Ship-Mounted Real-Time Surface Observational System on board Indian Vessels for Validation and Refinement of Model Forcing Fields*

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(Manuscript received 16 November 2011, in final form 30 October 2012)

ABSTRACT

A network of ship-mounted real-time Automatic Weather Stations integrated with Indian geosynchronous satellites [*Indian National Satellites* (*INSATs*)] *3A* and *3C*, named Indian National Centre for Ocean Information Services Real-Time Automatic Weather Stations (I-RAWS), is established. The purpose of I-RAWS is to measure the surface meteorological–ocean parameters and transmit the data in real time in order to validate and refine the forcing parameters (obtained from different meteorological agencies) of the Indian Ocean Forecasting System (INDOFOS). Preliminary validation and intercomparison of analyzed products obtained from the National Centre for Medium Range Weather Forecasting and the European Centre for Medium-Range Weather Forecasts using the data collected from I-RAWS were carried out. This I-RAWS was mounted on board oceanographic research vessel *Sagar Nidhi* during a cruise across three oceanic regimes, namely, the tropical Indian Ocean, the extratropical Indian Ocean, and the Southern Ocean. The results obtained from such a validation and intercomparison, and its implications with special reference to the usage of atmospheric model data for forcing ocean model, are discussed in detail. It is noticed that the performance of analysis products from both atmospheric models is similar and good; however, European Centre for Medium-Range Weather Forecasts air temperature over the extratropical Indian Ocean and wind speed in the Southern Ocean are marginally better.

1. Introduction

Indian National Centre for Ocean Information Services (INCOIS) has established an ocean forecast system, named the Indian Ocean Forecasting System (INDOFOS). The purpose of this system is to predict ocean surface waves, general circulation features, and oil spill trajectories at various spatiotemporal scales. Forecast models of this system are forced by the analyzed and forecasted atmospheric products from the National Centre for Medium Range Weather Forecasting (NCMRWF), the European Centre for Medium-Range Weather Forecasts (ECMWF), the Global Forecast System (GFS), and the Met Office. However, focused validation experiments using independent in situ observations are required to validate the forcing fields. An important input to ocean models is the surface wind, which drives the surface stress and fluxes of latent and sensible heat. The wind field in the equatorial region is observed to be inaccurate in the analysis and reanalysis data products

* Indian National Centre for Ocean Information Services Contribution Number 125.

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DOI: 10.1175/JTECH-D-11-00212.1

(Ji and Smith 1995; Chen et al. 1999; Kelly et al. 1999; Putman et al. 2000; Praveen Kumar et al. 2013) and large biases are present in heat fluxes (Bony et al. 1997; Smith et al. 2001; Praveen Kumar et al. 2012). Errors in the wind field are known to have an impact on the modeled ocean circulation (Myers et al. 1998) and wave/swell parameters (SWIM 1985).

Surface wind data are available from shallow- and deep-water buoys at a few locations along the coasts of India since 1999 (Harikumar et al. 2011). The India Meteorological Department (IMD) collects meteorological data over oceans by an establishment of cooperation of voluntary observing fleet (VOF) of ships (Attri and Tyagi 2010). VOF comprises merchant ships of Indian registry, some foreign merchant vessels, and a few ships of the Indian navy. These ships, while sailing on the high seas, function as floating observatories. But the observations are having sparse temporal resolution (only 6 hourly at 0000, 0600, 1200, and 1800 UTC). Another drawback is that the records of observations are passed on as ''bulletins'' to the IMD for analysis and archival, only when the ships call at ports. International Comprehensive Ocean–Atmosphere Data Set (ICOADS) is a project that has global weather observations taken near the ocean's surface since 1854, primarily from merchant ships, into a compact and easy-to-use dataset of $2° \times 2°$ spatial resolution (Woodruff et al. 1987). Recently, the new release 2.5 of the ICOADS data range from early noninstrumental ship observations to measurements initiated in the twentieth century from buoys and other automated platforms (Woodruff et al. 2010). This newly released dataset has sparse spatial resolutions of $2° \times 2°$ (since 1800) and $1° \times 1°$ (since 1960).

Gathering real-time in situ data over oceans for validation and assimilation is laborious and expensive if cruises are exclusively dedicated for routine observations. Prior to 1970, ships were practically the only source of observations, and now modern sensors are deployed on ships, moored and drifting buoys, aircraft, and Earth-observing satellites, providing a variety of surface data (Smith 2011). The moored buoys ensure data continuity, but their spatial coverage is limited as they are few in number in the Indian Ocean region. The availability of in situ measurements from the Indian sector of the Southern Ocean is poor or nonexistent. Merchant, passenger, and research vessels spend considerable amount of time over the open ocean and can make contributions to marine data collection, if automated ocean and atmosphere monitoring systems are installed on board (Smith et al. 2001). Several countries, including India, have ongoing programs to collect surface meteorological–ocean data from voluntary observing ships (VOSs, e.g., Hellerman and Rosenstien 1983; Da Silva et al. 1994; Servain et al. 1996; Bourassa et al. 1997; Stricherz et al. 1996; Kent et al. 1998; Unger 2005; Smith et al. 1999; Attri and Tyagi 2010). But, most of them were designed to return data in delayed modes.

