Ground-zero met–ocean observations and attenuation of wind energy during cyclonic storm *Hudhud*

R. Harikumar[1], T. M. Balakrishnan Nair[1,]*, B. M. Rao[1], Rajendra Prasad[2], P. Ramakrishna Phani[1], C. Nagaraju[1], M. Ramesh Kumar[1], C. Jeyakumar[1], S. S. C. Shenoi[1] and Shailesh Nayak[3]

[1]ESSO-Indian National Centre for Ocean Information Services, Hyderabad 500 090, India
[2]Andhra University, Visakhapatnam 530 003, India
[3]Earth System Science Organisation, New Delhi 110 003, India

Ocean–met observations from INCOIS real-time automatic weather station on-board a ship *RV Kaustubh* served as strong ground truth for satellite- and model-derived forecasts during the very severe cyclonic storm *Hudhud*, which made a landfall at Visakhapatnam, India. The ship recorded maximum wind speed of 204 km/h (with a minimum central pressure of 945 hPa), which is the highest (lowest) ever instrumentally recorded value at a location on the Indian coastline during any cyclone. Though the global model forecasts of wind fields have shown good agreement inland, they failed in representing the reality along the coasts. Variation in wind energy from ocean towards inland suggests that it is attenuated exponentially inland (the maximum wind power density had reduced by 93,406 W/m^2 at Anakapalle (~25 km) compared to the ocean, and by 7022 W/m^2 at Chintapalle (~100 km inland) compared to Anakapalle). The present study reinforces the significance of having real-time near-shore ocean–met observations, and their operational usage for evaluation (assimilation) of (into) ocean–met forecast models in realtime.

Keywords: Automatic weather stations, bias-corrected wind forecasts, forecast models, tropical cyclones, ship-based observations, wind power density.

WEATHER information and track prediction during the course of a cyclone are updated regularly through bulletins by meteorological centres like Earth System Science Organisation-India Meteorological Department (ESSO-IMD), India, and Joint Typhoon Warning Center (JTWC, USA)[1,2]. Such information is derived based on the latest satellite observations prior to issue of bulletins in conjunction with numerical model outputs. There have been several discussions/debates related to the overestimated values/forecasts given by various global meteorological agencies in case of past cyclones, especially the very severe cyclonic storm (VSCS) *Phailin* (8–14 October 2013). The major hurdle to assess these derived parameters is the lack of adequate and reliable observations along or near the track of the cyclones. Since the spatial gradient in geophysical parameters within a cyclone, from its centre to the periphery is too high, it is important to have observations along or near the cyclone tracks. There have been atmospheric observations reported and analysed in the past in connection with the Indian Ocean cyclones, but far away from the centre of the cyclonic systems[3,4]. The present study depicts the ship-based met observations, which are exactly along the cyclone track; moreover at its landfall location. The objectives of the present study are: (1) evaluation of the model-predicted atmospheric parameters provided by ESSO-National Centre for Medium Range Weather Forecast (NCMRWF), IMD and European Centre for Medium range Weather Forecast (ECMWF), and bias-corrected wind forecasts issued from ESSO-Indian National Centre for Ocean Information Services (INCOIS) for the latest cyclone *Hudhud* during 7–12 October 2014 in the Bay of Bengal (BoB), and (2) quantification of wind energy attenuation from the shore towards inland.

VSCS *Hudhud*

A depression was formed east of Andaman and Nicobar Islands during 03 : 00 UTC on 7 October 2014; which strengthened to a deep depression by 12 : 00 UTC the same day, and then to a cyclonic storm *Hudhud* by 03 : 00 UTC on 8 October 2014. The system moved northwestward and crossed the Andaman and Nicobar Islands between 03 : 00 and 04 : 00 UTC on 8 October 2014. It further intensified to a severe cyclonic storm in BoB by 03 : 00 UTC on 9 October 2014 and became VSCS by 09 : 00 UTC on 10 October 2014. The system was steered northwestward during most of its lifespan. It continued as a VSCS and crossed the Andhra Pradesh coast over Visakhapatnam between 11 : 30 and 15 : 30 IST on 12 October 2014.

---

*For correspondence. (e-mail: bala@incois.gov.in)

