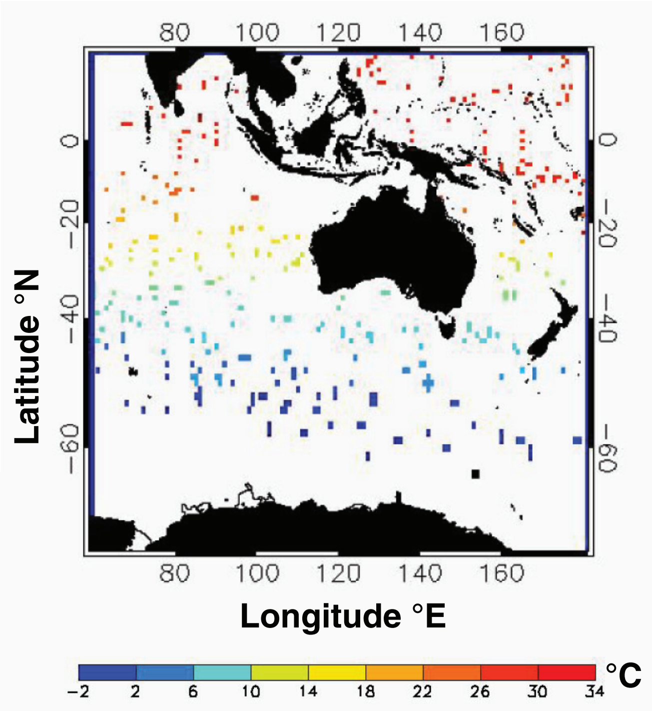

Fig 1: Drifting and moored buoy SST observations from the GTS for 21 September 2010 over the region 70°S to 20°N, 60°E to 180°E

Research vessels currently operating in the Australian region are instrumented with calibrated thermistors located in the water intakes to thermosalinographs, as close as possible to the hull inlet (eg, Table 1). These provide SST observations to a high resolution, but before 2008 the data were not generally available via the GTS and therefore not readily available to operational systems. Unfortunately, few owners of commercial vessels allow the installation of dedicated water intakes in their vessels for SST measurement, and engine water intakes are not always suitable for accurate SST determination due in part to heating in the engine room where the observations are made.[1,4] It was demonstrated in the 1990s that hull temperature sensors respond well to changes in the SST surrounding the hull and that the hull SSTs agreed closely (±0.1°C) with monthly optimum interpolation SST analyses based on satellite, buoy and ship temperatures.[4]

In recent years a small number of commercially-available Sea Bird SBE 48 hull-contact temperature sensors[5] have been deployed on research and commercial vessels by, among others, the National Oceanography Centre Southampton (NOCS)[6] and Woods Hole Oceanographic Institute (David Hosom, *pers. comm.*). Analysis of four years of SST data from an un-insulated SBE 48 installed at 5m depth on the interior hull of the *Pride of Bilbao* demonstrated that under high wind conditions at night the SBE 48 SST measurements were on average biased 0.3–0.35°C high compared with an RBR 1050 SST sensor towed behind the vessel at around 6m depth.[6] The authors concluded that hull thermometry on ships of opportunity did not appear capable of providing a proxy for SST at depths measured by thermal infrared radiometers on satellites (~10μm) with an accuracy better than 0.3–0.4°C, and therefore did not at that time offer a reliable means of expanding the source of data for satellite-derived SST validation activities.[6]

The aim of the Australian study was to demonstrate if equipping a fleet of commercial vessels with hull-contact temperature sensors, using careful positioning on the vessel and thermal insulation, could positively impact the operational validation of SST derived from satellites and ocean models. The following section presents the results of tests conducted on the *RV Southern Surveyor* and *RV Cape Ferguson* with an SBE 48 hull-contact temperature sensor in order to determine the optimum installation design for this type of sensor on ships of opportunity (SOOP) which can not be equipped with a temperature sensor in a water intake.

From 2008, the Integrated Marine Observing System (IMOS)[(a)] has enabled quality controlled SST data to be supplied in real-time (within 24h) from SBE 48 hull-contact sensors on commercial vessels and water injection sensors on research vessels in the Australian region. The remainder of this paper describes the various IMOS ship SST data streams, their quality control and assurance, and examples of operational applications of the IMOS ship SST data.

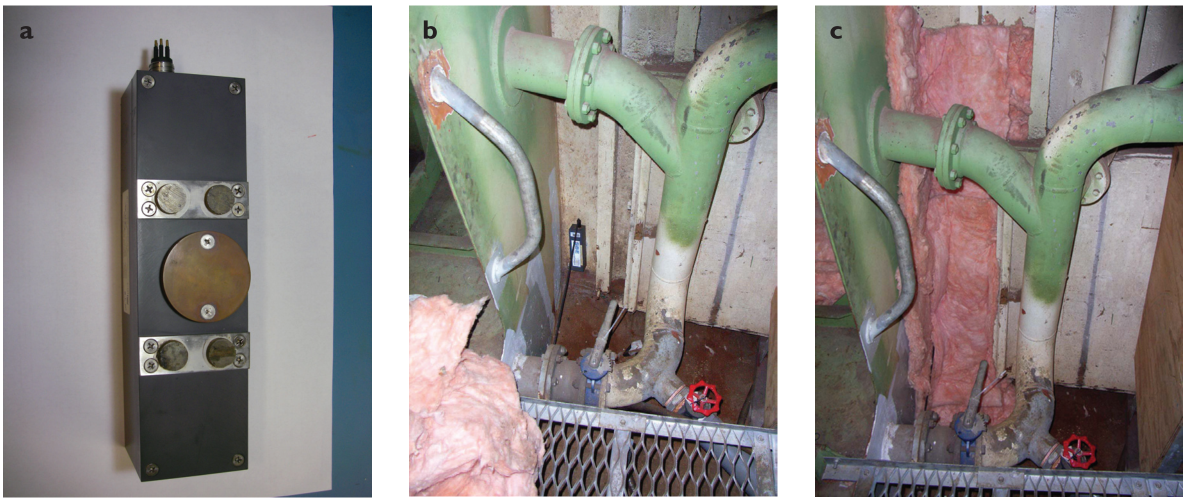

Fig 2: The Sea Bird SBE 48 hull contact temperature sensor (a) showing the thermal sink (brown disk) and four magnets, (b) installed against the exterior hull of the *RV Southern Surveyor* next to the grey water tank, and (c) covered with 'Pink Batt' ceiling insulation

Vessel	Callsign	IMOS data start	SST sensor	Sensor depth (m)	Distance from hull inlet (m)	Data Interval (minutes)	Data Uploaded to GTS
RV Southern Surveyor	VLHJ	4 Feb 2008	SBE 3	5.5	0.1	1 (averaged) 180 (instantaneous)	3 hourly trackob 3 hourly SHIP (from 10 Oct 2008)
RV L'Astrolabe	FHZI	14 Dec 2008	SBE 38	4	0.4	1 (averaged) 60 (instantaneous)	post-cruise trackob hourly SHIP (from 30 Dec 2008)
RSV Aurora Australis	VNAA	27 Jan 2008	SBE 38	5	0.3	1 (averaged) 180 (instantaneous)	half-hourly trackob 3 hourly SHIP (from 12 Oct 2008)
PV SeaFlyte (Rottnest Is Ferry)	VHW5167	30 Apr 2008	SBE 38 (in engine water intake)	0.1–0.5	0.5	1 (averaged)	Daily trackob
PV Fantasea One (Whitsundays Ferry)	VJQ7467	5 Nov 2008 – 29 Mar 2010	AD590 (in engine water intake) EI4000.4ZL (radiometer)	1.4 0	0.25 N/A	1 (averaged) 1 (averaged)	Daily trackob No
PV Spirit of Tasmania II (Bass Strait Ferry)	VNSZ	18 Dec 2008	SBE 48	1.5–2	N/A	60 (instantaneous)	hourly SHIP
MV Stadacona	C6FS9	13 Aug 2009	SBE 48	2–7	N/A	60 (instantaneous)	hourly SHIP
MV Portland	VNAH	20 Jun 2009	SBE 48	4–9	N/A	60 (instantaneous)	hourly SHIP
MV Highland Chief	VROB	30 Sep 2009	SBE 48	3–8	N/A	60 (instantaneous)	hourly SHIP
MV Iron Yandi	VNVR	10 Feb 2010	SBE 48	1–10	N/A	60 (instantaneous)	hourly SHIP
PV Pacific Sun	9HA2479	12 Dec 2010	SBE 48	1.5	N/A	60 (instantaneous)	hourly SHIP
RV Cape Ferguson	VNCF	31 Mar 2009	SBE 38 E14000.4ZL (radiometer)	1.9 0	2–3 N/A	1 (averaged) 1 (averaged)	< 40 days delayed mode trackob (from 5 Dec 2010) No
RV Solander	VMQ9273	24 Feb 2010	SBE 38	1.9	5	1 (averaged)	< 40 days delayed mode trackob (from 5 Dec 2010)
RV Tangaroa	ZMFR	27 Apr 2011	SBE 38	3	2	1 (averaged) 60 (instantaneous)	Daily trackob (from 14 Sep 2011) hourly SHIP (from 9 Apr 2011)
MV Pacific Celebes	VRZN9	15 Nov 2011	Aanderaa 4050 SBE 48	12 8	15–20 N/A	5 (instantaneous) 5 (instantaneous)	6 hourly trackob (from 15 Nov 2011) No
RV Linnaeus	VHW6500	TBD	SBE 38	0.5	0.4–0.5	1 (averaged)	TBD