To take advantage of the ships being operated by the Indian agencies, INCOIS started INCOIS Real-Time Automatic Weather Stations (I-RAWS) under the Ocean Observations and Information Services (OOIS) program of the Ministry of Earth Sciences (MoES), government of India in the year 2009. Under this program, automatic weather stations (AWSs) were installed on board Indian research vessels with real-time data transmission/reception by integration with Indian geostationary satellites [*Indian National Satellites* (*INSAT*s)] *3A* and *3C*. I-RAWS was installed on nine ships, and there are plans to bring more ships under this program in the coming years. I-RAWS measures air temperature, sea surface temperature, air pressure, specific humidity, wind speed and direction, rainfall, and downwelling shortwave (SW) and longwave (LW) radiation. The data from I-RAWS are also useful for the validation of satellite-derived data products and for near-real-time assimilation in forecast models. This will provide more initial conditions for assimilation into models, which in turn will give better forecasts. Real-time validation (displayed in real time on the INCOIS website) of forecasted products with I-RAWS data would enable users to judge them better. Moreover, this program gives a large quantity of surface meteorological–ocean data, especially in and around the Indian coasts, while other existing VOS datasets pertain mainly to the open ocean (Woodruff et al. 2010; Attri and Tyagi 2010). These coastal data would be valuable for assimilation and validation of very high-resolution coastal models being planned by INCOIS. Extensive validation exercises and real-time data assimilation would definitely lead to better refinement of the forecasts.

A recent release by the National Oceanic and Atmospheric Administration (NOAA) states, ''For budgetary reasons, stemming from pending large cuts at the NOAA Climate Program Office (CPO), ESRL [Earth System Research Laboratory] Directors have determined that it is no longer feasible for its Physical Science Division (PSD) to continue supporting any further ICOADS work—effective immediately… At this juncture there are no plans for any new major ICOADS delayed-mode updates or further Releases'' (ICOADS 2012, p. 24). In this context, the establishment of I-RAWS under the OOIS program of MoES, which aims for data collection over the Indian Ocean, gains importance and needs encouragement. The advantages of I-RAWS are as follows. Important surface variables

TABLE 1. Make and model, range of measurement, resolution, and accuracy of the sensors used in I-RAWS under the OOIS program of MoES, government of India.

Serial No.	Parameter	Sensor make and model	Range of measurement	Resolution	Accuracy
1	Air pressure	SETRA-S1079W	800–1100 mb	0.1 mb	0.5 mb
2	Air temperature	Rotronics-S93211	−50° to 50°C	0.1°C	±0.2°C
3	RH	Rotronics-S93211	0%–100%	0.02%	<3%
4	Wind speed	Gill-S1510 (sonic wind monitor)	0–60 m s^{-1}	0.01 m s^{-1}	±2%
5	Downwelling LW radiation	Eppley-S1425W	0–700 W m^{-2}	0.1 W m^{-2}	±1%
6	Downwelling SW radiation	Eppley-S1092W	200–1200 W m^{-2}	0.4 W m^{-2}	±2%
7	SST	Weatherpak (thermistor with water temperature module convert)-S3338	−50° to 50°C	0.1°C	±0.2°C
8	GPS	GPS Trimble-S9922	—	—	—
9	Gyro	Fluxgate compass-S1085W	—	—	±0.1°

are measured along the ship track with a high temporal resolution of 15 min; its data are available in real time because of its integration with INSATs; it provides more coastal data from ships, which are plying in and around the Indian coasts and also from the data-sparse region, namely, the Indian sector of the Southern Ocean; the observation density in the Indian Ocean is expected to increase because of the planned expansion of the I-RAWS network, and I-RAWS data will be uploaded to the Global Telecommunication System (GTS) soon and hence the datasets will become publicly available.

One of the objectives of this paper is to bring the existence of the I-RAWS program to the notice of the community. The other objective is to demonstrate how useful the I-RAWS data are in validating the analyzed products from NCMRWF and ECMWF (''model data''), which are used to force the ocean forecast models at INCOIS, using the data collected by I-RAWS on board the oceanographic research vessel (ORV) *Sagar Nidhi* during a cruise across three oceanic regimes, that is, the tropical Indian Ocean (TIO; between 23.5°N and 23.5°S), the extratropical Indian Ocean (ETIO; between 23.5° and 60°S), and the Southern Ocean (SO; south to 60°S) during from 2 January to 24 April 2010. The configuration of the system is described in section 2, followed by a description of the datasets used for validation in section 3. Results are shown in section 4, followed by a summary and conclusions in section 5.

2. I-RAWS configuration

The basic variables measured by I-RAWS include air temperature, sea surface temperature, pressure, relative humidity (RH), downwelling solar and longwave radiation, rainfall, wind speed, and wind direction. The sensors selected for I-RAWS are similar to those used in the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA), the Triangle Trans-Ocean Buoy Network (TRITON), and the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) mooring buoys under the Tropical Atmosphere Ocean (TAO) project of the National Oceanographic and Atmospheric Administration, United States (Hayes et al. 1991; McPhaden et al. 2010). The sensor details such as make/model, range of measurement, resolution, and accuracy are given in the Table 1. GPS receiver and gyro were incorporated into the system to enable the computation of true wind speed and wind direction in the datalogger in real time. The instrument was integrated with Indian geosynchronous satellites INSAT 3A and 3C. The usage of a geostationary satellite, INSAT, ensures high temporal frequency (in this case, half an hour). To minimize the flow distortions due to ship structure/geometry (e.g., Rahmstorf 1989), I-RAWS sensors were mounted on a 2.5-m-high (foldable) stainless steel mast on the front of forecastle deck (Fig. 1). The height of the wind sensor is about 13 m above sea level. This arrangement measures wind speed without significant distortions when the wind blows from the front and sides relative to the ship.