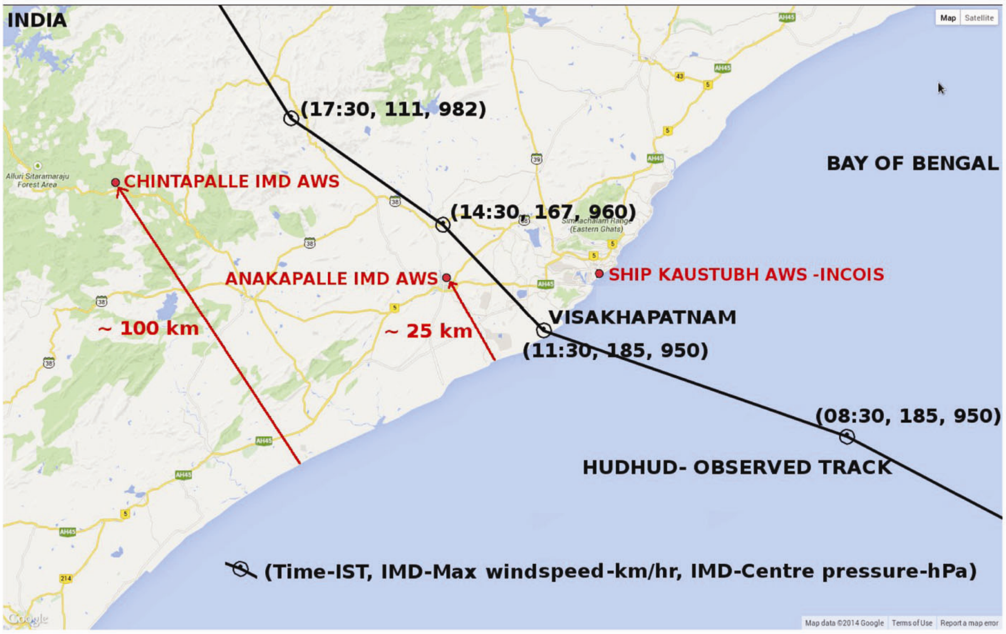

Figure 1. Location of automatic weather stations in a geographical map, and extreme values of wind and pressure (derived) along the track of very severe cyclonic storm *Hudhud* provided by ESSO-IMD.

Datasets

The real-time ship-mounted automatic weather station (AWS) (I-RAWS) network programme of ESSO (through the ESSO-INCOIS) now has 34 AWS[5]. Details about the programme and sensor characteristics are given in Harikumar *et al.*[5]. 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[6]. The main advantage of such marine sensors, which are mounted on-board ships, over the land-based sensors is that they are specially designed to withstand and take reliable measurements of marine atmospheric parameters even during extreme conditions like cyclones. One such ship, *RV Kaustubh* was anchored at the Visakhapatnam port (~83.303°E, 17.695°N, Figure 1) during the course of this cyclone, and she provided real-time ocean–met datasets of air temperature, air pressure, wind speed, wind direction, relative humidity, downwelling short-wave (SW) and long-wave (LW) radiations, to ESSO-INCOIS every 30 min, facilitated by the Indian National Satellite (INSAT) integration. These were the only datasets available exactly along the track; moreover at the landfall location of the cyclone. Data from two ESSO-IMD AWS[7] (Anakapalle, ~25 km from the coast and Chintapalle, ~100 km from the coast, Figure 1) were also utilized in the present study. No other reliable met observations were available within the near vicinity of the cyclone landfall point, i.e. Visakhapatnam. The ESSO-IMD Doppler Weather Radar at Visakhapatnam stopped working hours before the cyclone landfall. ESSO-IMD issues regular bulletins during the life cycle of a cyclone, providing the observed best track along with estimated maximum sustained wind speed and minimum central pressure, which are important cyclone parameters. The other wind datasets used in the present study are the forecasts from ECMWF and ESSO-NCMRWF, and the bias-corrected ESSO-INCOIS oceanic wind forecasts.

Methodology for bias-correction of ESMWF and ESSO-NCMRWF wind forecasts

Statistical bias-correction methods improve the direct model output-based forecast in terms of accuracy in forecast and have the potential for operational applications[8]. Several studies in the past have shown that winds from most of the re-analysed/forecast models are drastically and systematically underestimated beyond speeds of 15 m/s, which exists during depressions/cyclones[9]. Also, for such high wind speeds, the magnitude of bias is found to be directly proportional to the wind speed. So, a proper removal of this systematic bias/uncertainty can provide better data, especially in terms of magnitude. Range-wise average bias-correction technique/methodology has been applied to correct for the wind bias/uncertainty in the ECMWF and ESSO–NCMRWF forecast products[9]. The wind speeds have been divided into different ranges/bins of 1 m/s width. Since wind speeds <15 m/s are common,

