

Operational weather forecasting using data from Automatic Weather Stations and other modern observing systems - Case study of tropical cyclone Jal 2010

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सार – अब तक जिन स्थानों से मौसम संबंधी घंटेवार आँकड़े उपलब्ध नहीं हो पाते थे अब भारत मौसम विज्ञान विभाग से उपग्रह के आधार पर स्वचालित मौसम स्टेशनों (AWS) के संस्थापन के कारण ये आँकड़े प्राप्त होने लगे हैं और इन आँकड़ों का बहुत महत्व है। प्रचालनात्मक मौसम पूर्वानुमान के लिए इस प्रकार के ए. डब्ल्यू. एस. से प्राप्त किए गए आँकड़ों की संभावित उपयोगिता विशेषकर उस समय बहुत अधिक होती है जिस समय चक्रवाती तूफान जैसी मौसम की प्रतिकूल स्थितियाँ होती हैं। इस शोध पत्र में, बंगाल की खाड़ी में 4–8 नवम्बर, 2010 की अवधि में उष्णकटिबंधीय चक्रवात (TC) जाल के बनने तथा उसके चेन्नै के उत्तरी भाग को पार करने के मामले का अध्ययन किया गया है। इसमें मुख्यतः भारतीय प्रायद्वीप के दक्षिणी क्षेत्र में ए. डब्ल्यू. एस. से प्राप्त किए गए आँकड़ों का उपयोग किया गया है। इसमें जाल की तीव्रता का निर्धारण करने में आँकड़ों की उपयोगिता को बताया गया है। 7 नवम्बर, 2010 को 1800 यू.टी.सी. के आसमास श्रीहरिकोटा (SHR) के निकट जाल के स्थल प्रवेश के स्थान को उच्च पवन गति अभिलेख, चेन्नै में डॉप्लर मौसम रेडार (DWR) के उत्पादों तथा कल्पना-1 उपग्रह से प्राप्त उच्च विभेदन वाले चित्रों जैसे अन्य आधुनिक उपकरणों से प्राप्त की गई सूचनाओं को सहसंबंधित करते हुए उसका सही ढंग से पता लगाया गया है। सैद्धांतिक रूप से व्युत्पन्न अनुपातिक स्थिरांक (के.) का उपयोग करते हुए चक्रवात वाले क्षेत्र में दाब की कमी और अधिकतम पवनों को आकलित किया गया है। चेन्नै के उत्तर में स्थित एन्नूर बंदरगाह में लगे ए. डब्ल्यू. एस. द्वारा अभिलेखित किए गए पवन गति मानों का उपयोग करते हुए भू-स्टेशन में प्रक्षिप्त किए गए अधिकतम पवनों का पर्यावरणी प्रवाह, उसके आगे बढ़ने की दिशा और घर्षण के प्रभाव का विश्लेषण किया गया है। समुद्र में चक्रवात की पवन गति की संभव न्यून सीमा को आकलित किया गया और यह सत्यापित किया गया कि 7 तारीख को 0600 यू.टी.सी. पर चक्रवाती तूफान के रूप में टी. सी. जाल से की गई प्रचालनात्मक घोषणा सही थी।

ABSTRACT. The hourly meteorological data available from hitherto unrepresented locations due to the installation of satellite-based Automatic Weather Stations (AWS) by India Meteorological Department are valuable. The potential utility of data from such AWS for operational weather forecasting is tremendous, particularly during adverse weather situations like that of a cyclonic storm. In this paper, a case study of the Tropical Cyclone (TC) Jal which formed during the period 4-8 November, 2010 over Bay of Bengal and crossed north of Chennai has been undertaken mainly by utilising data from AWS in the southern Indian peninsula. Utility of the data in assessment of the intensity of Jal has been explained. The landfall location of Jal near Sriharikota (SHR) around 1800 UTC of 7th November, 2010 could be pinpointed using wind and hourly pressure data correlated with inputs from other modern equipments like the High Wind Speed Recorder, products from Doppler Weather Radar (DWR) at Chennai and high resolution imageries from Kalpana-1 satellite. The pressure defect and maximum winds in the cyclone field have been computed by using a theoretically derived proportionality constant (K). An analysis on the effect of environmental flow, direction of movement and friction on the maximum winds observed in a land station has been made using the wind speed values recorded by AWS at Ennore Port located north of Chennai. The possible lower bound of wind speed of the cyclone while out at sea has been computed and verified that the operational declaration of the TC Jal as a cyclonic storm at 0600 UTC of 7th was correct.

