

Article

Comparison of Himawari-8 AHI SST with Shipboard Skin SST Measurements in the Australian Region

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Abstract: Sea surface temperature (SST) measurements from the geostationary satellite Himawari-8 Advanced Himawari Imager (AHI) are compared with in situ skin SSTs derived from shipboard Infrared SST Autonomous Radiometers (ISAR) in the Australian region. The mean bias and standard deviation of the differences between Himawari-8 AHI and ISAR skin SST of best quality are 0.09 K and 0.30 K, with total matchups numbering 2701. Shipboard bulk SST measurements at depths between around 7.1 and 9.9 meters are compared with the matchups in a case study. Analyses show significant differences between skin and bulk SST measurements of maximum value 2.23 K under conditions of high diurnal warming. The results also demonstrate that Himawari-8 AHI skin SST with high temporal resolution has the ability to accurately measure diurnal warming events.

Keywords: sea surface temperature; ISAR; Himawari-8; Australian region; validation

1. Introduction

Sea surface temperature (SST) is used as a key variable in numerical weather prediction and in global climate modeling. Satellite-derived SSTs cover large areas and worldwide SST products have been created. The geostationary satellite has several important advantages over the polar orbiter for monitoring SST variability, such as high temporal resolution [1]. The first Geostationary Operational Environmental Satellite (GOES) was launched by the National Aeronautics and Space Administration (NASA) in October 1975 and since then there have been many more meteorological satellites in geostationary orbit. The first Japanese Geostationary Meteorological Satellite (GMS-1, aka Himawari-1) was launched by the Japan Meteorological Agency (JMA) in 1977 and was followed by five GMS units by 2003 [2]. The Stretched-Visible Infrared Spin Scan Radiometer (S-VISSR) onboard GMS-5 (Himawari-5) provided SST estimation with a root mean square (RMS) error of 0.8 K [3]. The Multi-Functional Transport SATellite (MTSAT) series had two satellites MTSAT-1R (Himawari-6) and MTSAT-2 (Himawari-7), which were in operation from 2005 to 2010 and 2010 to 2015 [2]. The SST from the MTSAT-2 imager showed a bias of 0.26 K and a standard deviation of 0.48 K compared with subsurface in situ temperature measurements in the Tropical Western Pacific Ocean from August to October 2015 [4].

A successor to MTSAT-2, the new generation Japanese geostationary satellite, Himawari-8, was launched on 7 October 2014 and its geostationary position is on the equator at 140.7°E. Himawari-8 began operational use on 7 July 2015 and was designed for a meteorological mission of 8 years or longer [5]. The Advanced Himawari Imager (AHI) on board Himawari-8 provides full disk images with 10-min sampling frequency in 16 spectral bands with 2 km spatial resolution for IR channels at nadir. The Japan Aerospace Exploration Agency (JAXA) provides Himawari-8 AHI skin SST products (at around 10 μm depth) calculated in near real time from 10.4, 11.2, and 8.6 μm radiances [6], to seek synergies with Japan Aerospace Exploration Agency (JAXA)'s Low Earth Orbiting IR imagers, such as the Second-Generation Global Imager (SGLI) onboard the Global Change Observation Mission-Climate (GCOM-C). The SST were calculated using a new quasi-physical SST algorithm, which derives skin SST by a parameterized IR radiative transfer equation [5]. The NOAA Center for Satellite Applications and Research (STAR) also provides Himawari-8 AHI SST products using NOAA's Advanced Clear-Sky Processor for Oceans (ACSPo) [7], and the Australian Bureau of Meteorology produces various Himawari-8 AHI SST products [8] for Australian applications.

Satellite SST used in Climate Data Records (CDRs) needs to be validated using in situ SST measurements with high accuracy that are traceable to the International System of Units (SI) [9]. JAXA Himawari-8 AHI skin SST products were compared with drifting and tropical moored buoy data. Results showed a root mean square difference (RMSD) of 0.59 K and a bias of -0.16 K [5]. The NOAA ACSPo Himawari-8 SST product was validated against in situ data in the NOAA SST Quality Monitor (SQUAM, <https://www.star.nesdis.noaa.gov/sod/sst/squam>). The validation statistics against drifters and tropical moorings showed a bias within ± 0.2 K and standard deviation within 0.4–0.6 K from June to September 2015 [7]. The NOAA ACSPo Himawari-8 AHI SSTs have been validated using comparisons with in situ measurements from the Triangle Trans-Ocean Buoy Network (TRITON) moored buoys in the Tropical Atmosphere Ocean (TAO) array and from the self-recording thermometers at the depths of corals over the Great Barrier Reef (GBR) [4]. The results were discussed under various conditions of wind speed and diurnal heating. The data showed that NOAA ACSPo Himawari-8 AHI had an average SST difference of 0.18 K with a standard deviation of 0.53 K and an average median of 0.16 K from August to October 2015 [4].

The validation results above were compared using in situ bulk SST measurements. Both the buoys and temperature loggers measure SST at different depths. Due to the vertical distribution of SST [10], this will introduce discrepancies compared to satellite-derived skin SST. Using well-calibrated shipboard radiometers to validate satellite SST is the basis for generating the CDRs of SST [9]. Shipboard infrared radiometers provide the potential to obtain a matched set of in situ and coincident satellite skin SST data that can be used to validate the JAXA Himawari-8 AHI skin SST. The uncertainty introduced from matching satellite IR skin SST with the different depths sampled by conventional in situ SST sensors can be completely eliminated [11]. In October 2014, an infrared SST autonomous radiometer (ISAR) Model 5D was installed on the Australian Marine National Facility research vessel (RV), RV Investigator, by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), and has operated on most cruises of this vessel up to the present, covering seas around the Australian coast and south to Antarctica (<http://mnf.csiro.au/Voyages/Investigator-schedules/Plans-and-summaries.aspx>). The ISAR was developed by the University of Southampton (<http://www.isar.org.uk>). It is a self-calibrating instrument and was designed for in situ skin SST measurements with an accuracy of around 0.1 K [12]. The ISAR has an infrared wavelength range from 9.6 to 11.5 μm to obtain both the sea surface radiance and the downwelling atmosphere radiance, which are calibrated by two internal reference blackbody cavities. Both of the blackbody cavities have an emissivity of >0.999 in the spectral range of the ISAR. One cavity remains at an ambient temperature, while the other one is heated and maintained at about 12 K higher. The temperature of the two blackbody cavities are monitored by internal thermistors. Radiances from the sea surface and atmosphere are self-calibrated using the linear relationship between the voltage output of the radiometer and integrated incoming radiance [12]. Considering the ship

structure and wake characteristics, the ISAR is mounted on the port bridge wing, approximately 19 meters above the summer load line, with sky and sea view angles of 25° and 155° from nadir [13].