To intercompare the sensors, the Indian Institute of Science (IISc), Bengaluru, India, installed an automatic weather recording system consisting of temperature, relative humidity, pressure, wind, and radiation sensors on the same mast but at a lower level during a cruise, namely, the continental tropical convergence zone (CTCZ) cruise, during July–August 2009 (cruise track is shown in Fig. 2). Figure 3 shows the time series plots from the IISc and I-RAWS systems for the period from 1 to 7 August 2009, when continuous common data were available from both systems. During this period, the ship was positioned at 8°N, 85°E (the location is shown on the CTCZ cruise track in Fig. 2). In addition, a sonic anemometer mounted on the ship at a height of 23 m as part of its dynamical positioning (DP) system also was used

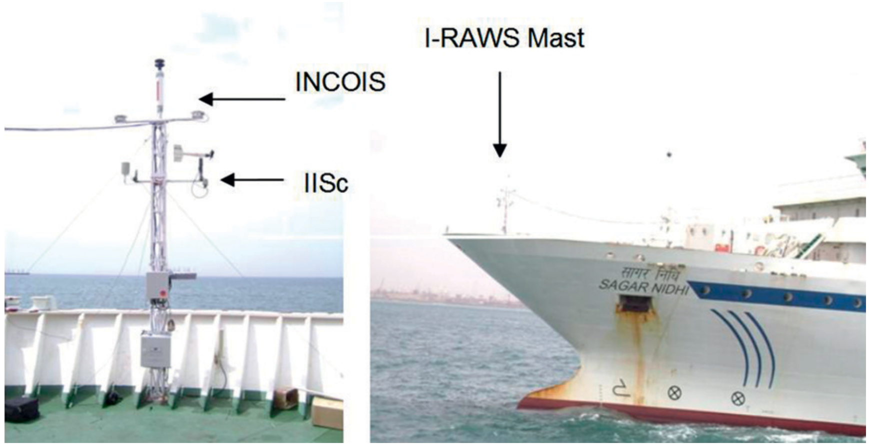

FIG. 1. The I-RAWS installed on the mast on the forecastle deck on board ORV *Sagar Nidhi*. The positions of I-RAWS and IISc AWSs are shown.

for the intercomparison. Good agreement was seen in humidity, pressure, and wind direction. Temporal variations in air temperature were well captured by both systems though the IISc values were higher (by ~0.5°C). Initially the reasons were not very clear, and the difference was thought to be related to intersensor differences. Now the systematic bias of ~0.5°C in the IISc temperature measurements is traced to not accounting for the voltage drop in the extension cable used on board the ship that was not included while the sensor was calibrated. The overall accuracy of the individual temperature measurement is about 0.2°C. Therefore, a difference of 0.4°C is within the sensor measurement uncertainties. The average sea surface temperature (SST) during the week was 28.5°C, which was less than the average air temperature (29.2°C). Air temperature

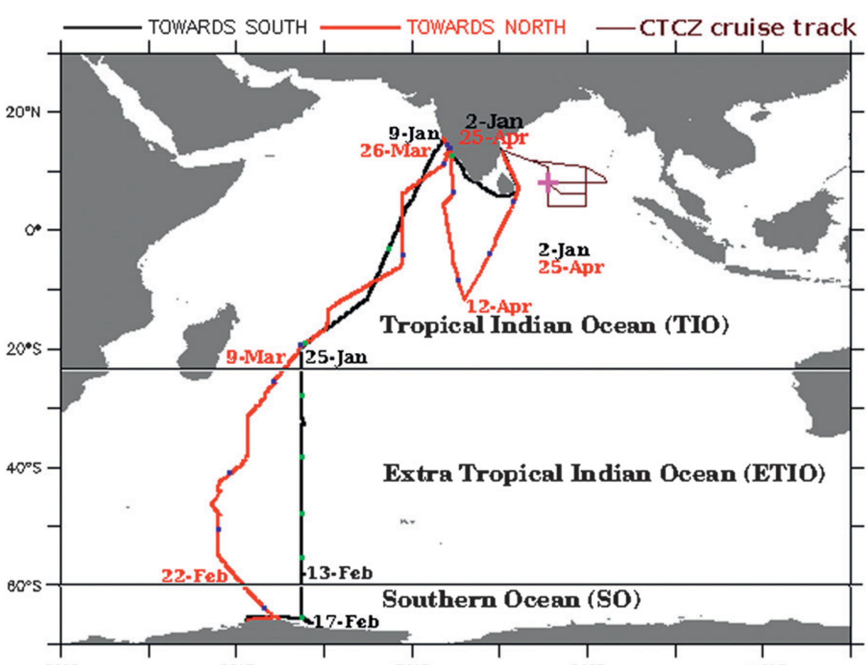

FIG. 2. Track of ORV *Sagar Nidhi* during the Southern Ocean cruise. Onward track is shown by the black line with green dots and the return track by the red line with blue dots. Interval between two dots corresponds to 5 days. CTCZ cruise track also is shown in brown. Center of the pink plus (+) sign indicates the ship position during the period of comparison (1–7 Aug 2009) shown in the Fig. 3.