Table 1: Details of vessels either currently providing or planned to supply QC'd SST data streams to IMOS and the GTS

HULL-CONTACT SENSOR TESTS

A Sea Bird SBE 48 hull-contact temperature sensor[5] was installed on the *RV Southern Surveyor* (Fig 2) for comparison tests with the SBE 3 calibrated thermistor[7] installed in the thermosalinograph water intake at 5.5m depth. The SBE 48 was attached using magnets to the interior of the steel hull at a depth of approximately 3m below the water line and approximately 20m aft of the bow. The SBE 48 was located approximately 3.5m to port of the SBE 3 sensor and approximately 2.5m higher up on the hull plating. Thermal contact between the SBE 48 heat sink and the ship's hull was achieved by the use of contact grease with a high thermal conductivity. Both SST sensors supplied 1 min averaged SST observations for the study.

The SBE 48 sensor housing and surrounding hull was insulated on 27 July 2008 using three layers of Bradford 'Pink Batt' glass wool R2.5 ceiling insulation covering the sensor and surrounding hull to an approximate thickness of 270mm and a minimum distance of 250mm from the sensor (Fig 2(c)). The results presented here are for the cruise commencing 24 July 2008 at 16.6°S, 145.8°E and finishing on 11 August 2008 at 23.8°S, 151.6°E. Prior to insulation, the SBE 48 temperature was on average 0.28°C warmer than the SBE 3 temperature, with a standard deviation of 0.14°C (N = 3630). After insulation, the average offset was 0.19°C with a standard deviation of 0.12°C (N = 20540). The majority of the bias occurred during periods when the water mass exhibited sharp horizontal thermal gradients. In water masses with low thermal gradients the average offset was approximately 0.15°C. The observed SBE 48 SST warm bias may have been due to the hull surrounding the sensor being heated by the internal ship atmosphere with the 250mm wide insulation covering the sensor and hull possibly insufficient to completely remove this effect. In this case, the separation of the hull ribs restricted the area of hull that could be insulated. The vertical separation of the sensors (~2.5m) may also have been partially responsible for the observed differences in SST due to surface stratification, water flows around the hull and disturbance of the ocean surface layer by the vessel's movement.

An example of the sensor comparison after insulation is presented in Fig 3 for the transect between 2 August 2008, 18.4°S, 147.8°E and 6 August 2008, 21.8°S, 152.9°E. The SBE 48 temperatures exhibited lower amplitude, short term (of the order of minutes) fluctuation compared to the thermosalinograph water intake SBE 3 temperatures, as expected from measurements of SST integrated over part of the ship's hull. Although the *RV Southern Surveyor* has a particularly thick steel hull of 25mm, and the positioning of the SBE 48 surrounded by black water pipes and hull ribs was far from ideal, this study indicates that the SBE 48 is capable of providing ship SST observations within 0.19 ± 0.14°C of those from a water injection sensor installed on the same vessel.

An additional verification of the same SBE 48 sensor against a water injection SBE 38 SST sensor[8] was performed on the *RV Cape Ferguson* which has a thinner steel hull of thickness 8mm. The SBE 48 sensor was covered by a foil backed, 60mm thick, fibreglass panel over an area of 500mm x 500mm and attached to the hull at a depth of 1.6m, approximately 0.3m above the height of the water intake to the SBE 38 sensor at a position isolated from local heat sources. During the *RV Cape Ferguson* cruise (15–24 February 2009 from 21°S, 149.5°E to 17°S, 146°E) the SBE 48 temperature was on average 0.05°C warmer than the SBE 38 temperature with a standard deviation of 0.07°C.

The reduction in warm bias of the SBE 48 SSTs on the *RV Cape Ferguson* compared with the observed warm bias on the *RV Southern Surveyor* (0.05°C cf 0.19°C), with both vessels traversing similar regions, indicates that SBE 48 placement away from on-board heat sources and area of hull insulated are critical to reducing the warm bias. The reduction in standard deviation of SBE 48 SST minus water injection SST between the two vessels (0.07°C cf 0.14°C) may be linked to the *RV Cape Ferguson's* thinner hull allowing more rapid equilibration to the external ocean temperature as well as a larger area of the hull around the sensor being thermally insulated. It was therefore concluded that if the SBE 48 has good thermal contact with the hull, is positioned well below the water line away from on-ship heat sources, and the sensor and surrounding hull are sufficiently insulated from the interior ship's atmosphere, the hull-contact sensor should be capable of providing a sea surface temperature measurement approaching the accuracy of SBE 3 and SBE 38 water intake temperatures. The manufacturer quotes the initial accuracy of the SBE 48 as ±0.002°C[5] and the SBE 3 and SBE 38 as ±0.001°C.[7,8]

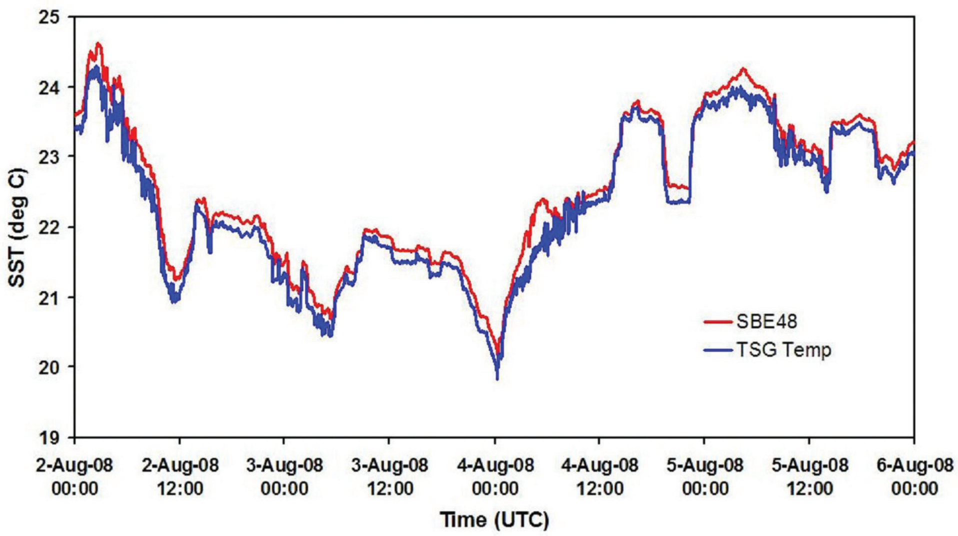

Fig 3: Example of the *RV Southern Surveyor* SST sensor comparison results after insulation of the hull-contact sensor. The SBE 48 hull-contact temperatures are shown in red and the SBE 3 temperatures in blue

Fig 4: The Sea Bird SBE 48 hull contact temperature sensor (a) installed against the exterior hull of the *PV Spirit of Tasmania II* in the bow thruster room, and (b) covered with the custom-made insulating pad

SHIP SST DATA STREAMS

The Australian Bureau of Meteorology (Bureau), as a contribution to IMOS, has instrumented six vessels of the Australian Voluntary Observing Fleet (AVOF) with hull-contact SBE 48 temperature sensors, supplying instantaneous SST observations every hour at a range of depths which vary among the ships (SSTdepth, Table 1). All the 'MV' vessels listed in Table 1 instrumented with SBE 48 sensors are either bulk carriers or container ships whose draft changes by up to several metres depending on load. The change in draft is not currently recorded automatically on these vessels so the precise SST depth measured by the SBE 48 sensors is not recorded. In addition to the six AVOF vessels instrumented with hull-contact sensors, there are also two passenger ferries reporting one minute averaged SSTdepth measurements using water injection temperature sensors for the Commonwealth Scientific and Industrial Research Organisation (CSIRO; Rottnest Island ferry, *PV SeaFlyte*) and the Australian Institute of Marine Science (AIMS; Whitsunday Island to Hook Reef ferry, *PV Fantasea One* – discontinued 29 March 2010). In addition, there are near real-time, water injection SST data streams available from six research vessels in the Australian region (*RV Southern Surveyor*, *RSV Aurora Australis*, *RV L'Astrolabe*, *RV Cape Ferguson*, *RV Solander* and *RV Tangaroa*) with a further data stream planned from *RV Linnaeus*.