Key words – Tropical cyclone, Automatic weather stations, Northeast monsoon, Vertical wind shear, Doppler weather radar, TRMM, Proportionality constant.

1. Introduction

The operational weather forecaster always faces the challenge and prime responsibility of assessing the likely

direction of movement of Tropical Cyclones (TC) and predicting the landfall location with utmost reliability. Enhanced accuracy in track prediction can be achieved by ensuring data availability from land as well as oceanic

areas. The mandate of National Meteorological Services all over the world has ever been to achieve better accuracy in forecasting TCs. Prior to the 1960s, weather forecasting depended entirely upon the manual observations recorded by observers working round the clock in various meteorological offices. Radars were inducted for weather observations subsequent to the second World War. With the advent of satellites since 1960s a bird's eye view of the earth with clouds at different parts of the globe could be obtained. The accuracy levels with which the tracks of cyclones could be monitored improved significantly with more frequent availability of satellite pictures. Satellite imagery is most useful at all stages of development of TCs, for first detecting their formation out at sea, then following their movement, determining their intensity and observing changes in their characteristics (Kelkar, 2007).

In India, the network of conventional, manned, surface observatories is generally not fully adequate to meteorologically represent regions having diverse seasonal weather patterns. The technology of satellite-based Automatic Weather Stations (AWS) is successfully used since 1997 by installing 15 of them on a trial mode to obtain reliable observations from hitherto unrepresented locations. Subsequently, 125 AWS were commissioned all over India during 2006-07 (Ranalkar *et al.*, 2008). IMD has further augmented its AWS network under the modernisation programme considering its utility in monitoring and prediction of weather events including monsoon circulations (Mohapatra *et al.*, 2011). Installation and commissioning of an additional 550 AWS (Ranalkar *et al.*, 2010) has been completed. Data from the AWS prove to be useful in enhancing the accuracy levels in weather forecasting. Utilisation and assessment of the extent of reliability of AWS data from remote locations during cyclonic disturbances of the year 2010 has been documented (Mohapatra *et al.*, 2011).

The objective of this study is to evaluate the utilities of AWS in operational weather monitoring, prediction of location, intensity, movement and landfall characteristics of cyclonic disturbances. AWS data is used as one of the main inputs and a case study has been attempted for the Severe Cyclonic Storm (SCS) Jal (4-8 November, 2010) which originated, traversed in the Bay of Bengal (BoB) and crossed the extreme northern part of Tamil Nadu coast, north of Chennai city on 7th November during the Northeast Monsoon (NEM) season of 2010. Observations from other modern observing systems such as the Doppler Weather Radar (DWR) have been compared with those from AWS to firmly conclude the time and place of landfall of Jal and to show that the results enhance the dependability of AWS data, more so during adverse weather. When used along with data from conventional synoptic stations, errors in locating the

landfall point can be minimised and the focus of this study is to evaluate the accuracy levels up to which AWS can be relied upon.