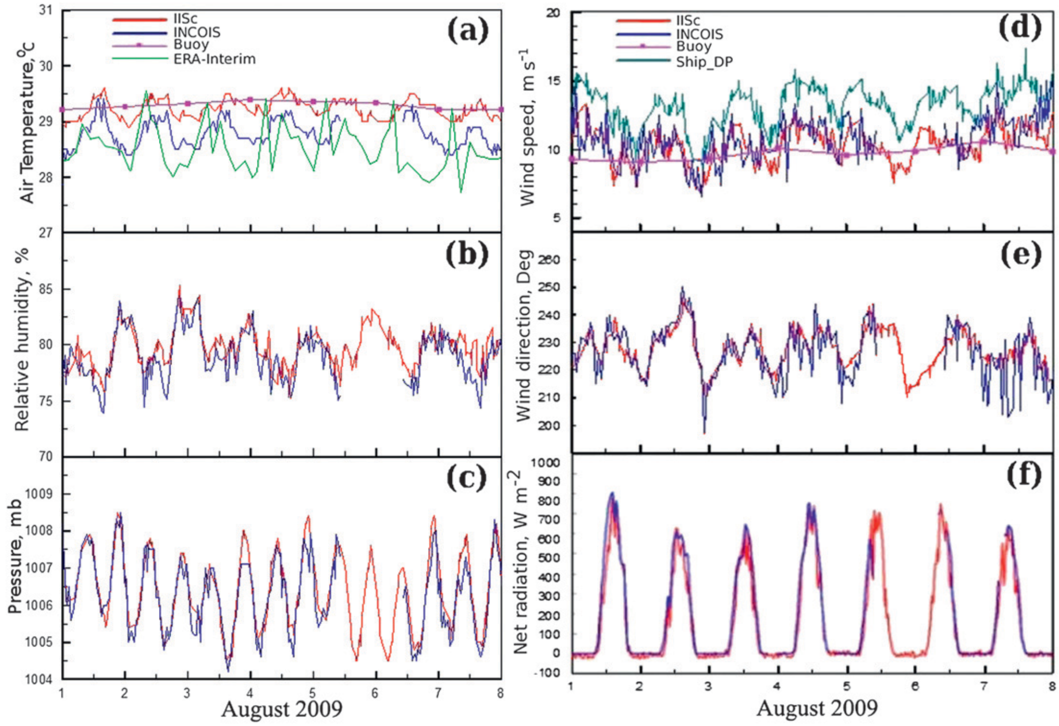

FIG. 3. Comparison of (a) air temperature, (b) RH, (c) pressure p, (d) wind speed, (e) wind direction, and (f) net radiation measured by IISc AWS and I-RAWS systems. For air temperature, nearby buoy as well as ERA-Interim data, and for wind speed, buoy as well as ship_dp data, are also shown. Buoy measurement height is 2 m.

more than SST is possible during the summer monsoon season over parts of the Indian Ocean under strong wind conditions (Jaswal et al. 2012), and the winds were indeed strong (>9 m s^{-1}; Fig. 3d). In Fig. 3a, we also show ECMWF Interim Re-Analysis data (Dee et al. 2011; http://data-portal.ecmwf.int/data/d/interim_daily/) of 3-hourly temporal and 1.5° × 1.5° spatial resolution. Daily average air temperature measured by buoy (at 8°N, 90°E) is also shown in Fig. 3a. It is seen that air temperature was more than 29°C. Therefore, high air temperature values shown by ERA-Interim as well as buoy data suggest that the air temperature of ~29°C is not uncommon over this part of the bay. Wind speeds measured by the IISc and I-RAWS systems separated in the vertical by about 1 m were in good agreement, but at times the difference exceeded 1 m s^{-1}. The net radiation derived from the I-RAWS data also was in good agreement with IISc AWS measurements (Fig. 3f). Overall, the agreement between the two AWSs was very encouraging and gave the confidence that the sensors are working fine. However, the I-RAWS sensors, especially the temperature sensor, was calibrated based on this intercomparison before the main Southern Ocean cruise (from 2 January to 24 April 2010). The IISc automatic weather recording system, installed for the CTCZ cruise on board ORV *Sagar Nidhi*, was removed before the Southern Ocean cruise.

3. Data and methods

For the purpose of intercomparison and validation of model data, we have considered the I-RAWS data collected on board ORV *Sagar Nidhi*, in its Southern Ocean cruise, with the largest spatial and temporal coverage from 2 January to 24 April 2010. Except for two short gaps from 31 January to 5 February and from 13 to 18 April 2010, the I-RAWS recorded continuous data on surface meteorological parameters. During this voyage, the ship sailed from 15.4°N in the Arabian Sea to 66.6°S in the Southern Ocean (Indian Ocean sector; almost touching Antarctica; Fig. 2), recording surface meteorological data and transmitting it in real time. These I-RAWS datasets are not uploaded to the GTS so far, and models have not assimilated them. Therefore, these data act as very unique and independent sources for validating the model products. The date and position of the ship at/near some important locations are shown in Table 2.

The details of the models, which provide the analyzed meteorological parameters, used here are given below. The T254L64 model analysis fields produced by

TABLE 2. Date and position of the ship at/near some important locations. Positive and negative signs for latitude refer to north and south of the equator, respectively, and longitude is east (see Fig. 1).

Position	Lat	Lon	Date
Start	13.10	80.30	2 Jan 2010
Equator	0.40	68.45	16 Jan 2010
Tropic of Capricorn	−23.17	57.50	25 Jan 2010
Southern Ocean	−59.92	57.52	13 Feb 2010
Southernmost	−66.50	58.64	17 Feb 2010
Southern Ocean (while returning)	−59.75	50.65	22 Feb 2010
Tropic of Capricorn (while returning)	−22.76	55.90	9 Mar 2010
Northernmost	15.40	73.79	26 Mar 2010
Equator (second southward trip)	0.47	74.13	8 Apr 2010
Second southward trip	−11.65	75.93	12 Apr 2010
Equator (while returning)	0.93	80.47	21 Apr 2010
End	13.10	80.30	25 Apr 2010

NCMRWF at 6-hourly intervals were considered in this study. This analysis utilizes all conventional and nonconventional data received through the GTS at the regional telecommunication hub (RTH) in New Delhi (NCMRWF 2010). Nonconventional data include cloud motion vectors (CMVs) from INSAT, the Japanese Geostationary Meteorological Satellite (GMS), the Geostationary Operational Environmental Satellite (GOES), and Meteorological Satellites (Meteosat); NOAA satellite temperature profiles and three-layer precipitable water content; surface wind information from the *European Remote Sensing Satellite-2* (*ERS-2*), etc. (Parrish et al. 1997; Rizvi et al. 2000). ECMWF has in the past produced three major reanalyses, namely, the First Global Atmospheric Research Program Global Experiment (FGGE), the 15-yr ECMWF Re-Analysis (ERA-15; ECMWF 2008; Gibson and Uppala 1996), and the 40-yr ECMWF Reanalysis (ERA-40; Uppala et al. 2005). The last of these consisted of a set of global analyses describing the state of the atmosphere and land, and ocean wave conditions from mid-1957 to mid-2002. ERA-Interim is an ''interim'' reanalysis of the period 1989 to the present in preparation for the next-generation extended reanalysis (Dee et al. 2011) to replace ERA-40. ERA-Interim was recently extended backward by a decade to the year 1979, and it continues to be updated forward in time. The ERA-Interim data assimilation system uses a 2006 release of the Integrated Forecast System (IFS Cy31r2), which contains many improvements, both in the forecasting model and analysis methodology relative to ERA-40 (Dee et al. 2011). The ERA-Interim reanalysis caught up with operations in March 2009, and is now being continued in near–real time to support climate monitoring. As part of the Year of Tropical Convection (YOTC), ECMWF has provided the ERA-Interim analyzed fields for the year 2010 with a spatial resolution of $0.125° \times 0.125°$ online (at http://data-portal.ecmwf.int/data/d/yotc_od/). The 12-h four-dimensional variational data assimilation (4DVar) scheme with in situ/satellite data assimilation is used in the ERA-Interim reanalysis. ECMWF assimilates more observation data than NCMRWF and gives more importance for satellite observations than in situ observations (Simmons and Gibson 2000; Dee et al. 2011). The spatial resolution of the YOTC data from ECMWF was $0.125° \times 0.125°$, whereas that of the NCMRWF model was $0.5° \times 0.5°$. Hence, for the purpose of comparison, the ECMWF data were regridded to a spatial resolution of $0.5° \times 0.5°$.