Near real-time SSTs are also available from water injection and SBE 48 hull-contact sensors on the *MV Pacific Celebes*, courtesy of the National Oceanography Centre Southampton. As of 1 January 2012, 15 vessels contribute near real-time data to IMOS (Table 1). The vessels equipped with meteorological sensors provide meteorological data and SST to the GTS in the World Meteorological Organization (WMO) MET transmission SHIP (FM13-XIV) reports (Table 1), whereas those providing SST-only data streams to the GTS provide 1min averaged data in Trackob (FM62-VIII) reports.[9] Some vessels (*RV Southern Surveyor*, *RSV Aurora Australis, RV Tangaroa* and *RV L'Astrolabe*) provide both Trackob and SHIP reports to the GTS.

Each SBE 48 sensor is installed on the interior of the ship's hull below the summer load line in either the engine room or bow thruster compartment (eg, Fig 4(a)). The approximate depth of the sensor below each vessel's summer load line is given in Table 1. The actual sea level departure from summer load line is not currently included in the data files but will be considered for future installations. The sensor and surrounding hull is insulated from the air using a flexible foam pad of dimensions approximately 1m x 1m x 0.15m, fabricated to fit between the hull ribs (Fig 4(b)). In order to overcome cabling issues on AVOF vessels, SBE 48 data are transmitted to the automatic weather station on the ship's upper-most deck using Digi X Stream-PKG RF modems.[(b)] The RF modem frequencies used are 2.4 GHz to penetrate through closed doors via small openings in the door surfaces and ventilation shafts and 900 MHz for longer distances through air. Depending on the size of the vessel and location of the SBE 48 sensor, several pairs of modems have been installed as repeaters of the SBE 48 data.

All SST data are quality controlled (see next section), placed in real-time on the GTS and if available within 24h of observation are fed into the Bureau's satellite versus *in-situ* SST match-up database system[10] and operational regional and global SST analyses.[11] The quality controlled SST data with quality control flags are also available in netCDF format via the IMOS ocean portal web site[(c)] and IMOS OPeNDAP server.[(d),(e),(f)] Fig 5 shows the tracks of ships providing IMOS SST data from 4 February 2008 to 1 June 2011 to the IMOS ocean portal and the GTS.

Quality control and assurance

The IMOS ship SST quality control (QC) procedure is a fully automated process, and has been adapted from the system developed by the Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University, for the Shipboard Automated Meteorological and Oceanographic System Initiative (SAMOS),[(g),12] with small differences due to varying IMOS/Bureau requirements. The QC system flags data that fail to pass the following QC tests, in order of application:

1. Verify the existence of time, latitude and longitude data for every record;
2. Flag data that are not within physically possible bounds;

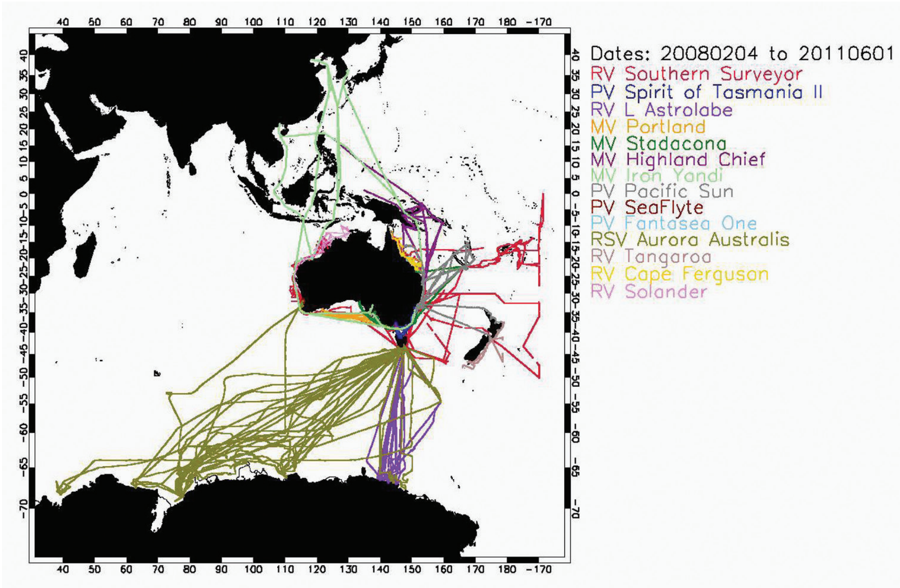

Fig 5: Locations of IMOS QC'd ship SST observations from 4 February 2008 to 1 June 2011 from the first 14 vessels listed in Table 1

In-Situ Data Stream	SST Sensor	Number of Match-ups	Mean Difference (°C)	Standard Deviation Difference (°C)	AATSR SST Standard Deviation (°C)	In-Situ SST Standard Deviation (°C)
RV Southern Surveyor	SBE 3	22662	–0.09	0.41	5.25	5.31
RV L'Astrolabe	SBE 38	7148	–0.11	0.27	4.21	4.22
RSV Aurora Australis	SBE 38	8030	–0.13	0.27	7.48	7.46
RV Cape Ferguson	SBE 38	32821	–0.07	0.47	2.52	2.60
RV Solander	SBE 38	17854	–0.11	0.39	2.72	2.64
RV Tangaroa	SBE 38	4075	–0.03	0.34	0.99	0.88
PV SeaFlyte	SBE 38	17639	–1.19	1.39	2.14	2.46
PV Fantasea One	AD590	2401	–0.42	0.34	0.91	0.88
PV Spirit of Tasmania II	SBE 48	448	–0.17	0.34	2.53	2.51
MV Portland	SBE 48	273	–0.15	0.36	2.42	2.48
MV Highland Chief	SBE 48	295	–0.10	0.34	4.09	4.08
MV Stadacona	SBE 48	248	–0.17	0.50	4.19	4.22
MV Iron Yandi	SBE 48	188	–0.14	0.31	4.52	4.47
PV Pacific Sun	SBE 48	161	–0.10	0.29	1.59	1.60
SBE48 Ships	SBE 48	1613	–0.14	0.37	4.92	4.90
IMOS Ships	Various	96266	–0.10	0.41	7.69	7.70
Non-IMOS Ships	Various	7167	–0.11	1.51	4.77	4.86
Drifting and Moored Buoys		33895	–0.07	0.44	8.15	8.15

Table 2: Mean and standard deviation of satellite observations of 10 arcmin averaged AATSR (ATS_MET_2P) SSTfnd minus collocated observations of SSTdepth from 14 IMOS and at least 1632 non-IMOS ships and observations of SSTfnd from drifting and moored buoys over the region 60°E – 190°E, 70°S – 20°N for the period 1 December 2008 to 30 May 2011. Observations were considered 'matched' if measured within the same UTC calendar date, centres of observations were separated by no more than half the resolution of the AATSR SST observation (1/12° latitude, 1/12° longitude), AVOF ship speed was > 2.5ms^{-1} and absolute SST difference was <10°C. The standard deviations of the AATSR SSTfnd and *in-situ* SST data sets used for the match-ups are included to indicate the SST variability over the region sampled by each *in-situ* observing platform. Note that 'IMOS Ships' corresponds to all ships listed in this table except *PV SeaFlyte* which displayed relatively poor agreement with the AATSR SSTs. 'SBE48 Ships' corresponds to all vessels listed in this table that are instrumented with an SBE 48 hull-contact sensor

3. Flag non-sequential and/or duplicate times;
4. Flag positions where the vessel is over land;
5. Flag vessel speeds that are unrealistic;
6. Flag data that exceeds 3°C above/below the Bureau's most recent operational daily SST analysis (blended from satellite and *in-situ* SST data) Note: This is simply a warning flag that is not used to reject data from the statistical analyses reported in this paper;
7. Flag data where AVOF ship speed is below 2.5ms^{-1} (since the AVOF vessels' hull-contact sensors exhibited anomalous SST values when in port).