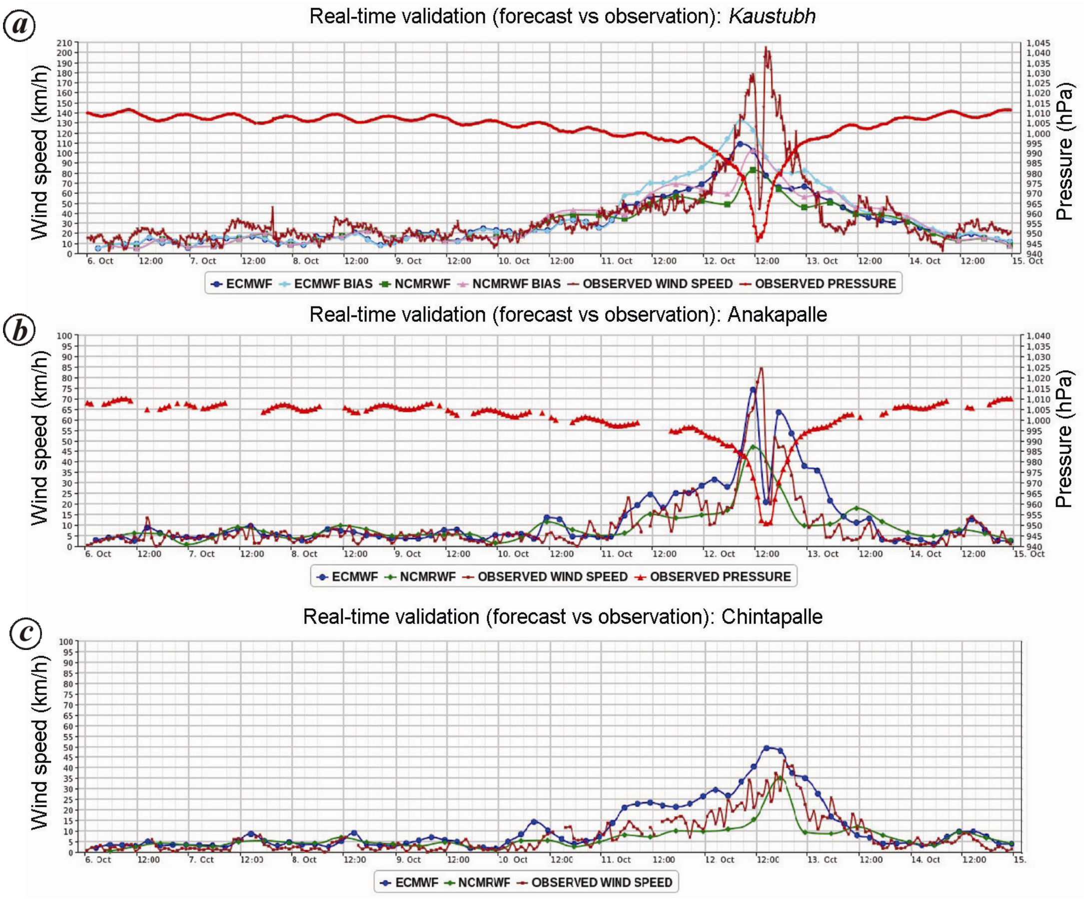

Figure 2. Comparison of wind speeds from AWS, ECMWF, NCMRWF and bias-corrected INCOIS forecasts at Visakhapatnam (***a***) and nearby locations (Anakapalle (***b***) and Chintapalle (***c***)). (Atmospheric pressure also is shown, except for Chintapalle, where data was not available.)

range-wise biases have already been found for ranges up to 15 m/s, especially using the I-RAWS mounted on-board Indian ships. However, during depressions/cyclones, satellite-based observations of high wind speeds (say >15 m/s) are available only from the bulletins issued by the operational cyclone warning centres like ESSO-IMD and JTWC. They periodically issue and keep updating these bulletins during the course of depressions/cyclones. Hence the biases within the bins of >15 m/s wind speeds have been found using these observations. The range-wise biases/uncertainties, derived up to maximum observed wind speeds, have been removed from the direct forecasted output products of ECMWF and ESSO-NCMRWF. These newly derived wind products have also been evaluated using *in situ* observations from ESSO-National Institute of Ocean Technology (NIOT) buoys and costal AWS at Gopalpur, Kakinada and Paradip, installed jointly by ESSO-INCOIS and CSIR-National Institute of Oceanography, and were found to have reasonable agreement. Verification of bias-corrected winds using these observations suggests that, on an average, the correlation (bias) improved (reduced) from 0.79 (3.7 m/s) to 0.9 (1.2 m/s) in BoB during the VSCS *Phailin*[9]. Thus, a new dataset of wind fields was prepared, which was evaluated using *in situ* observations during VSCS *Phailin* (October 2013) onwards, and utilized for forcing operational ocean state forecast models at ESSO-INCOIS. The same methodology has already been incorporated in the operational ocean state forecasting set-up at ESSO-INCOIS[10,11].

Data analysis, results and discussion

Figure 2 shows the maximum wind speed and minimum central pressure values observed from all the AWS and from the re-analysed products. The extreme values recorded and the time of such measurements are found to be varying since the locations are different; however, interpretation of all these four AWS data is important because all are within the influence limit of the cyclone ($R_{\max}$ was reported to be ~60 km as evidenced from the AVHRR satellite data[12]).

Figure 2 shows a comparison of wind speeds from AWS, ECMWF, ESSO-NCMRWF and bias-corrected wind forecasts (derived by ESSO-INCOIS) extracted at Visakhapatnam (where *RV Kaustubh* was anchored) and nearby locations (Anakapalle and Chintapalle).