The relative wind speed measured by the I-RAWS was combined with the ship speed and direction provided by GPS and gyro to obtain the true wind speed and direction. The models reported the wind speed at 10-m height; hence, the true wind reported by I-RAWS was logarithmically converted to 10-m height by using the Monin–Obukhov similarity relations for the boundary layer (Monin and Obukhov 1954). NCMRWF reanalysis provided specific humidity, and the corresponding humidity variable was derived for ECMWF data using dewpoint temperature and air pressure. Corresponding I-RAWS specific humidity was calculated using measured relative humidity, air temperature, and air pressure following Bolton (1980). I-RAWS data were 15-min averages and essentially point measurements, while the model data were 6-hourly averages over a $0.5° \times 0.5°$ area. Hence, for collocation purposes, the model data corresponding to the grid(s) through which the ship track passed through were extracted at a 6-hourly time interval. I-RAWS data, averaged over the past 6 h, were used while comparing the values at model output time interval. In cases where the ship passed through more than one model grid during the averaging period, the area-weighted average of the model data was compared with the I-RAWS data. Statistical parameters, namely, bias, root-mean-square error (RMSE), and Pearson correlation coefficient (r), were used to assess the agreement between data.

4. Results and discussion

Figure 4 shows the time series of six meteorological parameters, plotted using 6-hourly collocated I-RAWS and model data, except for shortwave radiation. Since shortwave radiation has strong diurnal variation (that masks the actual differences in a time series plot for the entire period), daily averaged values of the downwelling shortwave radiation are shown in Fig. 4e. Black