Once any datum's flag is changed, it will not be altered further by any subsequent test.

In order to assess the accuracy of the IMOS ship SST datasets, the SST observations from the first 14 IMOS vessels in Table 1 were compared against 10 arcmin (~17km) spatially averaged Meteo Product SST observations from the Advanced Along Track Scanning Radiometer (AATSR) on the EnviSat polar-orbiting satellite over the region 60°E – 190°E, 70°S – 20°N, during 1 December 2008 to 30 May 2011 (Table 2). Night-time Meteo Product AATSR SST observations have been observed through a three-way error analysis of AATSR, AMSR-E and buoy SST data to have a very low standard deviation of 0.16°C globally.[13] For the Australian study, the Meteo Product 'skin' (~10 μm depth) SST (SSTskin) observations from AATSR were converted to an approximation of the 'foundation' SST (SSTfnd). The 'cool skin layer' is present during day or night and is a thin, thermally stratified ocean layer at the air-sea interface. The 'foundation' SST is defined as the ocean temperature below the ocean's cool skin layer (termed the 'subskin' SST) in the absence of any diurnal signal.[14] The conversion of the AATSR SSTskin observations to SSTfnd was performed using empirical skin to subskin SST correction algorithms[14] (equations 1 and 2 below) and the Bureau's operational, 0.375° resolution, Numerical Weather Prediction (NWP) ACCESS-R model mean hourly surface wind fields.[15]

The algorithms apply a small correction to convert from skin to subskin SST, depending on surface wind speed, and filter out SST values suspected to be affected by diurnal warming by excluding cases which have experienced average hourly surface wind speeds of below 6ms^{-1} during the day and below 2ms^{-1} during the night. Under the remaining wind speed regimes SSTsubskin approximates SSTfnd and therefore under these conditions SSTfnd – SSTskin approximates SSTsubskin – SSTskin, ΔT (in °C), and can be written as:[14]

$$\Delta T = 0.17 \tag{1}$$

when surface wind speed exceeds 6ms^{-1} (night and day conditions), and

$$\Delta T = 0.14 + 0.3\exp\left(-\frac{u}{3.7}\right) \tag{2}$$

when surface wind speed, u, is between 2ms^{-1} and 6ms^{-1} (night conditions only).

The data were considered matched if within the same UTC calendar date and ± 1/12° in latitude and longitude to the AATSR observation, AVOF ship speed was > 2.5ms^{-1} and absolute SST difference was <10°C. For comparison, match-ups between SST observations from AATSR and at least 1632 non-IMOS ships (from the GTS) in the same region are included. Note that many ships reporting SST to the GTS use a generic 'SHIP' identifier to mask their call sign, making it impossible to determine the exact number of vessels used in the study. The same AATSR SSTfnd observations were compared with collocated, SSTfnd observations from drifting and moored buoys (from the GTS) over a similar area and the same 30 month period. A 24h match-up period was chosen for the quality assurance to enable an adequate number of match-ups to be obtained for each vessel. Similar statistics were obtained using both 24h and 1h match-up periods, with standard deviations of 0.41°C for both match-up periods for all IMOS ships combined (minus *PV SeaFlyte*) and 1.51°C and 1.55°C, respectively, for non-IMOS ships.

Table 2 indicates that 13 of the 14 IMOS ship SST data streams included in the study (excluding *PV SeaFlyte*) have match-up standard deviations within ±0.06°C of those obtained from drifting and moored buoys (0.44°C) and 12 have biases within 0.1°C (excluding *PV SeaFlyte* and *PV Fantasea One*). *PV SeaFlyte* (Rottnest Island Ferry), instrumented with an SBE 38 sensor located in the engine intake, had a significantly higher warm bias and standard deviation with respect to AATSR SSTfnd (1.19 ± 1.39°C, N = 17639) than the other 13 IMOS vessels (0.10 ± 0.41°C, N = 78750), concluded from contemporaneous *in-situ* SST observations to be due to inadequate water flow past the SBE 38 sensor and/or engine room heating of the water measured by the sensor.[16]

Another factor that may have caused the high warm bias between SSTs measured on *PV SeaFlyte and PV Fantasea One* and AATSR SSTfnd, besides warming of the water in the engine intake, may have been the preponderance of daytime only transects for these tourist ferries. Eleven of the IMOS ship SST data streams (*RV Southern Surveyor, RV L'Astrolabe, RSV Aurora Australis, RV Solander, RV Tangaroa, PV Fantasea One, PV Spirit of Tasmania II, MV Portland, MV Highland Chief, MV Iron Yandi* and *PV Pacific Sun*) exhibited lower standard deviations than those from drifting and moored buoys (Table 2). The standard deviations of the AATSR SSTfnd observations used in the match-ups are shown in Table 2. These indicate that there is no correlation between the standard deviation in the AATSR SSTfnd – *in-situ* SSTfnd and variability of SST in the region covered by each vessel. There were significantly higher numbers of match-ups for the case of 'IMOS ships' (96266, excluding *PV SeaFlyte*) compared with 'non-IMOS ships' (7167) with similar warm biases compared with the AATSR SSTfnd (0.10°C cf 0.11°C) and 27% of the standard deviation (0.41°C cf 1.51°C).

The SST data streams from ships equipped with SBE 48 hull-contact sensors exhibited slightly higher average warm biases than drifting and moored buoys in relation to the AATSR SSTfnd (0.14°C cf 0.07°C) but lower standard deviation (0.37°C cf 0.44°C; Table 2). The relatively small warm bias indicates that thermal insulation and careful location of the hull-contact sensors are key to producing hull temperatures that are within around 0.1°C of the ocean temperatures measured by the AATSR under well-mixed ocean conditions.

The results of the comparison between SSTs from AATSR, ships and drifting and moored buoys are in general agreement with the finding that for equal numbers of observations, research-grade ship-borne subsurface temperature measurements provide better retrieval accuracy than those from operational data buoys.[17] The standard deviation of drifting and moored buoy SST observations has been estimated to be 0.23°C globally for 2003 through a three-way error analysis using AATSR and AMSR-E SST observations.[13] The finding that non-IMOS ship SST observations from the GTS have more than three times the standard deviation of buoy SST observations (1.51°C cf 0.44°C) also agrees with the results of an earlier study.[2]

All SST sensors on the IMOS vessels are recalibrated approximately every one to two years. The SBE 3 and SBE 38 sensors on *RV Southern Surveyor*, *RV L'Astrolabe*, *SRV Aurora Australis* and *PV SeaFlyte* are calibrated annually by CSIRO in their Hobart Calibration Facility to the International Temperature Scale of 1990 (ITS-90) using a Standard Platinum Resistance Thermometer (SPRT) and a controlled temperature bath to an uncertainty of 0.0015°C over the temperature range. The SBE 38 sensor on *RV Fantasea One* was calibrated by AIMS using a Fluke 1590 thermometer and a water bath. AIMS and the National Institute of Water and Atmospheric Research (NIWA) have not yet recalibrated their recently installed SBE 38 sensors on *RV Cape Ferguson*, *RV Solander* and *RV Tangaroa*. The SBE 48 hull-contact sensors deployed on AVOF vessels were recalibrated in 2011 by SeaBird using a Standard Platinum Resistance Thermometer to ITS-90. The calibrations indicated that the maximum drift over the period September 2007 to June 2011 was 0.002°C. This result agrees with the SBE 48 Hull Temperature Sensor Users Manual[5] which states that demonstrated drift is typically less than 0.002°C per year.

The next section illustrates that in waters with little or no coverage by buoys, validation of satellite SST products, analyses and forecasts can be improved by using IMOS ship SST observations in addition to available drifting or moored buoy SST data.