Table 1. Highest recorded maximum wind speeds in the case of Indian cyclones

Cyclone duration	Landfall location	Observation location/source	Recorded maximum wind speed (km/h)	Reference	Remarks
7–12 October 2014	Visakhapatnam, Andhra Pradesh	Ship *RV Kaustubh* (I-RAWS, ESSO-INCOIS)	204	Present study	–
14–19 November 1977	Chirala, Andhra Pradesh	Ship *Jagatswamini* ATFY (10.7°N, 84.1°E)	193	15	Ship *Jagatswamini* went right into the 'eye' of the cyclone
8–4 October 2013 (VSCS *Phailin*)	Gopalpur, Odisha	Gopalpur	185	16	–
15–19 October 1999 (VSCS BoB 02)	Gopalpur, Odisha	Gopalpur	182	17	–
7–14 September 1972	Baruva, Andhra Pradesh	Puri	175	18	–
26–30 October 1971	Paradip, Odisha	Paradip	170	18	–
31 May–5 June 1976	Saurashtra, Gujarat	Ship *HAKKON MAGNUS*	167	19	Arabian Sea cyclone. Ship was reported to be anchored near the coast
10–13 May 1979	Ongole, Andhra Pradesh	Nellore	160	18	–
1–8 December 1972	North of Cudalore, Tamil Nadu	Cudalore	148	18	–
8–12 November 1977	South of Nagapattinam, Tamil Nadu	Thanjavur	120	18	–

Bias-corrected winds are derived only over the oceanic regime and not for the land; hence are not shown for Anakapalle and Chintapalle. Atmospheric pressure data are also plotted along with winds to ascertain the consistent 'low pressure–high wind' nature, which is expected. Pressure data were not available from Chintapalle AWS. The AWS on-board *RV Kaustubh*, being very near the track and a near-shore observation compared to other AWSs, showed maximum wind speed. It is worth mentioning here that these ship-mounted wind sensors are ultrasonic type with a measurement range 0–216 km/h, and a maximum error of ±2%. *RV Kaustubh* anchored in Visakhapatnam, which happened to be just beneath the eye of the cyclone, recorded maximum wind speed of 204 km/h (with a minimum central pressure of 945 hPa) on 12 October 2014. This is the highest (lowest) ever instrumentally recorded wind speed (pressure) at a location along the Indian-coastline during any cyclone. Table 1 lists the 10 highest instrumentally recorded maximum wind speeds during Indian cyclones. It may be noted that wind speed recorded by *RV Kaustubh* during VSSC *Hudhud* is the highest. Maximum sustained winds of 185 km/h and a minimum central pressure of 950 hPa at 11 : 30 IST on 12 October 2014, during the cyclone landfall, have been reported by IMD through their cyclone bulletins (Figure 1). This is in good agreement with ship AWS observations (Figure 2) of the wind speed (180 km/h) and central pressure (953 hPa) at 11 : 30 IST. It can be observed from Figure 2 that none of the global models or bias-corrected forecasts could pick an expected double peak in wind speed near the centre of the passing cyclone. Rather they have shown a single peak consistent with the first peak in the observation from *RV Kaustubh*, which was anchored in the coastal waters (but with a huge underestimation of 45 km/h for ECMWF bias-corrected, 70 km/h for ECMWF, 75 km/h for ESSO-NCMRWF bias-corrected and 90 km/h for ESSO-NCMRWF data). Further scrutiny revealed that the reason for lack of double-peak structure in the wind is because of the small difference in the landfall location seen in ECMWF and ESSO-NCMRWF forecasts fields. The landfall location represented in ECMWF and NCMRWF forecast is ~50 km south of the actual landfall point. Thus, the eye of the cyclone may not be represented in collocated forecast data with AWS, which exactly falls along the track. Hence, a double-peak wind structure is not seen in the forecasts, while it appears in *RV Kaustubh* AWS observations. Surprisingly, however, at a location 25 km interior to the coast (Anakapalle), the ECMWF forecasts showed a better match with the observations (underestimated just by 9 km/h); moreover with a double peak (but, ESSO-NCMRWF could only pick the first peak with an under-estimation of 37 km/h at Anakapalle; Figure 2). So, the deterioration of ECMWF and ESSO-NCMRWF forecasts at coastal land–ocean mixed grids compared to either inland location (as explained above) or the open ocean[9] reinforces the fact that such re-analysed and forecasted products fail to pick up the real conditions at mixed land–ocean grids along the coastline. However, we should also keep in mind that the ECMWF and ESSO-NCMRWF models are global in nature, meant for forecasting the synoptic features, and under such a context,