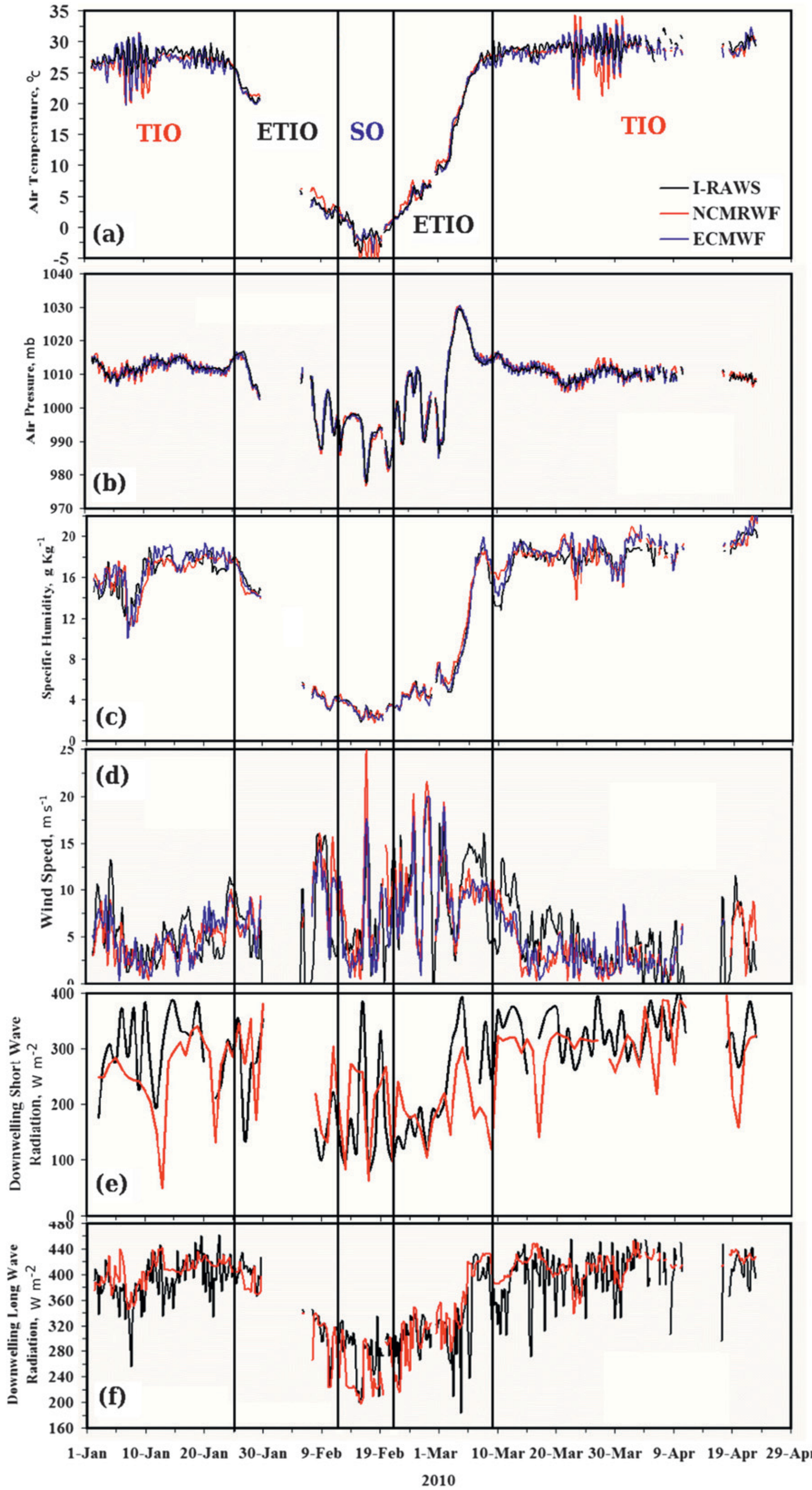

FIG. 4. The comparison of the time series along the ship track for (a) air temperature; (b) air pressure; (c) specific humidity; (d) wind speed; (e) downwelling SW radiation; and (f) downwelling LW radiation from I-RAWS, NCMRWF, and ECMWF. The time series of downwelling SW radiation is plotted using daily averaged values, for better clarity of the variability.

vertical lines delineate different oceanic regimes. Figure 5 shows the corresponding scatterplots of I-RAWS observations against model data. The statistics are summarized in Table 3. Two-tailed Student's *t* test was applied to assess the significance of all these statistical parameters. It was found that all the statistical parameters are significant at the 95% confidence level. This gives confidence in using the data from the SO, though that was less in number compared to that from the TIO and ETIO.

Figure 4 indicates that the latitudinal variations of all variables were well captured by both models (exception for longwave and shortwave radiation in NCMRWF data). The model air temperature and surface pressure show large amplitude (diurnal) variations in the TIO and SO. This was true for both models. Examination of the corresponding ship positions revealed that such cases were seen when the ship was moving along the coast and at port calls, and the model grids contained both land and sea areas. During the daytime, air temperature was normally warmer over the land compared to that over the ocean and vice versa during the nighttime. Thus, while the model data reflected contributions from land and sea, I-RAWS measured properties only over water. The fact the model and I-RAWS diurnal variations differed in these cases is an indication that present-day models are able to simulate mixed land–ocean grids realistically. The best agreement in all variables was seen in the ETIO (Fig. 5 and Table 3). For other ocean basins also, the statistics improved when the values near the coast were excluded. For example, in the TIO, the correlation improved from 0.48 to 0.64 for air temperature and that improved from 0.66 to 0.70 in case of specific humidity when coastal data were excluded from the analyses. In the case of wind speed, over the SO, the correlation improved from 0.54 to 0.60 after the exclusion of data near the coast. However, in the case of radiation parameters, the scatter index increased when the coastal data in the TIO and SO were excluded.

Goswami and Rajagopal (2003) had analyzed the NCMRWF surface winds based on an earlier version of model. They reported an easterly bias (1.0–1.5 m s^{-1}) in the equatorial Indian Ocean (IO) and northerly bias (2.0–3.0 m s^{-1}) in the south equatorial IO during 1999 and 2000 when compared with Quick Scatterometer (QuikSCAT) winds. In the present case, the wind speed bias is less than 1.0 m s^{-1} between the in situ and model data. This suggests that the new version of the NCMRWF model used here has improved compared to that existed during 1999–2000. The broad features of the temporal variations in wind speed were captured well by both models. RMSEs of NCMRWF and ECMWF were comparable in the TIO (~2.7 m s^{-1}) and the ETIO (~3.4 m s^{-1}); however, in the SO, the RMSE was less for ECMWF (2.9 m s^{-1}) than that for NCMRWF (4.6 m s^{-1}). Correlations in wind speed in the TIO and ETIO for NCMRWF and ECMWF data are comparable, but they are higher for ECMWF in the SO. Obviously, the ECMWF winds were better in the SO, where the in situ observations are sparse.

The correlation between I-RAWS and NCMRWF downwelling shortwave radiation is 0.9 in the TIO and ETIO and 0.74 in the SO. Biases were less than 10% in all oceanic regimes. The diurnal variation of downwelling shortwave radiation was also captured well by the model (Fig. 6). I-RAWS data showed greater variability in downwelling longwave radiation compared to the smooth behavior of NCMRWF model data. The mean longwave radiation estimated from models and I-RAWS data were comparable in all three oceanic regimes. Correlations between I-RAWS observations and models were above 0.8 in the SO and ETIO, and it was 0.54 in the TIO.

5. Summary and conclusions

This paper described data obtained from I-RAWS, a new surface monitoring system installed on board Indian vessels with INSAT integration for real-time data reception, under the OOIS program of MoES, the government of India. Its usage for the validation of model-derived atmospheric parameters and to force the ocean forecasting models is demonstrated in detail. Compared to ICOADS, IMD, and other existing surface meteorological–ocean datasets in the Indian Ocean, the advantages of I-RAWS observations are that 1) important surface variables are measured along the ship track with a high temporal resolution of 15 min; 2) its data are available in real time because of its integration with INSATs; 3) it provides more coastal data from ships, which are plying in and around the Indian coasts and also from the data-sparse region, namely, the Indian sector of the Southern Ocean; 4) the observation density in the Indian Ocean is expected to increase because of the planned expansion of I-RAWS data; and 5) the I-RAWS data will be uploaded to the GTS soon, and hence the datasets will become publicly available.