OPERATIONAL APPLICATIONS OF IMOS SHIP SST DATA

There are several potential operational applications for IMOS ship SST observations at the Australian Bureau of Meteorology. This section investigates three applications.

Validating satellite SST products

With support from IMOS, High Resolution Picture Transmission (HRPT) Advanced Very High Resolution Radiometer (AVHRR) SST products[10] from NOAA polar-orbiting satellites are produced operationally at the Bureau of Meteorology to provide input into operational optimum interpolation SST analyses and other systems. The AVHRR radiances were calibrated to SST using drifting buoy SST observations available from the GTS. The AVHRR thermal infrared bands are sensitive to the temperature in the top 20µm of the ocean surface (SSTskin), whereas the drifting buoys measure temperature at a depth of typically 20–30cm (SSTdepth). In the absence of any vertical mixing a temperature differential will exist. The calibration data set was therefore restricted to drifting buoy measurements obtained at wind speeds > 6ms^{-1} during the day and > 2ms^{-1} during the night.[14] In addition, a cool skin correction of –0.17°C was applied to the calibration to correct for the difference between the skin temperature and the drifting buoy SSTdepth measurements. The final AVHRR SST product is therefore an estimate of the skin SST.[10]

The IMOS ship SSTdepth observations were compared with the IMOS 1km resolution, HRPT AVHRR SSTskin as a validation of the AVHRR SST using an independent source of *in-situ* SST data not used in their calibration. For the comparison, the AVHRR SSTskin values were converted back to drifting buoy depths by adding 0.17°C. The AVHRR SSTdepth and the *in-situ* SSTdepth observations were then converted to foundation SST estimates by filtering out observations for NWP ACCESS-G[15] forecast 10m winds of < 6ms^{-1} during the day and < 2ms^{-1} during the night.[14] Table 3 gives the mean and standard deviation of IMOS night-time and daytime AVHRR SSTfnd (from NOAA-17, 18 and 19 satellites) minus SSTfnd data from 11 IMOS ships, at least 1632 non-IMOS ships and drifting buoys over the region 60°E to 190°E, 70°S to 20°N, during 1 December 2008 to 1 June 2011. The data were considered matched if within ± 2h, collocated within the same AVHRR pixel, absolute SST difference was <5°C and AVHRR SST quality level[10] was ≥ 4 (ie, cloud-free, acceptable to best quality data). The 5°C cut-off was chosen after an analysis of quality level ≥ 4 match-ups indicated that large AVHRR – buoy SST deviations were due to drifting buoy errors and not to AVHRR errors.

It can be seen from Figs 1, 5 and the NESDIS *in-situ* Quality Monitor (iQUAM) web site[(h)] that the IMOS ship SST observations cover a greater proportion of coastal waters than drifting and moored buoy SST observations reported on the GTS. Seven out of the 11 IMOS vessels studied exhibited lower standard deviations (and 10 within 0.04°C) when matched with night-time NOAA-19 HRPT AVHRR SST observations than observations from drifting buoys (Table 3(c)). In addition, it should be noted that match-ups between night-time SSTfnd from NOAA-17, 18 and 19 satellites with all six of the hull-contact sensor data streams exhibited standard deviations up to only 0.15°C higher than those from drifting buoys and biases within ±0.2°C (Table 3).

Daytime match-ups between AVHRR SSTfnd and the hull-contact sensor SSTfnd exhibited standard deviations up to 0.28°C higher than those from drifting buoys and biases within ±0.25°C (Table 3). The slight increase in relative standard deviations during daytime compared with night-time is more likely linked to increased uncertainty in HRPT AVHRR SSTs during daytime,[10] reflected in match-ups with drifting buoys, rather than any environmental effects on the ship-borne SST sensors. Interestingly, the SBE 48 SSTs were biased warmer during day compared with night when matched with NOAA-17 AVHRR SSTs (as were the drifting buoy SSTs), but colder when matched with NOAA-18 and NOAA-19 AVHRR SSTs (Table 3).

Match-ups between the AVHRR SSTfnd and Antarctic vessels (*RV L'Astrolabe* and *RSV Aurora Australis*) gave night-time biases within ±0.1°C (except for NOAA-17 match-ups with *RSV Aurora Australis*) and standard deviations ≤ 0.36°C, giving an independent validation of the HRPT AVHRR SST L2P data over the Southern Ocean and confidence in the AVHRR SST calibration method. At high

(a) NOAA-17	Night			Day		
In-Situ Data Stream	Number of Match-ups	Mean (°C)	Standard Deviation (°C)	Number of Match-ups	Mean (°C)	Standard Deviation (°C)
RV Southern Surveyor	66	–0.07	0.26	25	0.08	0.35
RV L'Astrolabe	26	0.03	0.27	19	0.00	0.44
RSV Aurora Australis	155	0.34	0.36	10	–0.34	0.35
RV Tangaroa	0	-	-	0	-	-
PV SeaFlyte	106	–0.66	0.86	127	–0.20	0.68
PV Spirit of Tasmania II	611	0.00	0.29	51	–0.18	0.53
MV Portland	87	0.07	0.34	19	–0.03	0.41
MV Highland Chief	94	–0.07	0.35	44	–0.20	0.44
MV Stadacona	272	–0.12	0.44	53	–0.25	0.43
MV Iron Yandi	64	–0.21	0.35	38	–0.30	0.48
PV Pacific Sun	1	-	-	1	-	-
IMOS Ships	1254	0.02	0.37	190	–0.18	0.51
Non-IMOS Ships	1280	–0.01	1.50	628	–0.21	1.55
Drifting Buoys	5174	0.02	0.30	2965	–0.05	0.44

(b) NOAA-18	Night			Day		
In-Situ Data Stream	Number of Match-ups	Mean (°C)	Standard Deviation (°C)	Number of Match-ups	Mean (°C)	Standard Deviation (°C)
RV Southern Surveyor	132	–0.02	0.24	51	0.11	0.35
RV L'Astrolabe	28	–0.03	0.22	33	0.14	0.35
RSV Aurora Australis	135	–0.03	0.26	49	0.06	0.38
RV Tangaroa	9	0.09	0.21	1	-	-
PV SeaFlyte	20	–0.20	0.71	94	–0.38	1.02
PV Spirit of Tasmania II	830	–0.01	0.29	107	0.02	0.58
MV Portland	153	0.12	0.36	66	0.12	0.45
MV Highland Chief	167	–0.03	0.34	62	0.05	0.46
MV Stadacona	388	0.03	0.42	132	0.03	0.48
MV Iron Yandi	102	–0.01	0.31	54	0.15	0.45
PV Pacific Sun	106	0.04	0.26	36	0.26	0.43
IMOS Ships	1858	0.02	0.33	452	0.03	0.52
Non-IMOS Ships	1440	–0.07	1.46	841	–0.41	1.53
Drifting Buoys	7528	0.05	0.31	5751	0.01	0.44

(c) NOAA-19	Night			Day		
In-Situ Data Stream	Number of Match-ups	Mean (°C)	Standard Deviation (°C)	Number of Match-ups	Mean (°C)	Standard Deviation (°C)
RV Southern Surveyor	121	–0.08	0.25	21	0.16	0.45
RV L'Astrolabe	23	0.06	0.34	8	–0.01	0.14
RSV Aurora Australis	55	0.05	0.28	28	–0.12	0.22
RV Tangaroa	9	–0.16	0.32	3	0.02	0.30
PV SeaFlyte	4	–0.46	1.27	28	–0.96	1.35
PV Spirit of Tasmania II	755	–0.07	0.26	82	0.00	0.31
MV Portland	144	0.08	0.32	76	0.17	0.41
MV Highland Chief	169	–0.09	0.37	77	0.04	0.58
MV Stadacona	341	–0.07	0.37	139	–0.04	0.40
MV Iron Yandi	112	–0.04	0.39	55	0.16	0.48
PV Pacific Sun	89	–0.12	0.27	26	0.13	0.69
IMOS Ships	1656	–0.04	0.32	399	0.02	0.42
Non-IMOS Ships	1246	–0.24	1.48	720	–0.40	1.51
Drifting Buoys	7342	–0.02	0.35	5430	–0.01	0.41

Table 3: Mean and standard deviation of night-time (left) and daytime (right) satellite observations of 1km resolution HRPT AVHRR L2P SSTfnd (for quality level ≥ 4) from (a) NOAA-17, (b) NOAA-18 and (c) NOAA-19 minus collocated observations of SSTfnd from 11 IMOS and at least 1632 non-IMOS ships or drifting buoys over the region 60°E – 190°E, 70°S – 20°N for the period 1 December 2008 to 1 June 2011. Observations were considered 'matched' if measured within ± 2h and within the same pixel. Match-ups with either buoys or ships were rejected if the absolute difference in SST exceeded 5°C and daytime 10m winds were < 6ms^{-1} or night-time 10m winds were < 2ms^{-1}. Note that 'IMOS Ships' corresponds to all the ships listed in this table except PV SeaFlyte

southern latitudes the drifting buoy observations used to calibrate the AVHRR radiances were weighted by a factor of 10 to ensure that the numerically dominant matches from mid-latitudes did not skew the errors at extreme southern latitudes. This gave a very slight overall error in the fit (0.01°C), but much better bias results at southern latitudes (0.1°C).