A low pressure area over South Andaman Sea formed at 1200 UTC of 2nd November, 2010, became more marked on 3rd over the same area, concentrated into a Depression at 0000 UTC of 4th, was seen within half a degree of Lat. 8.5° N / Long. 91.0° E at 0300 UTC of 4th, intensified into a Deep Depression within half a deg. of Lat. 9.0° N/Long. 88.5° E at 0000 UTC of 5th, further intensified into a Cyclonic Storm (CS) and was named as 'Jal'. It was seen centered near Lat. 9.0° N / Long. 87.5° E, about 900 km ESE of Chennai at 0600 UTC of 5th. Jal took a northwesterly course, intensified into SCS near Lat. 10.0° N/Long. 86.0° E, about 700 km southeast of Chennai, at 2100 UTC of 5th. Jal continued to be SCS till 7th / 0300 UTC then it weakened into a CS at 0600 UTC of 7th Nov., 2010 over southwest BoB with centre near Lat. 12.5° N / Long. 82.5° E about 250 km east southeast of Chennai. While continuing its northwesterly track, it weakened as a Deep Depression (DD) at 1200 UTC of 7th and lay centred at Lat. 13° N / Long. 81° E (IMD, 2011). Jal crossed the coast as a DD north of Chennai near Sriharikota (Lat. 13.66° N / Long. 80.22° E) at 1800 UTC on 7th November, 2010 (RSMC, New Delhi, 2011).

An important aspect of the tracking and intensity estimation of Jal when it was out at sea was that its intensity appeared to have been slightly overestimated by some of the international monitoring agencies, in this case, Joint Typhoon Warning Centre (JTWC), Hawaii. The various users and general public in Tamil Nadu who were closely monitoring Jal's movement through updates in IMD web site had a view that Jal crossed the coast in the morning of 7th November itself due to cessation of rain. The reanalysed wind output of the gridded data made available by the National Centre for Environmental Prediction (NCEP), Earth System Research Laboratory (ESRL) of National Oceanic and Atmospheric Administration (NOAA) showed presence of high easterly wind shear in the upper tropospheric levels. Under the influence of the easterlies, the rain-bearing cloud mass sheared off towards the west by 0600 UTC on 7th November, much ahead of the landfall of the vortex circulation. Jal entered a region of low ocean thermal energy in the BoB which led to unsustainability of convection over the region (RSMC, New Delhi 2011). The wind and mean sea level pressure (m.s.l.p.) data available from AWS and the products from Doppler Weather Radars (DWRs) at Chennai and Sriharikota provided an indication of the presence of the vortex circulation in the sea devoid of moisture. IMD had declared the intensity of Jal which was bereft of clouding but still out at sea as CS at 0600 UTC of 7th November.