Initially, the I-RAWS system was calibrated against an AWS installed on board by IISc before taking it on a voyage to the southern Indian Ocean. Later, the data from I-RAWS collected during a longer voyage to the southern Indian Ocean was used to validate the data generated by two models. Results derived from the comparison of all the six meteorological parameters obtained from model analyzed products with I-RAWS are depicted in detail in the Table 3. In general, the data from the NCMRWF and ECMWF models matched well

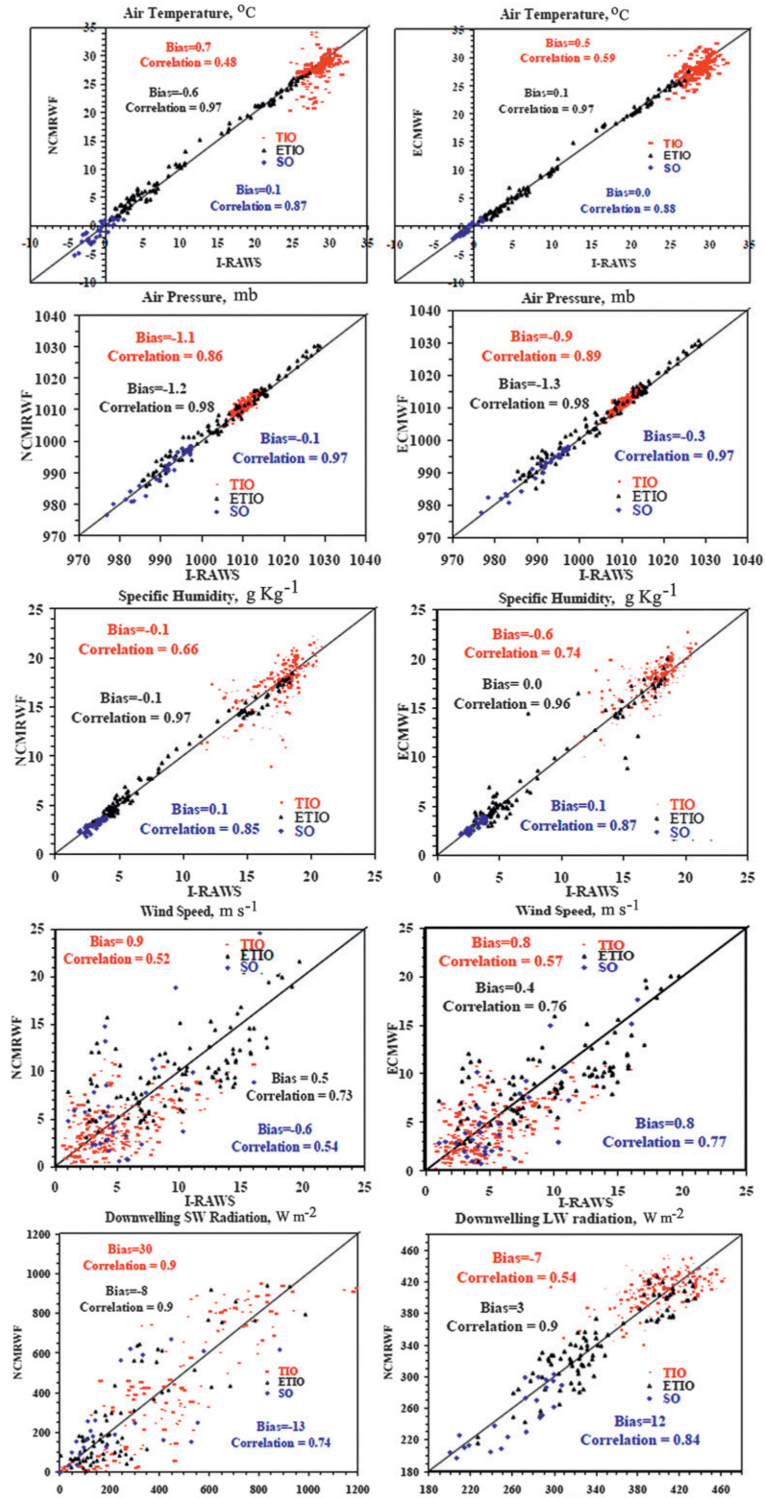

FIG. 5. Scatterplots (NCMRWF and ECMWF vs I-RAWS) of all the parameters separately for each oceanic regime. All but bottom two panels contain the comparison of both (left) NCMRWF and (right) ECMWF with I-RAWS. (bottom) The comparison of (left) downwelling SW radiation and (right) downwelling LW radiation. The bias and correlation are also shown. The black line shown diagonally across the figures indicates a perfect match.

TABLE 3. Mean, bias, correlation, and RMSE between IRAWS and NCMRWF ECMWF data and scatter index. The values given inside the brackets are after removing the coastal data points. Note that I denotes I-RAWS, N denotes NCMRWF, and E denotes ECMWF.