To illustrate the usefulness of the IMOS ship SST data over Australian coastal regions where there are few SST observations from drifting and moored buoys (Fig 1), the IMOS HRPT AVHRR SSTdepth from NOAA-17, 18 and 19 (Fig 6(a)) were compared against the IMOS ship SSTfnd over a region including Bass Strait (143°E to 149°E, 37°S to 42°S) during 21 September 2010 (Fig 7(a)). Over this region and time period the AVHRR SSTdepth observations were between 0 and 0.4°C cooler than the individual IMOS ship SSTfnd observations.

Validating regional SST analyses

The IMOS ship SST observations from the first 13 vessels listed in Table 1 were compared against the Bureau's operational, 1/12° resolution, daily foundation SST (SSTfnd) analysis, RAMSSA.[11] Table 4 gives the mean and standard deviation of RAMSSA SSTfnd minus SSTfnd data from IMOS ships or drifting and moored buoys for the subsequent UTC date over the region 60°E to 190°E, 70°S to 20°N, during 1 August to 31 December 2010. The data were considered matched if collocated within the same 1/12° x 1/12° pixel and the *in-situ* observations were from the next UTC calendar date to the RAMSSA analysis. *In-situ* observations from the day after the RAMSSA analysis were chosen for the study to ensure a mostly independent validation data set since both ship and buoy observations are ingested into the RAMSSA analysis system which ingests satellite and *in-situ* SST data over one UTC 24h day. The *in-situ* observations were converted to an approximate foundation SST using the method described in the previous section. Match-ups were rejected if the absolute SST difference was > 20°C.

During the study period RAMSSA SSTfnd analyses agreed slightly less closely with drifting and moored buoy SSTfnd observations than with IMOS ship SSTfnd observations (0.09 ± 0.55°C, N = 159415, compared with –0.03 ± 0.51°C, N = 5884) (Table 4). This is interesting since the proportion of IMOS ship SST observations that are in coastal regions is much greater than for drifting and moored buoys.[h] The implication is that in coastal regions RAMSSA performs with at least comparable accuracy to non-coastal regions.

The individual match-up differences are shown in Fig 8. South of 45°S, the reduction in match-up differences of the ship SSTfnd compared with buoy SSTfnd is very marked, and illustrates the value of using ship SST from the GTS for validating SST analyses over the Southern Ocean since vessels providing SST to the GTS over this region are almost invariably research

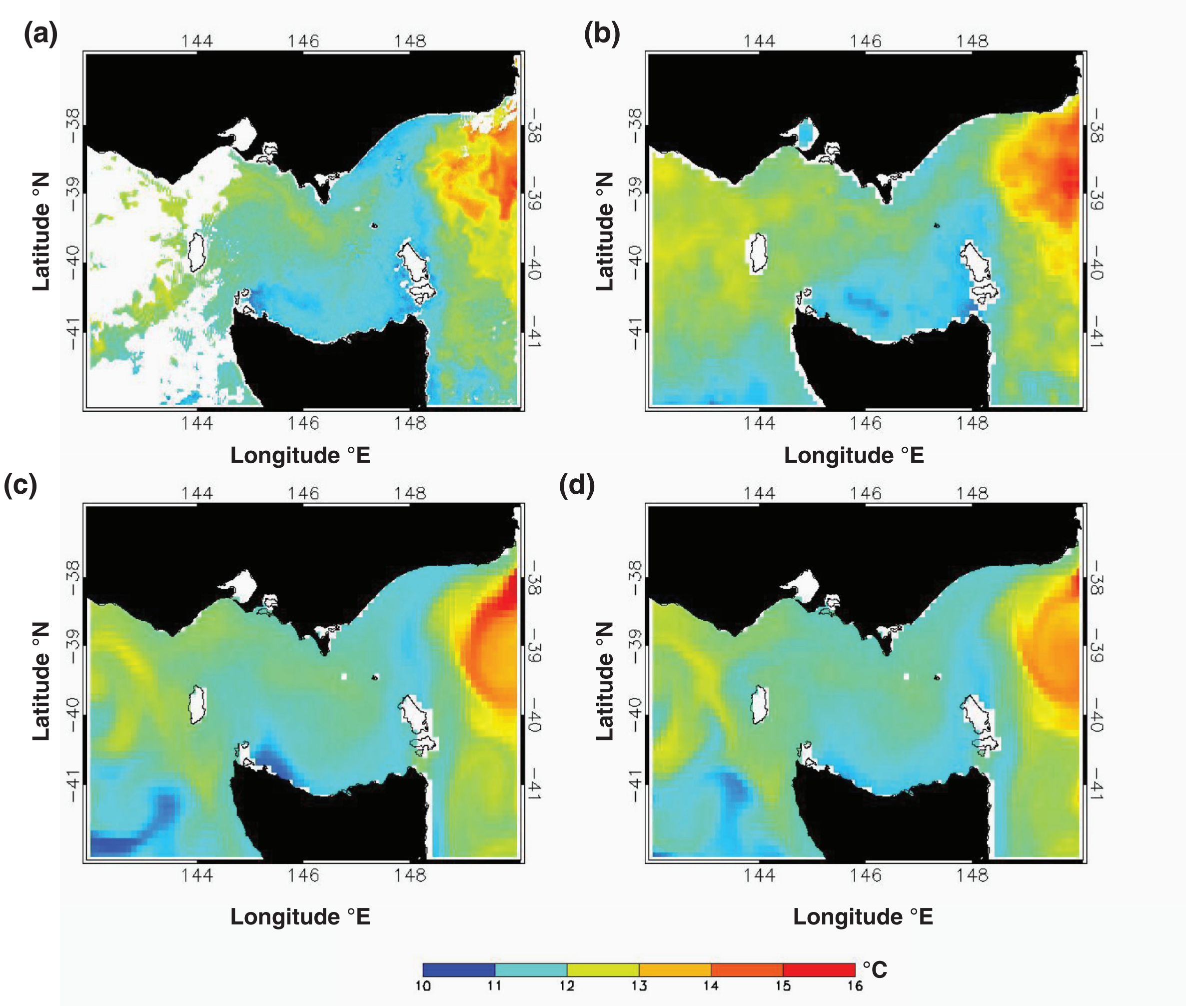

Fig 6: (a) IMOS HRPT AVHRR L2P SSTskin (from NOAA-17, -18 and -19), (b) RAMSSA Daily Analysis SSTfnd, (c) OceanMAPS Daily Analysis SST5m and (d) OceanMAPS 24h Forecast SST5m values plotted over the region 143°E to 149°E, 42°S to 37°S, for 21 September 2010

vessels. The increased variation in RAMSSA SSTfnd - buoy SSTfnd south of 45°S compared with north of this latitude is puzzling. Similar patterns of anomalously large standard deviations between various global SST analysis and drifting buoy SST over the region 40°S to 50°S are observed in Hovmoller diagrams obtained from the NESDIS SST Quality Monitor (SQUAM) web site.[i] The issue of what is the cause of the relatively high standard deviation in optimally interpolated analyses of satellite SST over the Southern Ocean warrants further investigation but is outside the scope of this paper.

The RAMSSA SSTfnd analyses (Fig 6(b)) were also compared against the IMOS ship SSTfnd over the Bass Strait region for 21 September 2010 (Fig 7(b)). Over this region and time period the RAMSSA SSTfnd values were between 0 and 0.4°C cooler than the IMOS ship SSTfnd observations. It is important to validate RAMSSA in Australian coastal regions not merely to give greater confidence to the boundary condition used for Australian Numerical Weather Prediction models in the vicinity of major coastal population centres, but also because RAMSSA has been used for several years to validate the Bureau's operational ocean general circulation model.