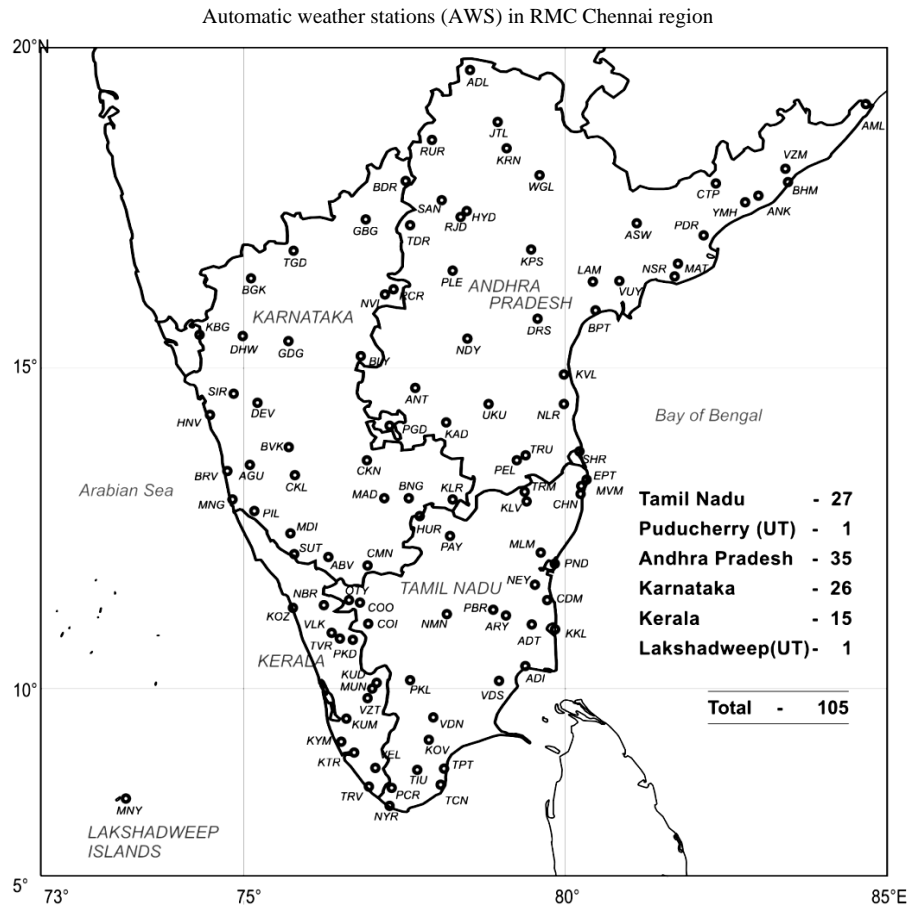


Fig. 1. Spatial distribution of AWS in the southern Indian peninsula

Jal crossed north of Chennai coast near Sriharikota on 7th November at 1800 UTC according to the DWR data and as per the data recorded by AWS.

In Section 2, the focus is to analyse various features of Jal by effectively using the data available from the AWS network, particularly of the southern peninsular India. Data from other modern equipments has also been utilised to support the inferences from AWS data. Section 3 traces the methodologies used in the analysis of AWS data. Section 4 highlights the inferences from the analysis of m.s.l.p., wind and rainfall data obtained from AWS. The results are compared with radar and other outputs from modern observing systems like satellite and reanalyzed upper level winds. The distance traversed and direction of movement have been calculated. Maximum wind speed associated with Jal when it is close to the coast has been derived utilising the wind data recorded by a coastal AWS after incorporating the effects of environmental flow. Section 5 discusses about the conclusions which emphasise the increased dependability

and accuracy of AWS for use in operational weather forecasting, during adverse weather situation in particular.

2. Data

The number of AWS in southern peninsular India which comprises of the states of Tamil Nadu, Andhra Pradesh, Kerala, Karnataka, Union Territories (UT) of Lakshadweep and Puducherry coming under the administrative jurisdiction of the Regional Meteorological Centre, Chennai is 105 (as on June 2012). Out of them, 35 were commissioned during 2007 and 70 in 2010. The conventional observatory at Chennai Nungambakkam (13° N / 80° E) also has an AWS in its premises since 2007. During October 2010, an AWS was commissioned at Ennore Port (13.25° N / 80.31° E), located north of Chennai, very close to the BoB coast at about a distance of 900 metres with ideal meteorological exposure conditions. It is a meteorologically unrepresented area and data from such vantage locations, in the coastal areas near