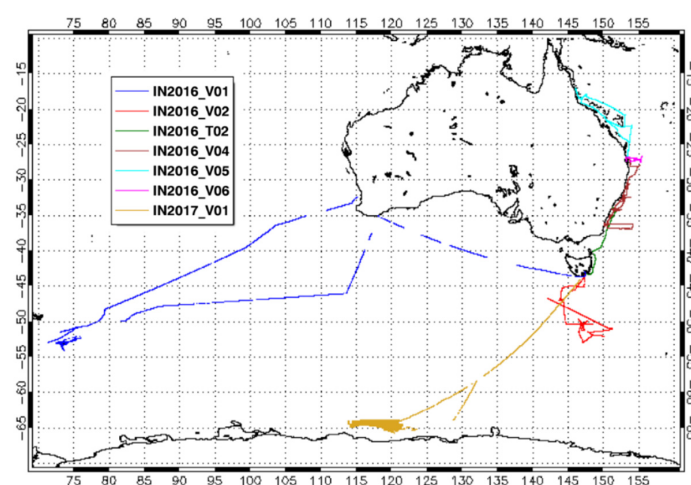
In this paper, we compare JAXA Himawari-8 AHI skin SST with collocated ISAR skin SST measurements over seven cruises of the RV Investigator. The next section introduces the matchup data and validation method. Section 3 presents the results of the comparison and Section 4 discusses the results. Finally, Section 5 provides a brief conclusion, which indicates future work.

2. Materials and Methods

ISAR skin SST measurements from seven cruises of the RV Investigator are used for the comparison with JAXA Himawari-8 AHI skin SST products. The cruise data, including meteorological and bulk SST observations, are provided by the Integrated Marine Observing System (IMOS), ranging from January 2016 to March 2017 [14]. The seven cruises cover the area in the southwest, south and east coast near Australia, including the GBR off the coast of Queensland, Australia. Details of the seven voyage datasets are given in Table 1. The cruise tracks and SST measurements are shown in Figure 1a,b. The main trend in the measurements is that SST becomes cooler as the latitude becomes higher. Before and after each cruise, the ISAR radiometer is calibrated by CASOTS II, the National Oceanographic Centre Southampton's manufactured blackbody [12], while immersed in a water bath controlled with a reference Hart Scientific platinum resistance thermometer [15]. The ISAR is maintained between cruises by replacing the reflecting mirror when necessary, depending on the calibration results and radiometer performance.

Table 1. Details of the research vessel (RV) Investigator's Infrared sea surface temperature (SST) Autonomous Radiometer (ISAR) cruises.

Voyage No.	Time Range	ISAR Skin SST Range	Longitude Range	Latitude Range
IN2016_V01	1.08–2.26, 2016	275.18 K–296.13 K	71°E – 148°E	-55°S – -32°S
IN2016_V02	3.14–4.15, 2016	280.18 K–293.19 K	141°E – 152°E	-53°S – -42°S
IN2016_T02	8.25–8.28, 2016	282.34 K–293.31 K	147°E – 152°E	-44°S – -33°S
IN2016_V04	8.31–9.22, 2016	288.47 K–296.79 K	150°E – 156°E	-38°S – -26°S
IN2016_V05	9.27–10.24, 2016	293.53 K–302.08 K	145°E – 155°E	-28°S – -16°S
IN2016_V06	10.28–11.12, 2016	294.96 K–298.68 K	153°E – 156°E	-28°S – -21°S
IN2017_V01	1.14–3.01, 2017	271.45 K–288.31 K	113°E – 148°E	-66°S – -43°S



(a)

Figure 1. Cont.

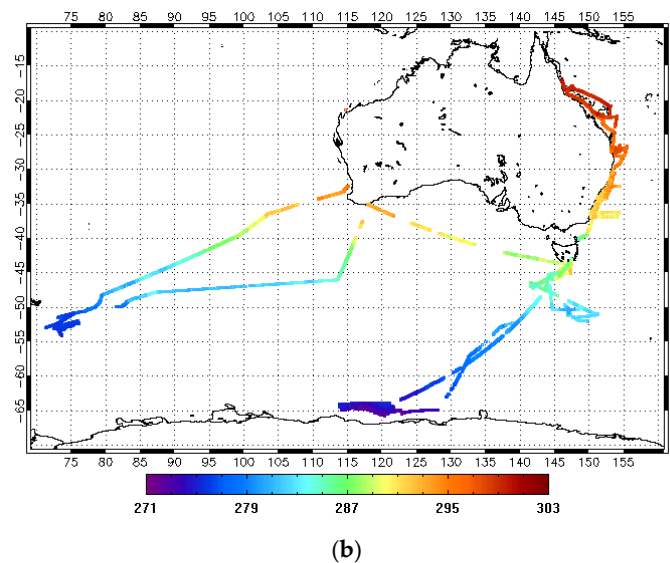


Figure 1. (a) The RV Investigator ISAR cruise tracks included in this study; (b) cruise tracks with ISAR skin SST measurements (K).

In order to conform to metrological standards, an ISAR skin SST uncertainty model is used to estimate a quality indicator for each skin SST measurement [16], using the version 3.1 uncertainty code developed by Werenfrid Wimmer (University of Southampton). In the uncertainty model, all sources contributing to the uncertainty of each measurement were analyzed and a total expanded uncertainty was assigned to each ISAR SST measurement. The total expanded uncertainty estimate is a combination of random (type A), systematic (type B), instrument and measurement uncertainty (including the uncertainty of the CASOTS II blackbody, set at 0.05 K), and varies with the roll of the ship and the internal ISAR temperature [17]. The ISAR total uncertainty corresponds to an estimate of the SST that differs from its true value by less than the stated uncertainty in 95% of cases, and in this case can be considered as about two times the standard deviation (SD) of the measurement [16]. In addition to the IMOS format ISAR_QC files used in this study [14], all reprocessed and quality-controlled measurements from the RV Investigator ISAR back to 2014 are also provided in the International SST Fiducial Reference Measurement Radiometer Network “L2R” data format [18] from Commonwealth Scientific and Industrial Research Organization (CSIRO)’s Marlin Data Portal [19]. These ISAR L2R files contain a variable named “quality_level” (QL) which is derived from the total expanded uncertainty estimate (variable “TEMP_2_SD” in the IMOS ISAR_QC files) as follows: QL = 0 to 2 corresponds to uncertainty >0.2 K, QL = 4 corresponds to $0.1 \text{ K} < \text{uncertainty} \leq 0.2 \text{ K}$, and QL = 5 (best) corresponds to uncertainty $\leq 0.1 \text{ K}$ [16]. The RV Investigator CSIRO ISAR temperature readings were compared with a National Physical Laboratory reference blackbody in laboratory tests during June 2016 and exhibited relatively low biases ($<0.15 \text{ K}$) over normal operating temperatures [20].