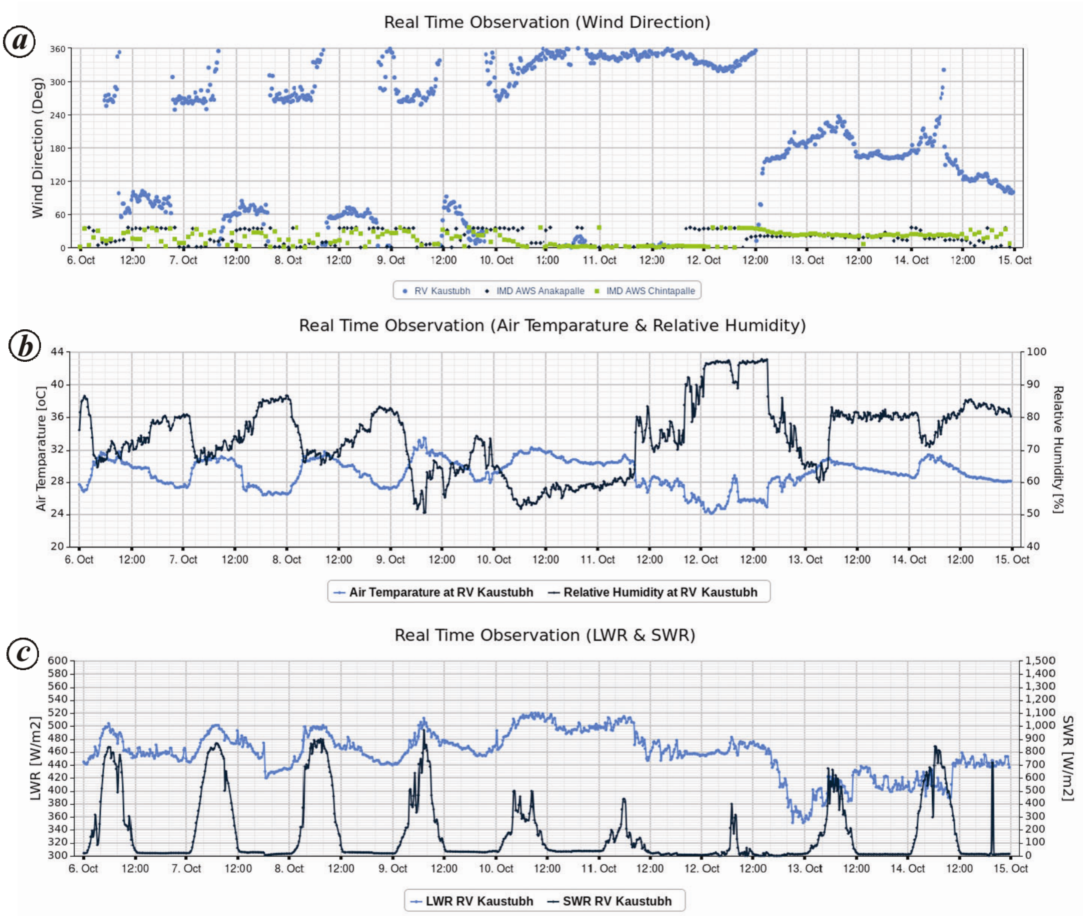

Figure 3. Wind direction observed from AWS on-board *RV Kaustubh*, at Anakapalle and Chintapalle (***a***), air temperature and relative humidity (***b***), and downwelling short-wave and long-wave radiations (***c***) from *RV Kaustubh*.

the agreements shown above for all locations are appreciable. Here lies the utmost importance of the observations on such coastal grids, which are to be accessed in real time (like that of I-RAWS), as in the present study. Such observations are useful not only to understand the real conditions and eventual necessary action, but can also be assimilated into the atmospheric and oceanic models for better predictions. Further, at a location which is ~100 km from the coast (Chintapalle), both ECMWF (with an overestimation of only 5 km/h) and ESSO-NCMRWF (with an underestimation of only 7 km/h) wind forecasts could pick up the single peak observed by the AWS (Figure 2).

Figure 3 *a* shows the wind direction. The land and sea breeze signatures can clearly be made out only from the coastline observations. Such an organized diurnal pattern is seen in the ship observations until 10 October 2014, two days before the landfall. During daytime the prevailing wind direction was ~90° (easterly), indicating sea breeze from BoB to the Indian continent; while at the night the wind direction was ~270° (westerly), indicating land breeze from the Indian continent to the BoB. But, the winds became northerly from 10 October 2014 morning onwards, and sustained to be northerly until 12 : 30 IST, an hour after the landfall on 12 October 2014. This indicates the effect of the cyclonic system, whose winds in its left (west) side will be northerly in the northern hemisphere. The cyclonic system moved further into the mainland, and there was an experience of calm condition during the passage of the cyclonic eye from 12 : 30 to 13 : 30 IST on 12 October 2014. Then the winds started strengthening with a reversal in direction (i.e. southerly) as expected when a cyclone passes through. This southerly trend continued until 14 October 2014 morning. After that the winds became westerly and then northwesterly, and again turned to be easterly to revive the normal diurnal pattern, as seen until 10 October 2014.

A consistent diurnal pattern of air temperature and relative humidity was observed until 12 : 00 IST on 10 October 2014 (Figure 3 *b*). Thereafter, a decreasing trend in the air temperature with an associated increasing trend in relative humidity was seen. A significant decrease of 6°C in air temperature (minimum was 24°C on the landfall day, while average during normal days was 30°C) and increase in relative humidity (maximum was 97% on the landfall day, while average during normal days was