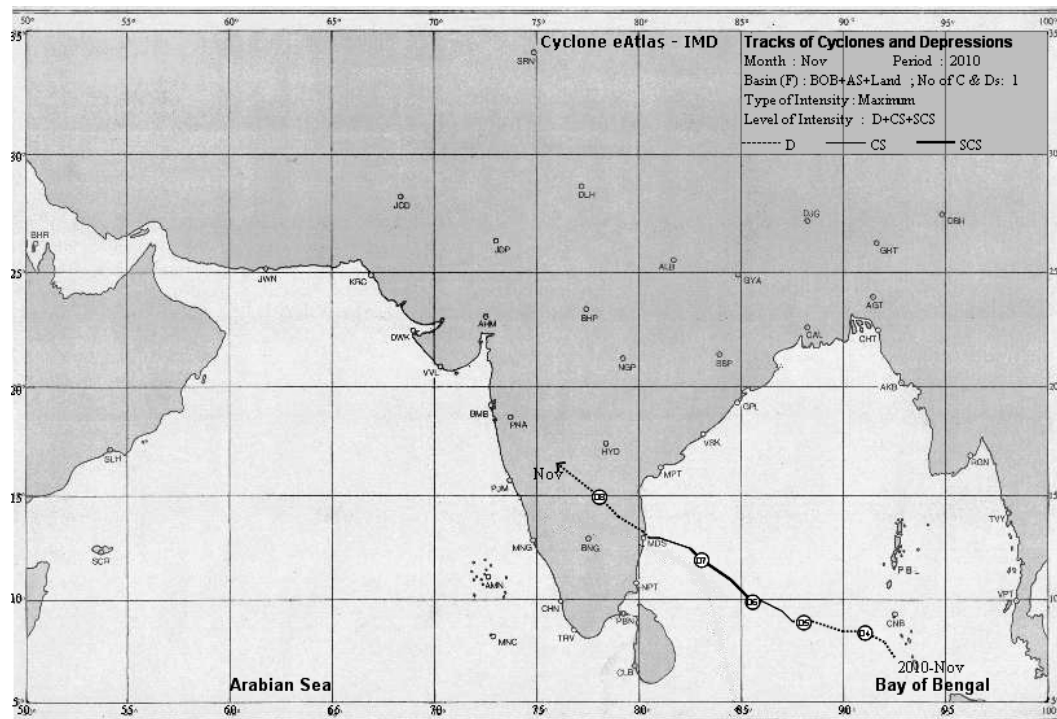


Fig. 2. Track of the tropical cyclone Jal, 4-8 November, 2010

Chennai city, are valuable during adverse weather situations like that of a barrage of a cyclonic storm. Madhavaram is another AWS located at 13.15° N / 80.23° E, near Chennai. Sriharikota, located 60 km north of Chennai was meteorologically unrepresented till the installation of AWS in the year 2007. The spatial distribution of the 105 AWS is depicted in Fig. 1. The AWS have ultrasonic wind sensors mounted at a height of 10 metres from ground level as per standards prescribed by the World Meteorological Organisation (WMO) for measurement of wind. Sampling at one second interval and the vector average of all the 180 samples recorded during the three minutes prior to the top of the hour at which observation is recorded gives the wind direction and speed. The temperature and humidity sensors are mounted at 2 metres height (WMO, 2008).

At the time of occurrence of TC Jal, work of installation of AWS was under progress in Tamil Nadu and Andhra Pradesh and so the data used for the study comprises of a much less number than 105. The number of AWS whose data has been used varies for wind, pressure and rainfall analysis depending upon the availability of data at those UTCs and has been explicitly stated at the appropriate locations. Since data validation has been done by comparison with conventional methods, the AWS data is dependable for utilisation in operational forecasting. Following data are considered for analysis.

(i) The quality-checked hourly m.s.l.p. data and 24 hours m.s.l.p. tendency of AWS of Tamil Nadu (TN), Puducherry (PND), Coastal Andhra Pradesh (CAP) and a few in Karnataka and Kerala, which were commissioned just prior to the occurrence of Jal.

(ii) The wind speed, wind direction and cumulative rainfall data of AWS in the region.

(iii) Wind data recorded at one minute interval, by the High Wind Speed Recorder (HWSR) installed at Chennai-Nungambakkam.