JAXA provides Himawari-8 AHI skin SST products, which are available at the JAXA Himawari Monitor P-Tree System [6]. Himawari-8 AHI skin SST used in this validation are JAXA Level 2 products. The Himawari-8 AHI skin SST products are extracted within the region covered by the RV Investigator ISAR cruises and remapped by the nearest neighbor method with a 0.02° equal angle projection. In the JAXA Himawari-8 files, each SST value has an associated quality level (QL), based on cloud probability calculated using satellite data, ancillary data and empirically generated probability density functions for those data [5]. We use the Himawari-8 AHI data with the highest quality level of five in the validation.

A temporal window of 5 minutes and spatial window of 0.02° are used to select the matchup data. All ISAR skin SST measurements located in the same satellite 0.02° grid cell are averaged, then matched with quality level five Himawari-8 AHI skin SST data.

Sea Bird SBE 38 (<https://www.seabird.com>) is a water injection temperature sensor deployed on the RV Investigator and is located in the thermosalinograph water intake pipe within the drop keel. The SBE 38 measures SST at depths of around 7.1–9.9 meters below the vessel's summer load line, depending on the position of the drop keel during each voyage. The SBE 38 sensor is calibrated on an annual basis over the range -1.5 – 32 °C by the CSIRO Oceanographic Calibration Facility and, in September 2017, had a calibration uncertainty of around 0.002 K. SBE 38 bulk SST measurements are compared with both ISAR and Himawari-8 AHI skin SST for a case study. SBE 38 SST are included with the IMOS meteorological data and reprocessed ISAR data from the RV Investigator [13], available from the "ISAR_QC" sub-directories of the Australian Ocean Data Network THREDDS server [14]. The temporal resolution of the ISAR data is ~2.5 minutes and is reported to the closest minute in the IMOS ISAR_QC files [14]. The ship's wind speed data, measured from sensors ~25 m above the summer load line, from the meteorological dataset [14] are also used in the analysis.

3. Results

Statistics are derived from the matchup data. We calculated the number (N), mean, median, standard deviation (SD), robust standard deviation (RSD), maximum (Max), minimum (Min) and the percentage within 0.3 K ($P(\pm 0.3K)$) and 0.5 K ($P(\pm 0.5K)$) of the SST difference (Himawari-8 AHI skin SST–ISAR skin SST) for the matchups. Himawari-8 SST, from matchups where any of the surrounding 7×7 grid cells have invalid data, are removed to reduce the influence of cloud detection failure at the edge of the cloud. Table 2 shows the statistics of the SST difference in the matchup data for each RV Investigator cruise studied. The upper rows in Table 2 correspond to all matchups, and the lower rows correspond to matchups centered in the 7×7 grid cloud-free cells.

Table 2. Statistics of the SST difference of the matchups for each cruise (number of matchups (N); standard deviation (SD) and robust standard deviation (RSD); maximum (Max) and minimum (Min) values; $P(\pm 0.3K)$ and $P(\pm 0.5K)$ are the percentages within 0.3 K and 0.5 K, which are the matchups.).

Voyage No.		N	Mean (K)	Median (K)	SD (K)	RSD (K)	Max (K)	Min (K)	P ($\pm 0.3K$)	P ($\pm 0.5K$)
IN2016_V01	all	246	−0.50	−0.47	0.77	0.67	1.30	−2.80	26%	42%
	7×7	46	−0.27	−0.23	0.47	0.40	1.13	−1.18	46%	61%
IN2016_V02	all	907	−0.67	−0.53	0.59	0.47	0.59	−3.21	27%	48%
	7×7	181	−0.31	−0.30	0.25	0.22	0.31	−1.10	50%	78%
IN2016_T02	all	376	−0.01	0.04	0.40	0.36	0.87	−1.71	58%	83%
	7×7	155	0.14	0.20	0.30	0.31	0.61	−1.39	60%	91%
IN2016_V04	all	1850	−0.01	0.01	0.46	0.35	4.58	−2.01	60%	80%
	7×7	977	0.05	0.04	0.34	0.30	1.63	−1.52	69%	89%
IN2016_V05	all	2830	0.05	0.06	0.40	0.30	3.77	−1.66	65%	84%
	7×7	1263	0.08	0.08	0.27	0.24	1.13	−1.32	75%	92%
IN2016_V06	all	1282	0.08	0.11	0.39	0.32	1.90	−1.69	58%	83%
	7×7	718	0.19	0.20	0.26	0.25	0.83	−0.93	60%	89%
IN2017_V01	all	315	−0.64	−0.53	0.51	0.41	1.45	−2.35	23%	47%
	7×7	34	−0.41	−0.39	0.54	0.23	1.45	−1.74	32%	62%
Total	all	7806	−0.09	−0.02	0.53	0.40	4.58	−3.21	55%	76%
	7×7	3374	0.07	0.08	0.32	0.28	1.63	−1.74	67%	89%

As shown in Table 2, the total number of all matchups is 7806 and matchups show a mean bias of -0.09 K and median bias of -0.02 K, with a $P(\pm 0.3K)$ of 55% and $P(\pm 0.5K)$ of 76%. The standard deviation and robust standard deviation are 0.53 K and 0.40 K, respectively. After removing the matchups close to any cloudy grid cells, 3374 matchups remained with mean and median bias increasing to 0.07 K and 0.08 K. The standard deviation and robust standard deviation decreased to 0.32 K and 0.28 K. $P(\pm 0.3K)$ increased from 55% to 67% and $P(\pm 0.5K)$ increased from 76% to 89%. The changes in the statistics indicate that some extreme values of Himawari-8 AHI skin SST contaminated by clouds

were eliminated. The maximum and minimum SST differences changed from 4.58 K and -3.21 K to 1.63 K and -1.74 K. Hereafter, we use the matchups centered within 7×7 grid cells containing only valid data for the following analyses.