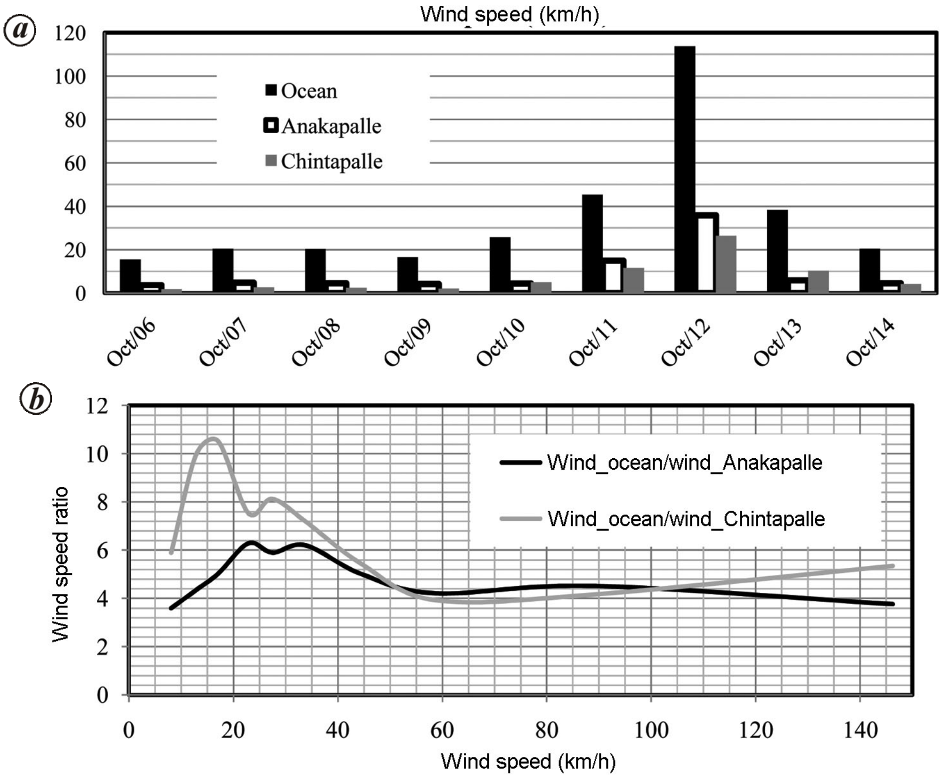

Figure 4. ***a***, comparison of daily wind speeds observed in the ocean, Anakapalle and Chintapalle. ***b***, Variation in the ratio of wind speed in the ocean to that at Anakapalle and Chintapalle versus wind speed.

75%, i.e. an increase of 22%) were noticed on 11 October 2014, 09 : 00 IST onwards, as expected owing to heavy precipitation associated with the cyclone.

It can be noticed from Figure 3 *c* that the maximum incoming SW radiation during normal days was ~900 Wm^{-2}, but it reduced to ~500 Wm^{-2} on 10 October 2014, and again reduced to ~430 Wm^{-2} on 11 October 2014, and to ~400 Wm^{-2} on the landfall day, because of a large cloud cover. Again it started increasing to ~600 Wm^{-2} on 13 October 2014, and subsequently ~820 Wm^{-2} on 14 October 2014. The LW radiation did not show any diurnal variation from 12 : 00 IST on 10–14 October 2014 indicating an overcast sky.

Variation of wind energy from ocean towards inland

To understand the impact of the cyclone, especially in terms of the devastating winds, wind power density and wind ratio analyses have been carried out for oceanic/near-shore (from *RV Kaustubh*), and inland locations (Anakapalle and Chintapalle). The main objective of such an analysis is to assess the attenuation of wind as it approaches the coast and traverses inland. Antony *et al.*[13] have done a detailed study on the wind speed attenuation at Kavaratti Island using land-based, offshore and satellite measurements. They found that round-the-year monthly mean wind speed measurements from Port Control Tower (PCT) located within the coconut palm farm at the Kavaratti Island were weaker by 15–61% relative to those made from the nearby offshore region. Moreover, during the November 2009 tropical cyclone *Phyan*, wind speed measurements from PCT indicated approximately 50–80% attenuation relative to those from the seaward boundary of the island's lagoon (wherein the influence of coconut palms is the least).

Figure 4 *a* shows a comparison of daily wind speeds observed at ocean, Anakapalle and Chintapalle. During normal conditions as well as during the cyclone period, winds are drastically high at the oceanic regime off Visakhapatnam, and less at Anakapalle and least at Chintapalle. The only exemption was on 13 October 2014, when the wind at Anakapalle was marginally less than that at Chintapalle. To check the measure of attenuation and its quantification, variation in the ratio of wind speed in the ocean to that at Anakapalle and Chintapalle is plotted (Figure 4 *b*). Higher ratio indicates more attenuation. Up to ~50 km/h wind speed, the ratio varies between 4.5 and 10.5 for Chintapalle, while it is less and varies between 3.5 and 6 for Anakapalle. For a wind speed range 50–110 km/h, the ratio at both Anakapalle and Chintapalle to the ocean is ~4. The ratio is again more (average = 4.5) at Chintapalle than at Anakapalle (average = 4)