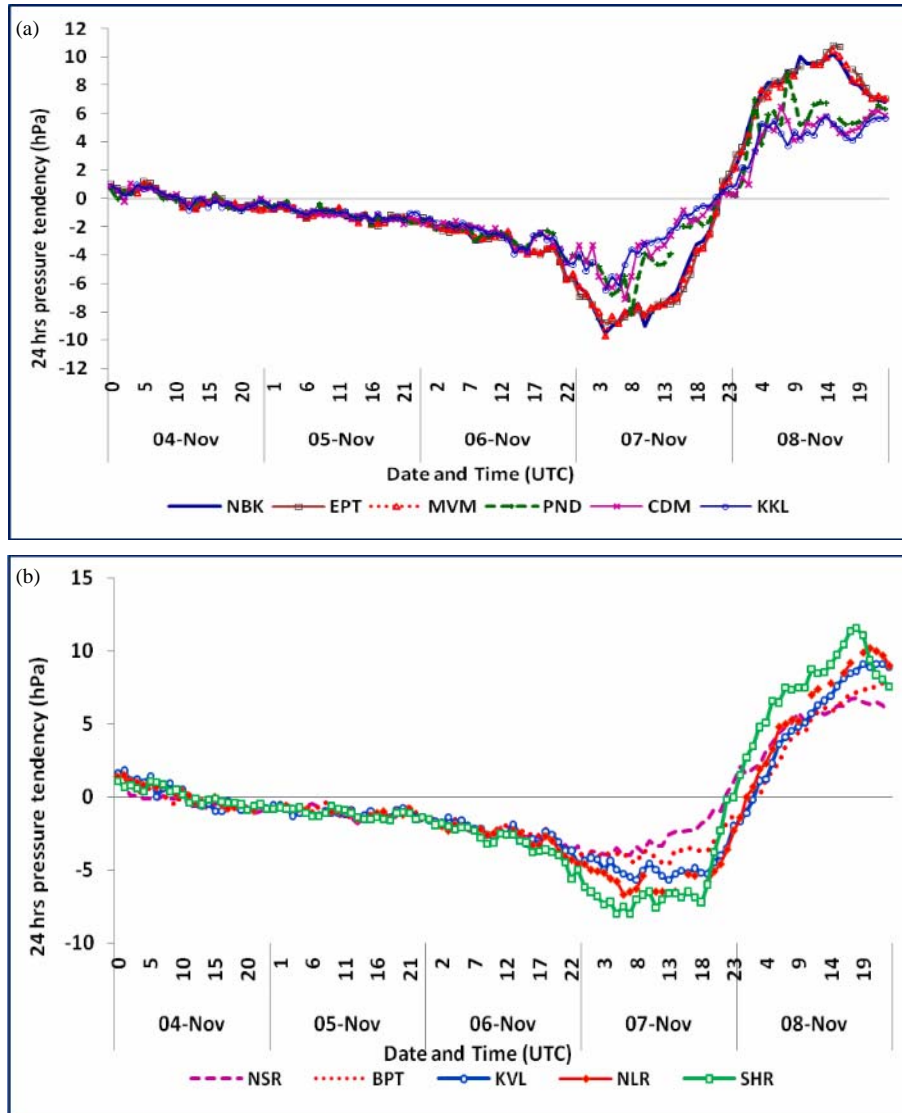
(iv) Kalpana-1 satellite pictures of the Very High Resolution Radiometer (VHRR) at $2.5^{\circ} \times 2.5^{\circ}$ resolution from the web site (<http://www.imd.gov.in>) of IMD.

(v) Products from Doppler Weather Radars (DWR) at Chennai and Sriharikota.

(vi) Cyclone track positions obtained from eAtlas, IMD.

3. Methodology and analysis

3.1. Data from AWS, HWSR and the products from DWRs at Chennai and Sriharikota have been utilised to show how these inputs helped the weather forecaster to track, monitor, assess the intensity and forecast the likely



Figs. 3(a&b). Variation in 24 hours m.s.l pressure tendency (a) six AWS of coastal Tamil Nadu and (b) five AWS of coastal Andhra Pradesh

landfall location of TC Jal. The track of the TC Jal generated by the eAtlas (IMD, 2008) is provided in Fig. 2. The variations in wind, hourly m.s.l.p. and 24 hours pressure tendency recorded by the AWS have been brought out. Surface level wind flow pattern using the hourly data of 66 AWS has been generated for 1500, 1600, 1700 & 1800 UTCs of 7th November. Variability in hourly m.s.l.p. of 7 AWS in TN and CAP located near the landfall point has been analysed for all the days and graphical results presented for 7th November alone. Rainfall is an important meteorological parameter during the passage of a TC. In order to prove the reliability of the rainfall values reported by AWS, validation is done for 11 AWS which have co-located conventional