For the comparison results shown above, we used all ISAR cruise data without any quality level classification. There are differences between the various cruise results. The main reason causing these differences is that ISAR data quality varies within and between cruises, with the quality level (QL) depending on the total expanded uncertainty (see Section 2), which is strongly dependent on the roll of the ship, which highly depends on sea surface roughness [16] and therefore surface wind speed, as demonstrated in Figure 2 in [17]. The numbers of matchups after QL classification are shown in Table 3. As shown in Table 3, after ISAR QL classification, most cruises have very few matchups with the highest ISAR quality (QL = 5). Cruise IN2016_V05 has the most matchups of higher quality levels, i.e., QL equal to four and five, namely 1261. Table 4 shows the total statistics for each ISAR QL classification. As the quality level increases from three to five, the mean and median bias increase from -0.04 K and -0.02 K to 0.10 K and 0.09 K, respectively. The reason for the increase in warm bias is that some matchups of the negative discrepancies were removed by using high QL data. The standard deviation and robust standard deviation decrease from 0.37 K and 0.33 K to 0.27 K and 0.24 K. $P(\pm 0.3K)$ increases from 64% to 72% and $P(\pm 0.5K)$ increases from 85% to 91%. Some of the extremely high and low values were eliminated. The number of matchups with ISAR QL equal to four and five is 2701 (about 80% of total matchups), which has a mean and median bias of 0.09 K and 0.10 K, a standard deviation and robust standard deviation of 0.30 K and 0.27 K. The results were classified using quality levels in Tables 3 and 4, indicating that the quality of shipboard ISAR SST measurements varies widely for different cruises and it is important to conduct quality control of data for validation. Since the requirement is for 0.1 K RMSE accuracy for ISAR SST measurements [12] and from the results shown above, we suggest using ISAR QL ≥ 4 when applying satellite SST validation. Zhang et al. (2020) showed the effect of wind speed on ISAR total uncertainty and also demonstrated that 0.2 K is a reasonable threshold, which refers to QL ≥ 4 [17]. Scatterplots of the matchups with ISAR QL ≤ 3 and QL ≥ 4 are shown in Figure 2a,b. The histogram for the SST differences with ISAR QL ≥ 4 is shown in Figure 2c. The skin temperature values range from around 277 K to 302 K. The temperatures of matchups with ISAR QL ≤ 3 are relatively low due to the data measured near the Antarctic. Results show good agreement between JAXA Himawari-8 AHI skin SST and ISAR skin SST, with a positive mean and median bias in Himawari-8 compared to ISAR temperatures below 0.1 K.

Table 3. Number of matchups for different ISAR quality levels (QLs).

Voyage No.	All	QL ≤ 3	QL = 4	QL = 5
IN2016_V01	46	43	3	0
IN2016_V02	181	124	57	0
IN2016_T02	155	15	138	2
IN2016_V04	977	420	550	7
IN2016_V05	1263	2	469	792
IN2016_V06	718	35	612	71
IN2017_V01	34	34	0	0

Table 4. Statistics of SST difference of the matchups for different ISAR QLs.

QL	N	Mean (K)	Median (K)	SD (K)	RSD (K)	Max (K)	Min (K)	P ($\pm 0.3K$)	P ($\pm 0.5K$)
QL ≤ 3	673	-0.04	-0.02	0.37	0.33	1.45	-1.74	64%	85%
QL = 4	1829	0.09	0.10	0.31	0.28	1.63	-1.52	66%	90%
QL = 5	872	0.10	0.09	0.27	0.24	1.13	-1.32	72%	91%
QL ≥ 4	2701	0.09	0.10	0.30	0.27	1.63	-1.52	68%	90%

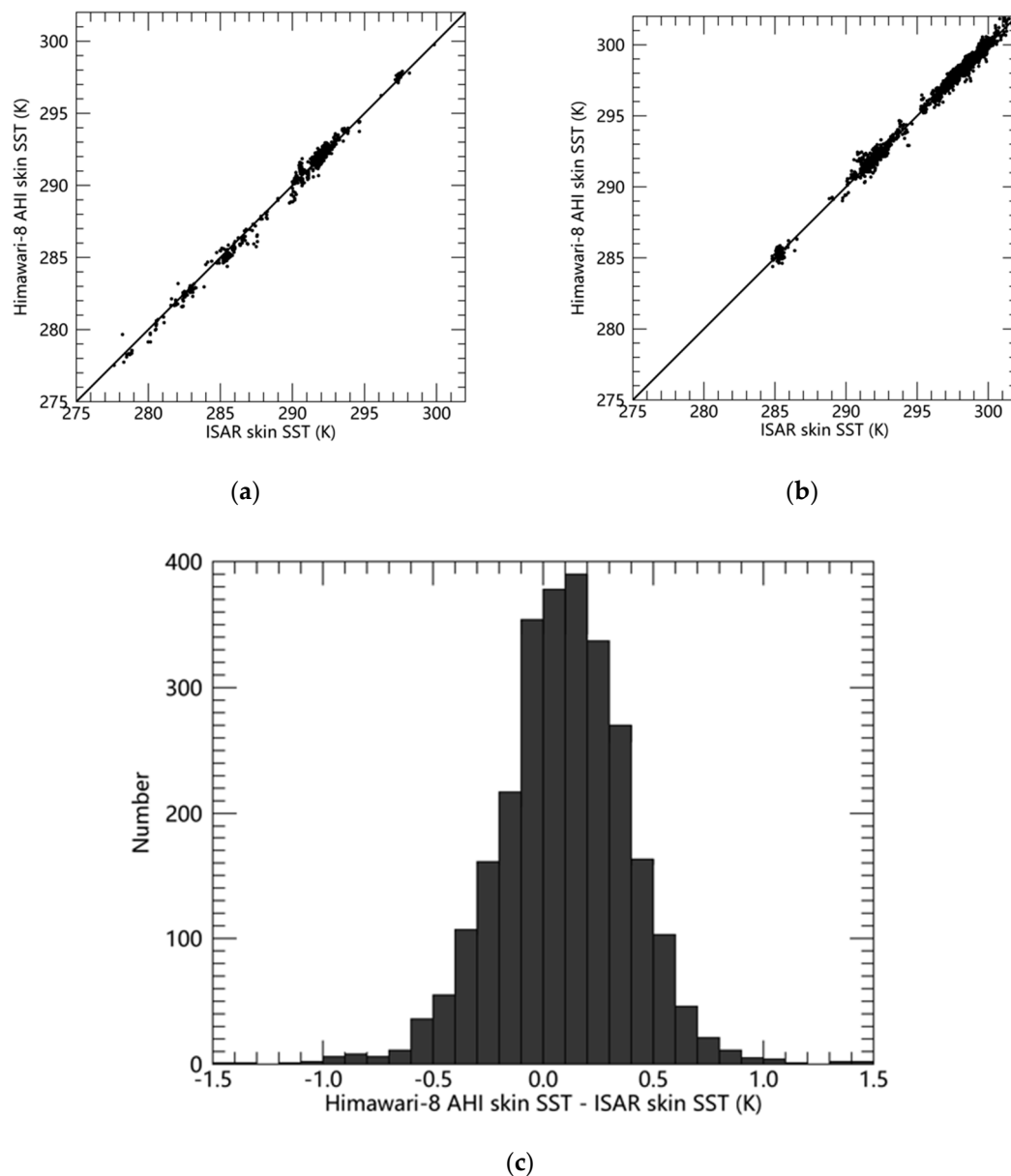
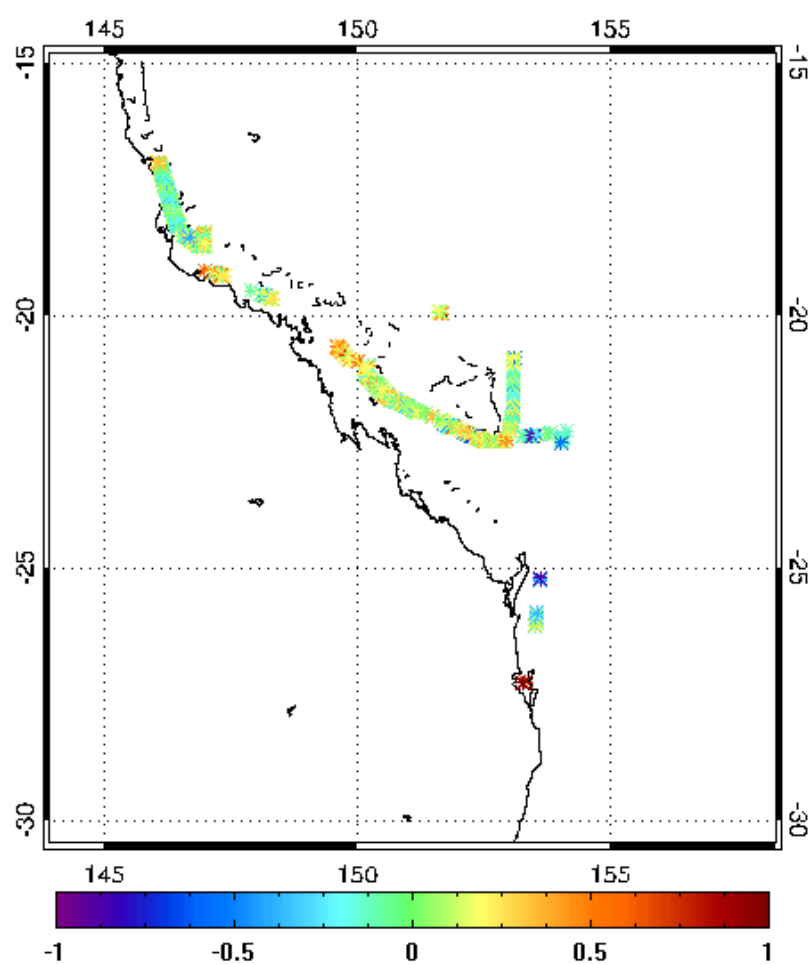