Validating regional ocean general circulation models

The Bureau's operational ocean prediction system (OceanMAPS)[18] is performed twice-weekly with 1/10° resolution in the Australian region, 90°E – 180°E, 75°S – 16°N.

	(a) IMOS Ship SSTfnd			(b) Buoy SSTfnd		
Analysis	Number of Match-ups	Mean (°C)	Standard Deviation (°C)	Number of Match-ups	Mean (°C)	Standard Deviation (°C)
RAMSSA SSTfnd	5884	–0.03	0.51	159415	0.09	0.55

Table 4: Mean, standard deviation and number of match-ups of the 1/12° resolution, daily RAMSSA SSTfnd analyses minus collocated observations of SSTfnd from (a) IMOS ships or (b) drifting and moored buoys over the region 60°E – 190°E, 70°S – 20°N for the period 1 August to 31 December 2010. Observations were considered 'matched' with RAMSSA for a particular UTC date if measured within the same analysis pixel and the next UTC date and absolute SST difference was < 20°C. 'IMOS Ship SSTfnd' refers to data from the first 13 vessels listed in Table 1

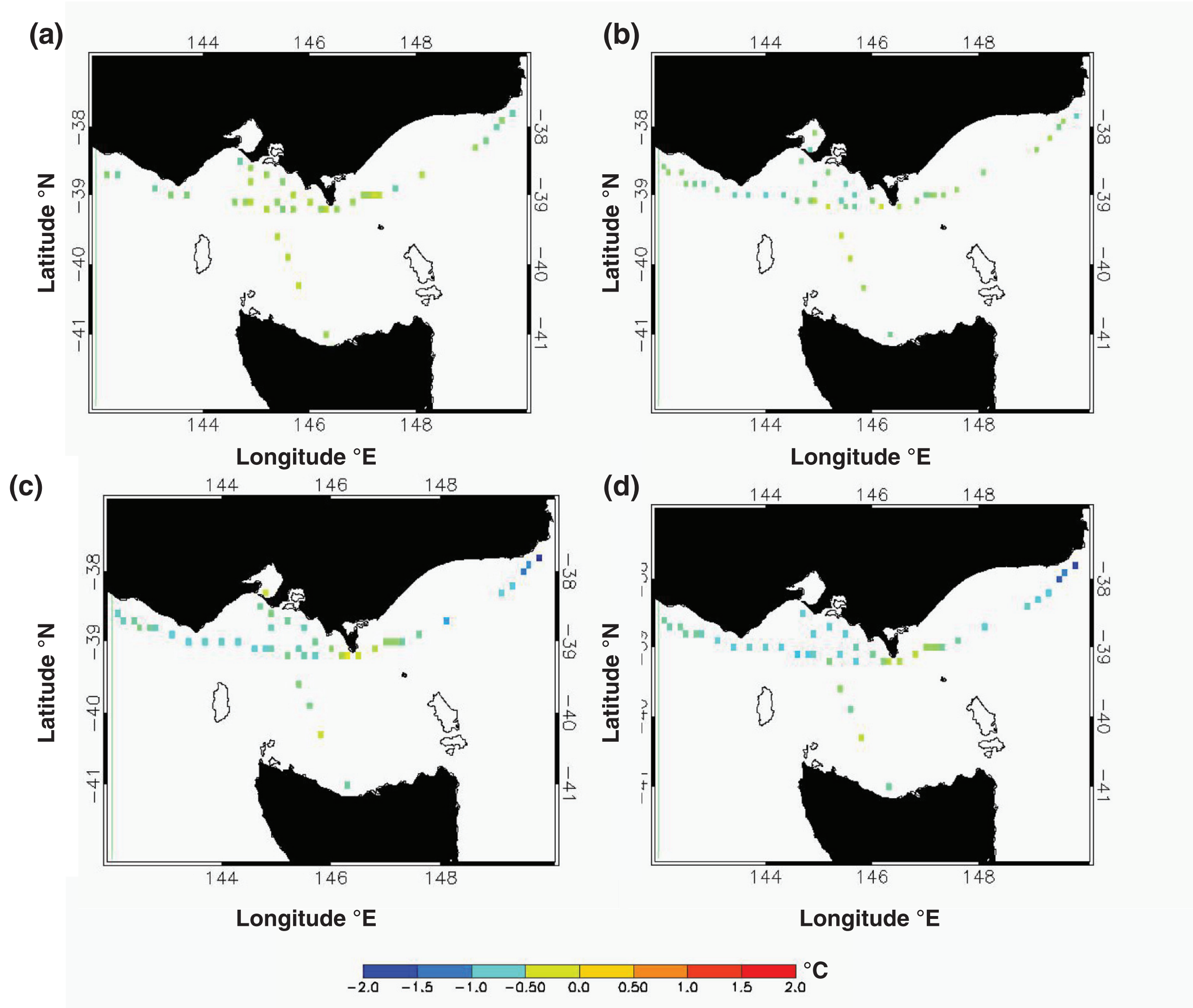

Fig 7: (a) IMOS HRPT AVHRR L2P SSTfnd (from NOAA-17, -18 and -19), (b) Daily Analyis RAMSSA SSTfnd, (c) OceanMAPS Daily Analysis SST5m and (d) OceanMAPS 24h Forecast SST5m minus IMOS Ship SSTfnd plotted over the region 143°E to 149°E, 42°S to 37°S, for 21 September 2010. Note that both the HRPT AVHRR L2P SSTfnd and IMOS ship SSTfnd for the 24h UTC day are ingested into the daily RAMSSA SSTfnd analysis

	(a) IMOS Ship SSTfnd			(b) Buoy SSTfnd		
Analysis	Number of Match-ups	Mean (°C)	Standard Deviation (°C)	Number of Match-ups	Mean (°C)	Standard Deviation (°C)
BODAS Analysis SST5m	1602	–0.16	0.70	25104	0.15	0.60

Table 5: Mean, standard deviation and number of match-ups of the 1/10° resolution, twice-weekly BODAS1 SST5m analyses minus collocated observations of SSTfnd from (a) IMOS ships or (b) drifting and moored buoys over the region 90°E – 180°E, 70°S – 15°N for the period 1 August to 31 December 2010. Observations were considered 'matched' with BODAS1 for a particular UTC date if measured within the same analysis pixel and UTC date and absolute SST difference was < 20°C. 'IMOS Ship SSTfnd' refers to the first 13 vessels listed in Table 1

The data assimilation is performed using version 1 of the BLUElink Ocean Data Assimilation System (BODAS1)[19] which is a multi-variate, ensemble optimal interpolation scheme. OceanMAPS uses the BLUElink Ocean Forecasting Australia Model (OFAM) which is an implementation of the Geophysical Fluid Dynamics Laboratory, Modular Ocean Model 4p0d[20] and has a top model cell of depth 10m, centred at 5m. Table 5 gives the mean and standard deviation of BODAS1 Analysis 5m depth SST (SST5m) minus SSTfnd data from IMOS ships or drifting and moored buoys over the region 90°E to 180°E, 70°S to 15°N, during 1 August to 31 December 2010. The data were considered matched if collocated within the same 1/10° x 1/10° pixel and the same UTC calendar date. Neither ship nor buoy SST observations are assimilated into BODAS. Match-ups were rejected if the absolute SST difference was > 20°C. Only the first 13 vessels listed in Table 1 were included in the comparison.