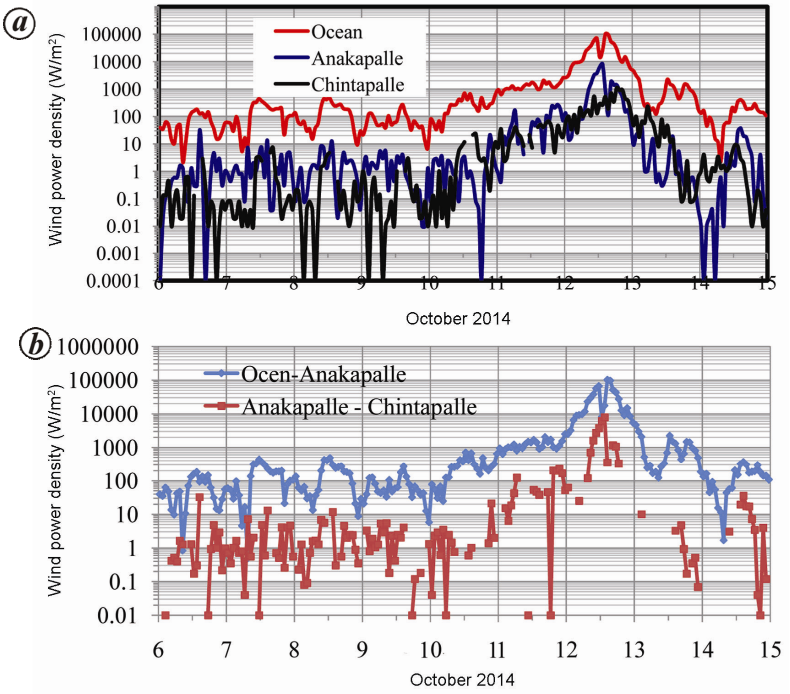

Figure 5. ***a***, Comparison of derived wind power density (WPD) (note *Y*-axis is logarithmic) for ocean, Anakapalle and Chintapalle. ***b***, Difference in WPD (note *Y*-axis is logarithmic) between ocean and Anakapalle, as well as Anakapalle and Chintapalle (gaps exist in the time series because of the presence of negative values of difference in WPD in the *Y*-axis, which is represented in the logarithmic scale).

Figure 6. Photograph showing the damage after the cyclone.

for wind speeds above 110 km/h. This analysis suggests that there is more attenuation of wind speed at Chintapalle compared to that at Anakapalle.

Devastation due to a cyclone happens because of the huge wind energy dissipation. To get a clear picture about the wind energy attenuation from oceanic regime towards inland, a study on the variation of wind power density (WPD) from ocean toward inland was carried out using observations from the ocean, ~25 km inland and ~100 km inland. Normally, wind assessment is done on the basis of WPD, which can be defined as the wind energy per unit area per unit time[14]. WPD is a function of cube of the wind speed; so a small increase in wind speed will cause a drastic increase in the wind energy, which will normally be significant and applicable, especially during cyclonic conditions. Figure 5 *a* shows the time series of WPD at Ocean, Anakapalle and Chintapalle. The exponential decrease in WPD at inland locations compared to oceanic location is evident from the figure (note that the *Y*-axis is made logarithmic to incorporate both very high and very low-values). As expected, WPD again decreased at Chintapalle (being the most inland location in the present study), compared to Anakapalle. Average WPD for normal days was 113.5 W/m^2 in the ocean, 2.1 W/m^2 at Anakapalle and only 0.56 W/m^2 at Chintapalle. WPD in the ocean increased from 124 W/m^2 (but only from 3.48 W/m^2 at Anakapalle and 0.2 W/m^2 at Chintapalle) on 10 October 2014, and reached a maximum of 101,535 W/m^2 (but up to only 8129 W/m^2 at Anakapalle and 1107 W/m^2 at Chintapalle) on landfall day. The average WPD during the time of landfall to time of full coastal crossing of *Hudhud* (considered to be the most devastating period) has been derived. It was 57,725 W/m^2 in the ocean, but was only 3876 W/m^2 at Anakapalle and just 280 W/m^2 at Chintapalle. Thus the cyclone with such high kinetic energy hit the coast of Visakhapatnam and caused extreme devastation upon landfall. Figure 6 shows the damage after cyclone passage at Visakhapatnam due to high winds and the consequential impending ocean waves formed in the near coast. After crossing the coast, WPD was found to dissipate and had a low value at Anakapalle, which is aerially ~25 km inside the land, and the lowest value at Chintapalle, which is aerially ~100 km from the coast. WPD attained a normal value of 108 W/m^2 (4.1 W/m^2 at Anakapalle and 0.13 W/m^2 at Chintapalle) by 15 October 2015. Figure 5 *b* shows the time series of the difference in WPD between ocean and that at Anakapalle, as well as between Chintapalle and Anakapalle (gaps exist in the time series because of the presence of negative values of difference in WPD on the *Y*-axis, which is represented in the logarithmic scale). If we look into the maximum values, WPD is found to be exponentially attenuated by a value of 93,406 W/m^2 at Anakapalle (~25 km inland) than in the ocean, and by 7022 W/m^2 at Chintapalle (~100 km inland) than at Anakapalle. This is a clear indication of the attenuation of wind energy as the cyclone passes from the ocean, crosses the coastline, traverses through the coastal areas and reaches an inland location.