Figure 2. (a) ISAR QL ≤ 3 matchups with both Himawari-8 AHI skin SST and ISAR skin SST measurements; (b) ISAR QL ≥ 4 matchups with both Himawari-8 AHI skin SST and ISAR skin SST measurements; (c) histogram of the differences between Himawari-8 AHI skin SST and ISAR skin SST measurements with ISAR QL ≥ 4 .

4. Discussion

We used results from cruise IN2016_V05, which has the greatest number of ISAR QL ≥ 4 matchups, for further analysis. In order to compare both in situ skin and bulk SST together with Himawari-8 AHI skin SST, SBE 38 bulk SST measurements were collocated with the same matching procedure, which resulted in 1220 matchups of the three kinds of data. Here, we used QC flag “Z” of the SBE 38 bulk SST measurements in the matchup, which means SST data passed all QC tests. The locations of matchups with SST differences between Himawari-8 AHI skin SST and ISAR skin SST measurements, SST differences between Himawari-8 AHI skin SST and SBE 38 bulk SST measurements are shown in Figure 3a,b, respectively. The matchups are located near the GBR in the eastern coastal ocean area of Australia, and the measurements were made in Austral spring.



(a)

Figure 3. Cont.

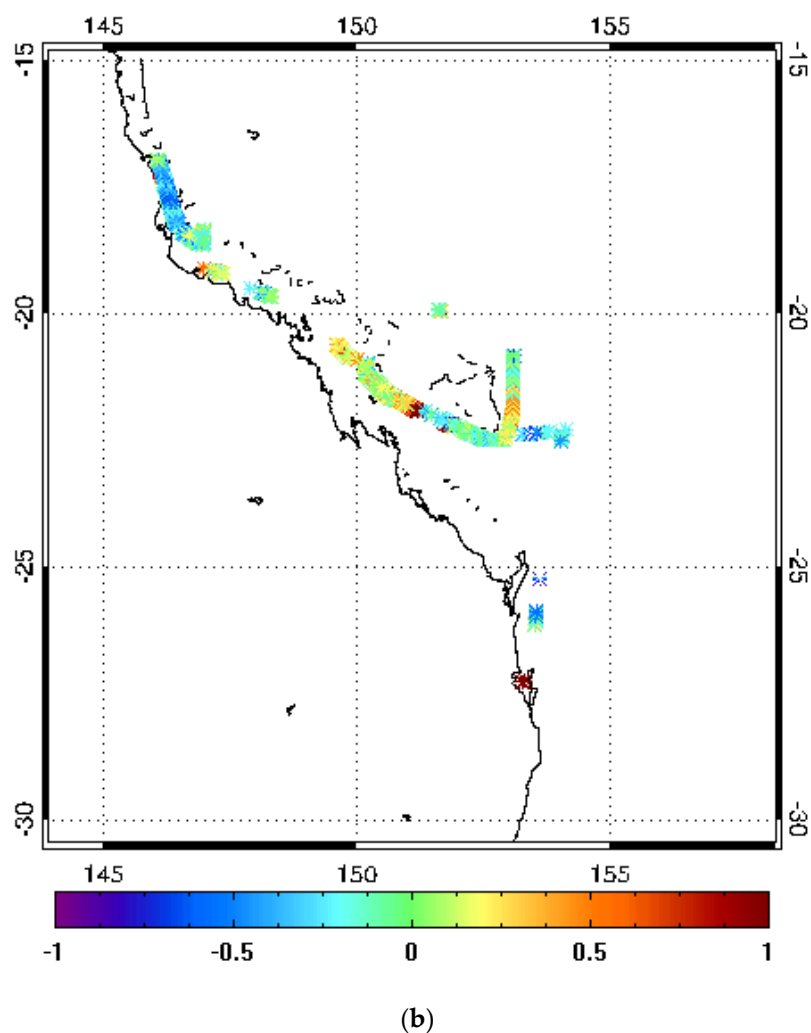


Figure 3. (a) Locations of matchups with the SST differences between Himawari-8 AHI skin SST and ISAR skin SST measurements (K); (b) Locations of matchups with the SST differences between Himawari-8 AHI skin SST and SBE 38 bulk SST measurements (K).

The SST differences between the 1220 matchups against local time are shown in Figure 4a,b. There is no significant local time dependence for Himawari-8 AHI and ISAR skin SST differences. However, large Himawari-8 AHI skin SST and SBE 38 bulk SST differences appear during 11 a.m. to 5 p.m. local time. The peak value reaches 2.23 K.