Parameter	Ocean	Mean			Bias		Correlation		RMSE		Scatter index (%)	
		I-RAWS	NCMRWF	ECMWF	I-N	I-E	I & N	I & E	I & N	I & E	I & N	I & E
Air temperature (°C)	TIO	28.5 (28.5)	27.8 (27.9)	28 (27.6)	0.7 (0.6)	0.5 (0.9)	0.48 (0.64)	0.59 (0.58)	2.1 (1.1)	1.8 (1.4)	7.36 (3.86)	6.31 (4.91)
	ETIO	11.8	12.4	11.7	−0.6	0.1	0.97	0.97	1.0	0.6	8.45	5.07
	SO	−1.0 (0.1)	−1.1 (0.1)	−1.0 (0.3)	0.1 (0.0)	0.0 (−0.2)	0.87 (0.88)	0.88 (0.88)	0.8 (0.9)	0.6 (0.6)	45.90 (51.64)	34.42 (34.42)
Pressure (mb)	TIO	1010.3 (1011.0)	1011.4 (1012.3)	1011.2 (1011.9)	−1.1 (−1.3)	−0.9 (−0.9)	0.86 (0.86)	0.89 (0.89)	1.7 (1.8)	1.3 (1.5)	0.16 (0.18)	0.13 (0.15)
	ETIO	1005.2	1006.4	1006.5	−1.2	−1.3	0.98	0.98	2.2	2.3	0.22	0.23
	SO	991.2 (990.3)	991.3 (990.7)	991.5 (990.6)	−0.1 (−0.4)	−0.3 (−0.3)	0.97 (0.98)	0.97 (0.99)	1.4 (1.6)	1.3 (1.3)	0.15 (0.16)	0.13 (0.13)
Specific humidity (g kg^{-1})	TIO	17.4 (17.6)	17.5 (17.9)	18 (18.2)	−0.1 (−0.3)	−0.6 (−0.6)	0.66 (0.70)	0.74 (0.72)	1.6 (1.2)	1.4 (1.4)	9.29 (6.81)	8.20 (8.11)
	ETIO	8.3	8.4	8.3	−0.1	0.0	0.97	0.96	1.0	0.9	11.82	11.10
	SO	3.0 (3.4)	2.9 (3.2)	2.9 (3.3)	0.1 (0.2)	0.1 (0.1)	0.85 (0.86)	0.87 (0.87)	0.3 (0.3)	0.3 (0.3)	11.41 (10.00)	9.73 (8.53)
Wind speed (m s^{-1})	TIO	5.0 (5.8)	4.1 (4.9)	4.2 (5.1)	0.9 (0.9)	0.8 (0.7)	0.52 (0.44)	0.57 (0.46)	2.8 (3.3)	2.6 (3.1)	56.57 (56.03)	52.53 (53.79)
	ETIO	9.7	9.2	9.3	0.5	0.4	0.73	0.76	3.5	3.3	36.27	34.20
	SO	6.0 (6.2)	6.6 (7.6)	5.2 (5.6)	−0.6 (−1.4)	0.8 (0.6)	0.54 (0.60)	0.77 (0.85)	4.6 (4.9)	2.9 (2.6)	76.67 (79.03)	48.33 (41.94)
Downwelling SW radiation (W m^{-2})	TIO	342 (372)	312 (312)	—	30 (60)	—	0.90 (0.90)	—	143 (164)	—	41.79 (44.09)	—
	ETIO	199	207	—	−8	—	0.90	—	112	—	56.08	—
	SO	187 (149)	200 (170)	—	−13 (21)	—	0.74 (0.92)	—	155 (128)	—	82.69 (85.91)	—
Downwelling LW radiation (W m^{-2})	TIO	404 (408)	411 (417)	—	−7 (−9)	—	0.54 (0.45)	—	56.9 (77)	—	14.08 (18.87)	—
	ETIO	342	339	—	3	—	0.90	—	22	—	6.54	—
	SO	263 (293)	251 (282)	—	12 (11)	—	0.84 (0.84)	—	23 (22)	—	8.83 (7.71)	—

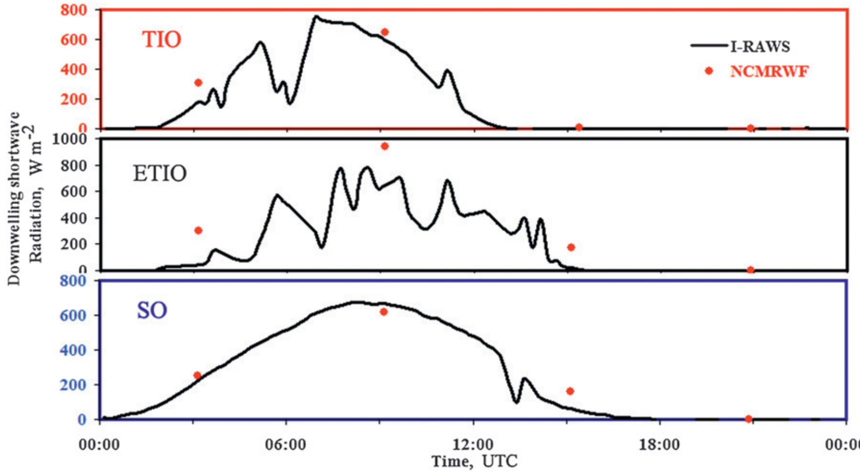

FIG. 6. Comparison of diurnal pattern of downwelling shortwave radiation for each oceanic regime.

with in situ data. While the bias and correlations were comparable for most of the variables, the RMS errors were generally lower for the ECMWF data. Best agreement between the model and in situ data was observed for the ETIO. Equally encouraging was the good agreement for the SO, where in situ data are practically absent.

This study throws more light on the measure of goodness of the model datasets, which are used as forcing fields of ocean models. Since the I-RAWS time series is unique and independent and also obtained from the data-sparse SO, it has a lot of potential uses. Net heat flux could be derived using bulk parameterizations if sea surface temperature data are also available. Keeping this in mind, the sea surface temperature sensor is also integrated with the I-RAWS. Such time series, if not assimilated into the models, could also be used to assess and remove the systematic biases present, if any, in the model reanalyzed products. The in situ data could be assimilated into the atmospheric models.

The I-RAWS being installed on board Indian ships is expected to provide in situ data over the Indian Ocean region for years to come. When data from all ships with I-RAWS installations are combined, they will enable the assessment of the quality of model reanalysis products and its eventual refinement. In addition, a denser network of IRWAS will generate data that can be assimilated into the models, thus improving the skills in monsoon forecasts.

Acknowledgments. Mr. Jeyamani, Mr. Murali, Mr. Arun, and Mr. Jayakumar are thanked for their efforts in the installation of ship-mounted AWS as well as for INSAT-3C integration. Thanks are also due to Mr. Rajasekhar, from NIOT, for the logistic supports extended during the installation of the ship-mounted AWS. We thank three anonymous reviewers for their constructive comments and suggestion on the manuscript and its eventual improvement. Special thanks to the editor for his valuable comments and editorial corrections. Ferret was used for data analysis and data visualization. Thanks are due to NCMRWF and ECMWF (through the ECMWF and YOTC websites) for providing the analyzed datasets derived from their models. Thanks are also due to the Ocean Observations and Information Services (OOIS) program of the Ministry of Earth Sciences (MoES), government of India. GSB thanks the Ministry of Earth Science, government of India, and the Department of Science and Technology, government of India, for support.

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