Conclusion

The real-time ocean–met observations obtained from AWS on-board *RV Kaustubh*, which was anchored at Visakhapatnam, the landfall location of VSCS *Hudhud*, served as a ground truth for validation of cyclone forecasts. The real-time reception of such ground truth was helpful for continuous monitoring of the cyclone during landfall, and also to understand the real met conditions during the entire course of the cyclone. This study has thrown more light on the 'adverse coastal mixed land–ocean grid effects', which is responsible for poor performance of the re-analysed products and related forecasts at such land–ocean boundaries, especially during extreme weather conditions. This study endorses the existence of very high (very low) wind speeds (pressure), even more than 200 km/h (less than 945 hPa), in the eye-wall of VSCS *Hudhud*, and also the possible highly fluctuating meteorological conditions evidenced from the pattern of air temperature, relative humidity, SW and LW radiations, and possible wind directions. Quantitative analyses of wind energy variation from open ocean towards inland have shown that there is an exponential attenuation of wind energy inland compared to the ocean. Thus, the present study justifies the need of near-shore real-time observation systems capable of withstanding severe cyclones. Presently, I-RAWS is comprised of 34 units, and it is planned to expand the network further in future. This would provide the much needed near-shore observations for assimilation in forecast models, leading to improvement in the forecast and advisories from major operational oceanographic and meteorological agencies around the world.

1. http://www.imd.gov.in/
2. http://www.usno.navy.mil/JTWC/
3. Murthy, B. S., Latha, R. and Manoj Kumar, Influence of tropical cyclone 'AILA' on atmospheric surface layer turbulence and fluxes at Ranchi during its landfall. *Atmos. Sci. Lett.*, 2014, **15**, 72–78.
4. Venkatesan, R. *et al.*, Signatures of very severe cyclonic storm Phailin in met–ocean parameters observed by moored buoy network in the Bay of Bengal. *Curr. Sci.*, 2014, **107**(4), 589–595.
5. Harikumar, R., Balakrishnan Nair, T. M., Bhat, G. S., Shailesh Nayak, Venkat Shesu Reddem and Shenoi, S. S. C., Ship-mounted real-time surface observational system on-board Indian vessels for validation and refinement of model forcing fields. *J. Atmos. Ocean. Technol.*, 2013, **30**, 626–637.
6. McPhaden, M. J. *et al.*, RAMA: The Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction. *Bull. Am. Meteorol. Soc.*, 2009, **90**, 459–480.
7. http://www.imdaws.com/viewawsdata.aspx
8. Durai, V. R. and Rashmi, B., Location specific forecasting of maximum and minimum temperatures over India by using the statistical bias corrected output of global forecasting system. *J. Earth Syst. Sci.*, 2014, **123**(5), 1171–1195.
9. Harikumar, R., Nagarju, C., Balakrishnan Nair, T. M., Remya, P. G., Hithin, N. K., Mehra, P. and Shenoi, S. S. C., Correction of wind fields during VSCS Phailin using bulletins from IMD & JTWC and ship-mounted INCOIS real-time AWS network. In Proceedings of the National Workshop on Enhanced and Unique Cyclone Activity during 2013, India Meteorological Department (IMD), New Delhi, 2014.
10. Balakrishnan Nair, T. M. *et al.*, Performance of the ocean state forecast system at Indian National Centre for Ocean Information Services. *Curr. Sci.*, 2013, **105**(2), 175–181.
11. Balakrishnan Nair, T. M. *et al.*, Wave forecasting and monitoring during very severe cyclone *Phailin* in the Bay of Bengal. *Curr. Sci.*, 2014, **106**, 1121–1125.
12. http://www.incois.gov.in/portal/remotesensing
13. Antony, J., Pradhan, R. and Balakrishnan Nair, T. M., Study of wind speed attenuation at Kavaratti Island using land-based, offshore, and satellite measurements. *Proc. SPIE*, 2012, **8372**, 10.
14. Harikumar, R., Sabique, L., Balakrishnan Nair, T. M. and Shenoi, S. S. C., Report on the assessment of wind energy potential along the Indian coast for offshore wind farm advisories. INCOIS Report No. INCOIS-MOG&ISG-TR-2011-07, 2011.
15. Desai, D. S. and Huparikar, M. G., Comparison of two super cyclonic storms over the Bay of Bengal (i) 14–20 November 1977, (ii) 25–31 October 1999. *Mausam*, 2004, **55**(4), 713–720.
16. IMD, Cyclones and depressions over the north Indian Ocean during 2013. *Mausam*, 2014, **65(3),** 299-318.
17. IMD, Report on cyclonic disturbances over north Indian Ocean during 2000. IMD-RSMC Report, IMD, New Delhi, 2001.
18. http://www.imd.gov.in/section/nhac/static/cyclone-history-bb.htm
19. http://www.imd.gov.in/section/nhac/static/cyclone-history-as.htm

ACKNOWLEDGEMENTS. We thank India Meteorological Department for providing the cyclone-observed best track and timely cyclone bulletins, and the land-based AWS data, and the anonymous reviewers for their suggestions that helped improve the manuscript. We are grateful to Geological Survey of India, Kolkata and National Institute of Ocean Technology, Chennai for providing all support in installing and maintaining I-RAWS in their ships. We also thank the Ministry of Earth Sciences, Government of India for financial support. This is ESSO-INCOIS contribution 214.

Received 29 January 2015; revised accepted 26 February 2016

doi: 10.18520/cs/v110/i12/2245-2252