Table 5 shows the statistics of the 1220 matchups both at daytime and nighttime. The mean and median biases are 0.13 K and 0.13 K in daytime and 0.00 K and 0.02 K in nighttime for Himawari-8 AHI and ISAR skin SST matchups. Daytime Himawari-8 skin SST are biased and are 0.13 K warmer than ISAR skin SST. The standard deviation and robust standard deviation are relatively close at 0.27 K and 0.26 K in daytime, and 0.25 K and 0.21 K during nighttime. As for Himawari-8 AHI skin SST and SBE 38 bulk SST matchups, the mean and median biases show large differences between day and night. The absorption of solar radiation heats the sea surface skin layer and causes skin SST to be higher than the bulk SST under high solar insolation and low surface wind speeds during daytime, a phenomenon known as diurnal warming [21]. Temperatures in the ocean thermal skin layer, extending to depths of around a tenth of a millimeter, are generally cooler than the underlying water because of both the radiant heat loss and the sensible and latent heat losses, referred to as the cool skin effect [10]. The depth of SBE 38-measured bulk SST in IN2016_V05 is approximately 7.9 meters. Both short-wave

radiation and wind speed data [14] in the IMOS meteorological files show clear sky and low wind speeds during some days of IN2016_V05. In daytime, some of the SBE 38 bulk SST are much cooler than the Himawari-8 AHI skin SST, likely due to diurnal warming, with the maximum value of 2.23 K. The mean and median biases during daytime are 0.18 K and 0.13 K. On the contrary, the cool skin effect during nighttime contributes to the negative mean and median biases of -0.23 K and -0.22 K. The standard deviation and robust standard deviation are 0.43 K and 0.28 K in daytime, much higher than the 0.25 K and 0.25 K in nighttime.

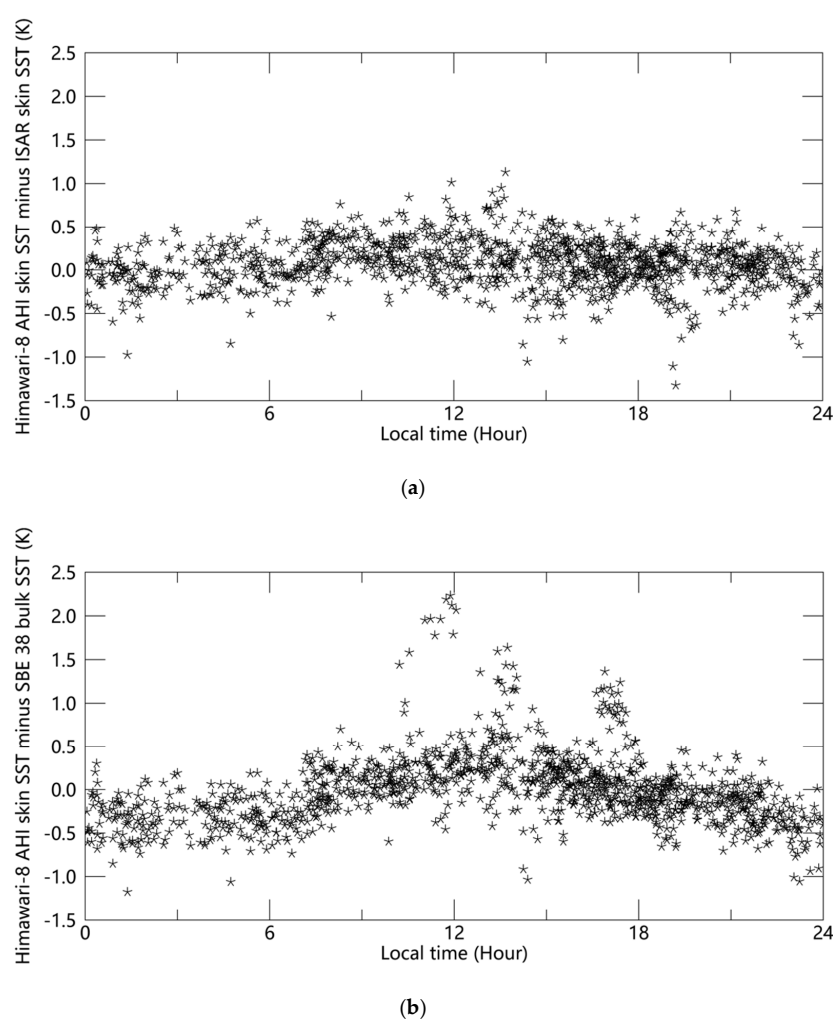


Figure 4. (a) Himawari-8 AHI and ISAR skin SST matchups against local time; (b) Himawari-8 AHI skin SST and SBE 38 bulk SST matchups against local time.

Table 5. Statistics of SST difference of the matchups for cruise IN2016_V05.

		N	Mean (K)	Median (K)	SD (K)	RSD (K)	Max (K)	Min (K)	P (± 0.3 K)	P (± 0.5 K)
AHI-ISAR	Day	685	0.13	0.13	0.27	0.26	1.13	-1.05	68%	91%
	Night	535	0.00	0.02	0.25	0.21	0.68	-1.32	83%	95%
AHI-SBE 38	Day	685	0.18	0.13	0.43	0.28	2.23	-1.04	65%	85%
	Night	535	-0.23	-0.22	0.25	0.25	0.56	-1.18	60%	86%

Figure 5a,b show the wind speed dependence of Himawari-8 AHI skin SST matchups with both ISAR skin SST and SBE 38 bulk SST. The red triangles represent matchups in daytime and blue squares

represent matchups in nighttime. Because both are skin SST measurements, Himawari-8 AHI skin SST and ISAR skin SST differences do not show a significant wind speed dependence in either daytime or nighttime. However, Himawari-8 AHI skin SST and SBE 38 bulk SST differences show some higher values at low wind speed (approximately less than 5 m/s) during daytime. For increasingly moderate to high wind speeds (approximately greater than 7 m/s), the differences between day and night matchups are relatively small. This is likely due to the heat in the skin layer being mixed by wind-generated turbulence and wave effects under high wind conditions [10,21,22].