During the study period BODAS1 SST5m analyses agreed more closely with buoy SSTfnd than with IMOS ship SSTfnd observations (0.15 ± 0.60°C, N = 25104, compared with –0.16 ± 0.70°C, N = 1602) (Table 5). It would therefore appear that unlike RAMSSA (Table 4), BODAS1 is on aver-

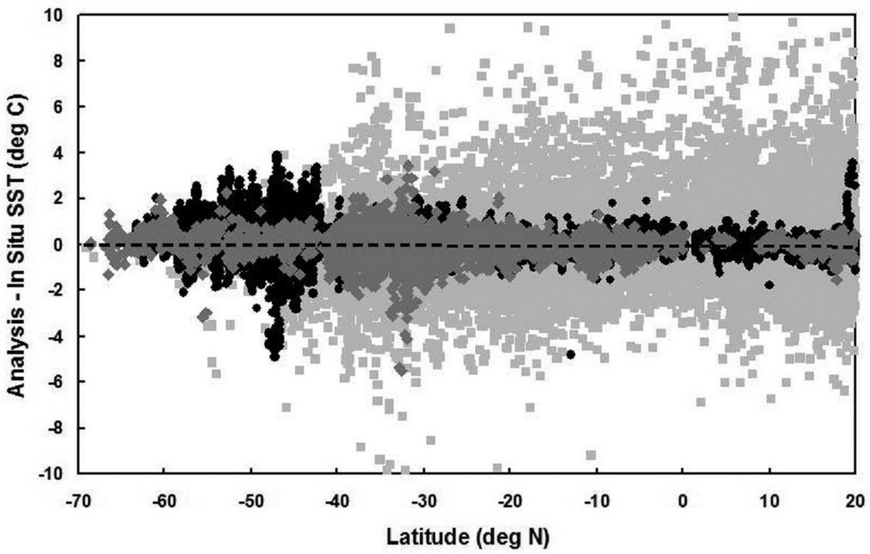

Fig 8: Match-ups of the 1/12° resolution, daily RAMSSA SSTfnd analyses minus collocated observations of SSTfnd from non-IMOS ships (light grey squares), IMOS ships (dark grey diamonds) and drifting and moored buoys (black circles) over the region 60°E – 190°E, 70°S – 20°N for the period 1 August to 31 December 2010. Observations were considered 'matched' with RAMSSA for a particular UTC date if measured within the same analysis pixel and the **next** UTC date and absolute SST difference was < 20°C. 'IMOS ships' refers to the first 13 vessels listed in Table 1

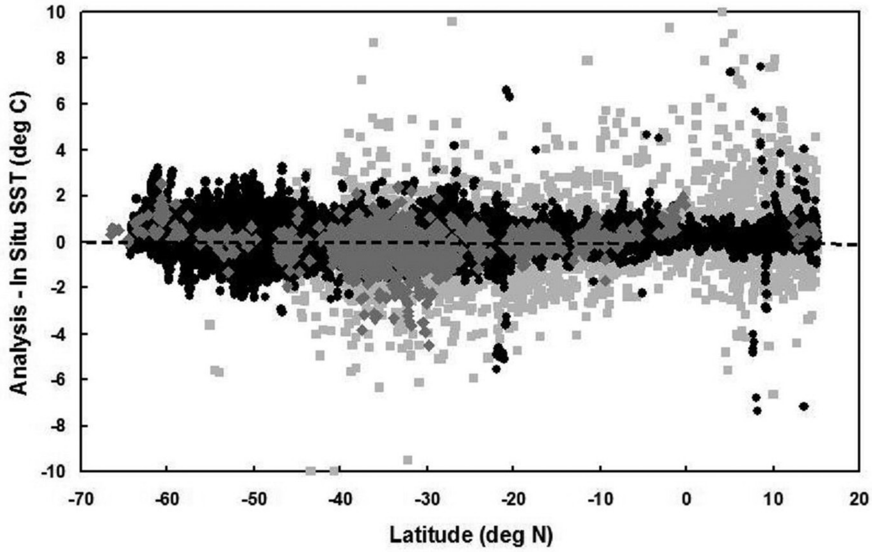

Fig 9: Match-ups of the 1/10° resolution, twice-weekly, BODAS1 SST5m analyses minus collocated observations of SSTfnd from non-IMOS ships (light grey squares), IMOS ships (dark grey diamonds) and drifting and moored buoys (black circles) over the region 90°E – 180°E, 70°S – 15°N for the period 1 August to 31 December 2010. Observations were considered 'matched' with BODAS1 for a particular UTC date if measured within the same analysis pixel and same UTC date and absolute SST difference was < 20°C. 'IMOS ships' refers to the first 13 vessels listed in Table 1

age colder in coastal regions (where IMOS ship observations dominate) than over the open ocean (where buoy observations dominate over those from IMOS ships).

The individual match-up differences are presented in Fig 9 which indicates that the greatest variation between BODAS1 SST5m and IMOS ship SSTfnd were seen between 30°S and 40°S. A plot of BODAS1 SST5m minus *in-situ* SSTfnd versus longitude (not shown) indicates that the greatest differences of BODAS1 SST5m and both IMOS ship SSTfnd and buoy SSTfnd were observed between 150°E and 160°E, indicating the greatest observed variation of BODAS1 SST5m compared with *in-situ* SSTfnd was within the East Australian Current, a region experiencing high dynamical instability.

The forecast cycle of OceanMAPS initialises each analysis field into the ocean model background using a 24h linear relaxation which is then integrated forward forced by operational NWP surface forcing to produce a 7 day forecast. As an example of the application of IMOS ship SST to ocean model verification, the OceanMAPS daily SST5m analysis (Fig 6(c)) and OceanMAPS SST5m 24h forecast (Fig 6(d)) were compared against IMOS ship SSTfnd over the Bass Strait region for 21 September 2010 (Figs 7(c) and 7(d)). Both the analysis and 24h forecast SST5m values were between 0 and 0.4°C cooler than the IMOS ship SSTfnd observations except in the vicinity of 149°E and 38°S where OceanMAPS SST5m analysis and forecast were up to 2°C cooler than the ship SSTfnd observations due to the slight southern offset of the Eastern Bass Strait (~149°E, 39°S) warm eddy in the OceanMAPS general circulation model (Fig 6). This highlights the usefulness of the IMOS ship SST observations to validate the location of eddies and fronts, particularly in ocean models. In ocean regions obscured by cloud, there are no recent SST observations from satellite infra-red radiometers (with spatial resolution ~ 1km), and ocean analyses such as BODAS1 in cloudy conditions are dependent on SST observations from satellite microwave sensors (with spatial resolution ~ 25km) for up-to-date SST observations.

CONCLUSIONS

During February 2008 to January 2012, as part of the IMOS project, new streams of quality assured, near real-time, SST observations from 15 vessels in the Australian region have become available on the GTS and the IMOS ocean portal.[c] Before June 2012, SST data from CSIRO's *RV Linnaeus* will be added to the project.

Comparisons between AATSR, drifting and moored buoy and IMOS ship SST observations indicate that 12 of the IMOS ship data streams, including all those from hull-contact temperature sensors, have comparable uncertainties to drifting and moored buoys, with standard deviations within ±0.06°C and biases generally within ±0.1°C to those obtained using buoys. Exceptions were the fast tourist ferries *PV SeaFlyte* and *PV Fantasea One*, installed with calibrated thermistors in engine water intakes, possibly due to a combination of the predominantly daytime cruises and warming by the engine of the water being sampled.

The SST data streams from SBE 48 hull-contact sensors installed on six commercial vessels exhibited overall lower standard deviations when matched with AATSR SST (0.37°C) compared with drifting and moored buoy SST match-ups with AATSR SST in the same region (0.44°C) but slightly higher warm bias (0.14°C cf 0.07°C). The SBE 48 SST data from the six AVOF vessels had a quarter of the standard deviation of non-IMOS ship SSTs over the same region reported to the GTS (0.37°C cf 1.51°C). Night-time comparisons between AVHRR, drifting buoy and IMOS ship SST observations also indicated that the standard deviation of the match-ups with hull-contact sensor SSTs were within 0.15°C of those from drifting buoys and the biases within ±0.2°C. Hull-contact temperature sensors have therefore been demonstrated to be capable of producing validation-quality SST data, provided that one obtains a good thermal contact with the hull, locate the sensor away from on-ship heat sources, and thermally insulate the sensor and surrounding hull to a distance of at least 0.5m from the sensor.

Moored and drifting data buoy SST observations are commonly used to calibrate, validate and bias-correct satellite SST observations.[1,17] In waters with little or no coverage by buoys, it is therefore expected that satellite SST validation and bias-correction, and the validation of operational SST analyses and ocean forecasts, will be improved by using IMOS ship SST observations in addition to available buoy SST data.

Future work will include using the IMOS ship SST data to validate the IMOS HRPT AVHRR SST products at high southern latitudes and over the Western Pacific Tropical Warm Pool where buoy SST observations are very scarce. Another application may be to use the IMOS ship SST in conjunction with buoy SST to assess the new version 2 of BODAS compared with BODAS1 (reported in this paper).

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