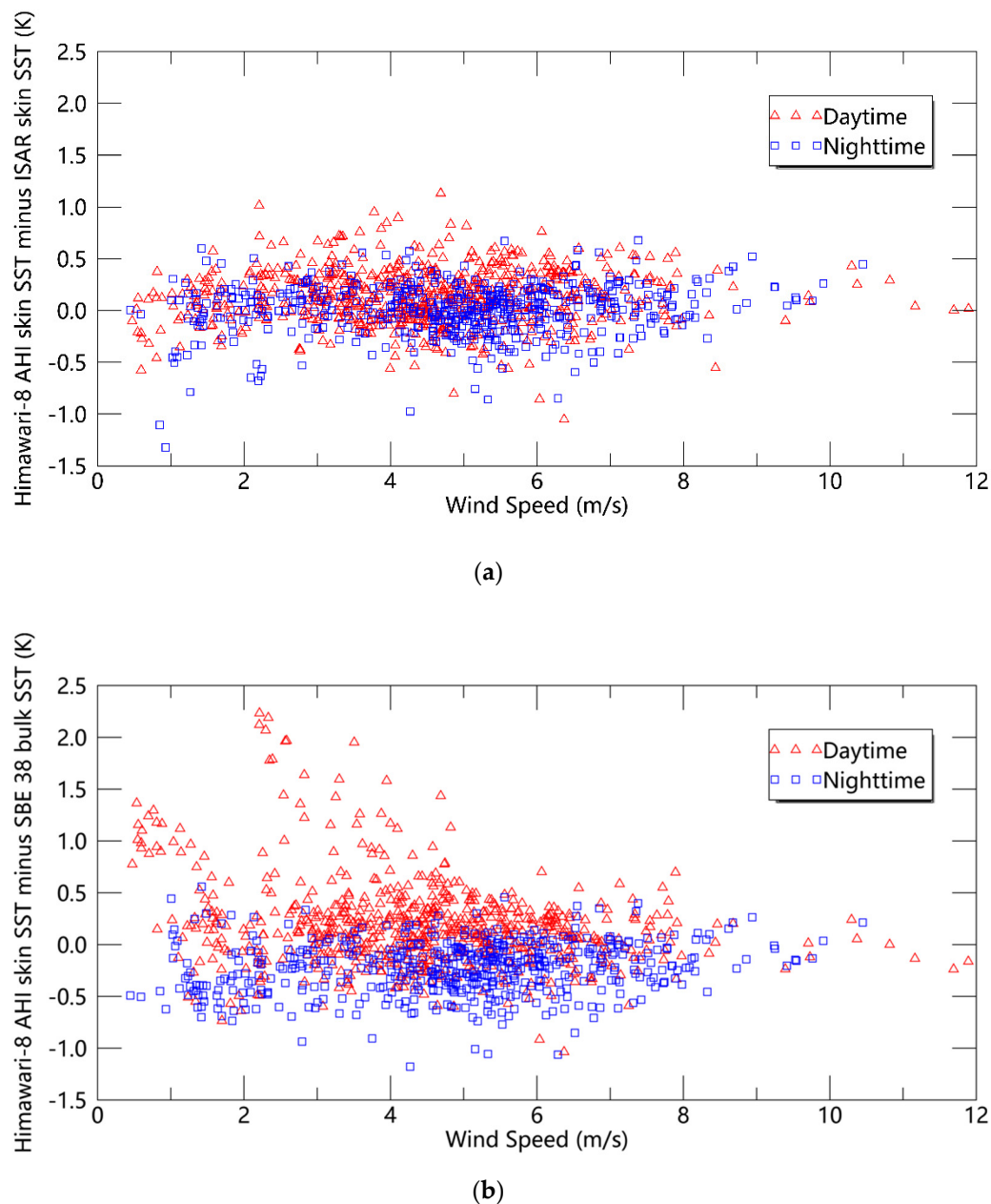


Figure 5. (a) Himawari-8 AHI and ISAR skin SST matchups against wind speed; (b) Himawari-8 AHI skin and SBE 38 bulk SST matchups against wind speed (red triangle: daytime, blue square: nighttime).

Figure 6 shows, plotted against local time, the values of ISAR skin SST, SBE 38 bulk SST and Himawari-8 AHI skin SST matchups on 12 October 2016, a day which exhibited significant diurnal warming. The missing data correspond to no matchups fitting the quality criteria at those times. We can see there is strong diurnal warming influencing the observations on this date. The skin SST of

both Himawari-8 AHI and ISAR reaches approximately 301.5 K at local times of 12 p.m. to 1 p.m., compared with SST of around 299 K during the preceding pre-dawn period. The close agreement with in situ skin SST indicates that the JAXA Himawari-8 skin SST has excellent sensitivity to diurnal warming events in the GBR region. SBE 38 bulk SSTs are lower than the skin SST measurements and are around 300 K at midday. The cool skin effect during nighttime is also evident in this figure, from the cool bias between the ISAR skin SST and SBE 38 bulk SST. The highest difference of 2.23 K between Himawari-8 AHI skin SST and SBE 38 bulk SST in the middle of the day demonstrates that validation using in situ bulk SST would display errors in such cases, and that skin SST measured by shipboard infrared radiometers has significant advantages.

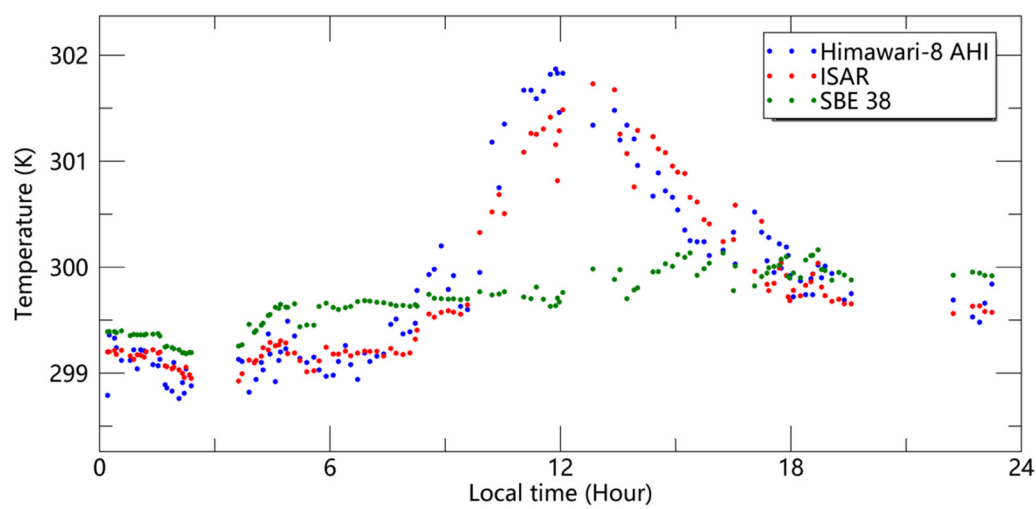


Figure 6. Matchups (red: ISAR skin SST, green: SBE 38 bulk SST, blue: Himawari-8 AHI skin SST) on 12 October 2016 against local time.

The matchup locations for 12 October 2016 local time are shown in Figure 7. RV Investigator moved from the northwest (146.35°E , -18.05°S) of the displayed region to the southeast (147.00°E , -18.65°S) during this period. The Himawari-8 AHI skin SSTs at 6 a.m., 12 p.m. and 6 p.m. local time in this region are shown in Figure 8a–c. SST differences between 12 p.m. and 6 a.m., and 12 p.m. and 6 p.m. are shown in Figure 8d,e. We can see that, in the region of the ISAR measurements, SST differences caused by the geographic location are around 0.5 K and relatively smaller than the SST differences of about 2.5 K due to the diurnal warming effect on the skin bulk temperature difference. This indicates that high temporal resolution JAXA Himawari-8 AHI skin SST products show a good ability to observe diurnal warming events. It also highlights that caution is necessary when using satellite SST observations depending on the contemplated use. The specific observation time of satellite SST should be considered by the researchers.

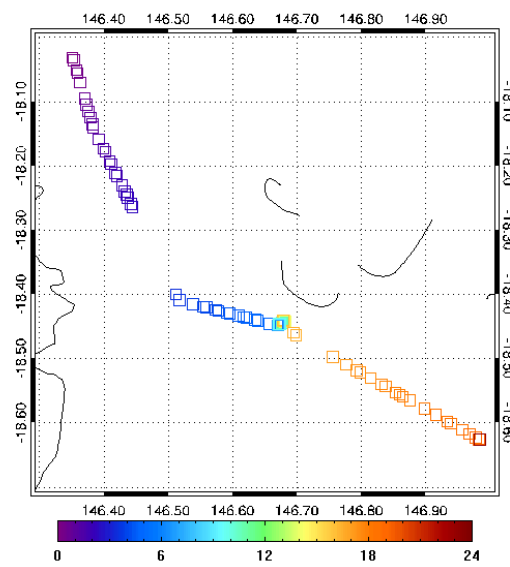
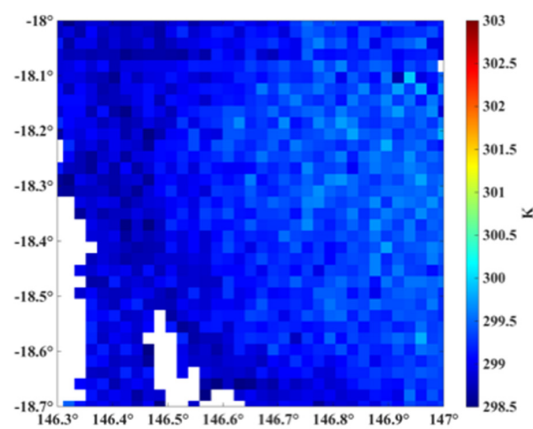
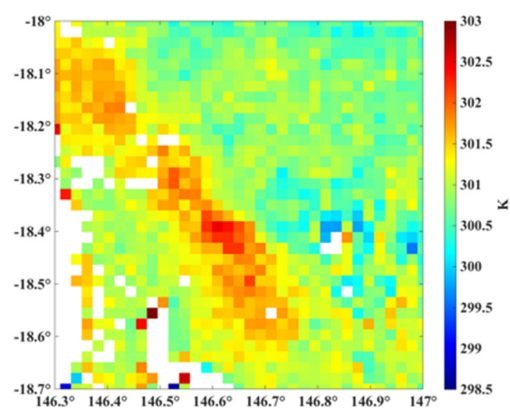


Figure 7. Matchups of cruise track on 12 October 2016, colors represent local time in hours.

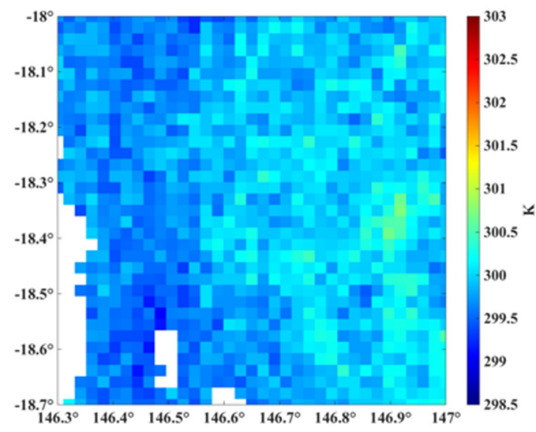


(a)

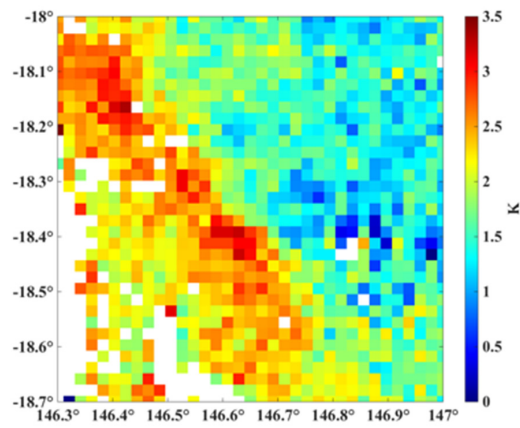


(b)

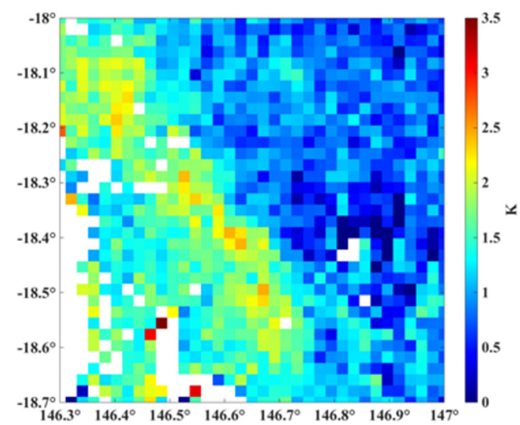
Figure 8. Cont.



(c)



(d)



(e)

Figure 8. Images of Himawari-8 AHI skin SST during a diurnal warming event on 12 October 2016: (a) 6 a.m.; (b) 12 p.m.; (c) 6 p.m.; (d) SST difference between 12 p.m. and 6 a.m.; (e) SST difference between 12 p.m. and 6 p.m.

5. Conclusions

Seven cruises of shipboard infrared radiometer ISAR skin SST data are compared with JAXA Himawari-8 AHI skin SST products in the Australian region. The results demonstrate that it is necessary to use quality control of both ISAR skin SST and Himawari-8 AHI skin SST measurements to effectively validate satellite SST using ISAR data. Using Himawari-8 AHI skin SST (quality level 5) centered in cloud-free 7×7 grid cells and ISAR skin SST with $QL \geq 4$, the results show good agreement. The mean bias and standard deviation are 0.09 K and 0.30 K with a total matchup number of 2701. The case study on cruise IN2016_V05 shows that the ISAR skin SST measurements are a more accurate way to validate satellite skin SST products than using SBE 38 SST measurements made by the ship at almost 8 m depth, which is deeper than the depth of typical moored buoys. The analysis of the 12 October 2016 data indicates that, under diurnal warming conditions, temperature differences between skin and bulk SST measurements reached a maximum value of 2.23 K at midday. A strong diurnal warming event observed by both Himawari-8 AHI and ISAR skin SST of approximately 2.5 K amplitude is observed on 12 October 2016 along the RV Investigator cruise track. The results indicate that Himawari-8 AHI skin SST with high temporal resolution and SST accuracy provides a highly effective means to measure diurnal warming. The advantage of this validation using shipboard measurements of in situ skin SST is that the bulk and skin temperature difference was removed from the error budget. However, the limited study area and temperature range also contribute to the better statistics. Future studies would increase the spatial coverage of validation with larger temperature ranges and more high-quality shipboard skin SST measurements.

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