observatories by one-to-one comparison of rainfall data and the results are presented for the period 4-9 November, 2010. Such validated rainfall data has been used as the yardstick for comparison of the rainfall values estimated through other techniques. A significant spatial variability is observed in the rainfall recorded by an AWS and a part-time observatory or DRMS (District-wise Rainfall Monitoring Scheme) station in the same locality when they are separated by even a few kilometres distance. Hence, a comparison of such data did not yield reliable results. By using the '3B42V6' algorithm derived precipitation estimates of the Tropical Rainfall Monitoring Mission (TRMM) satellite, it is easier to estimate rainfall with reasonable accuracy over a large area than a small

one and when the rainfall is widespread rather than localised (Durai *et al.*, 2010). Hence, the cumulative rainfall realised by 71 AWS has been compared, superimposed with the TRMM satellite rainfall and presented. It is observed from this analysis that for some stations the rainfall is overestimated by TRMM and underestimated for many others if one earmarks the standard for comparison as that validated with rainfall values of co-located AWS and observatory.

3.2. The distance traversed, speed and direction of movement during the life-time of Jal were calculated by using the six-hourly latitude / longitude positions from 4th November onwards up to the point of landfall utilising some of the concepts presented in Raj (2010) in which a detailed theoretical analysis on the relation between pressure defect and maximum wind in the field of a tropical cyclone has been carried out.

3.3. The formula used by Fletcher (1955) for calculation of maximum wind speed is given by the equation for V_m which is

$$V_m = K\sqrt{P(n) - P(o)}$$

Where, V_m is the maximum wind speed in knots, $P(n)$ is the m.s.l. pressure at the outer isobar and $P(o)$ is the m.s.l. pressure at the centre of the cyclone located over the sea. For North Indian Ocean, Mishra and Gupta (1976) derived the value of K as 14.2. The maximum wind speed associated with Jal has been calculated using the value of $K = 11$, which is a theoretical proportionality constant, derived by Raj (2010) after incorporating the effect of friction, environmental flow and direction of motion of the TC.

3.4. During the movement of Jal towards the coast, AWS at Ennore Port recorded a wind speed of 33.4 knots on 7th November at 0300 UTC and 33 knots at 0400 UTC when it was out at sea. Using this input, the actual maximum wind speed in the field of TC Jal prior to landfall, while out at sea has been derived. For this purpose, the mean environmental wind direction and wind speed during the cyclone period have been calculated by utilising the mean 0300 UTC zonal and meridional components of AWS-derived wind, five days prior and after the TC Jal period of 4-8 November, 2010. The effects of the (a) direction of movement (b) environmental flow and (c) friction on the wind speed reported by the AWS have been incorporated in this calculation. The results have been cross-checked with the operational forecasting / declaration of the intensity of the TC Jal and analysed.

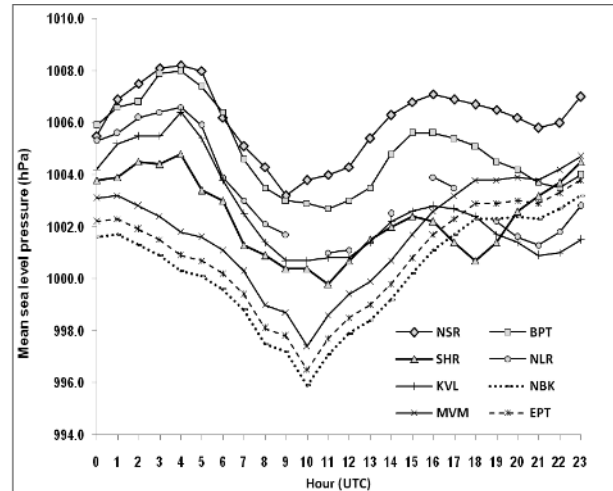


Fig. 4. Variation in hourly mean sea level pressure recorded by AWS on 7th November, 2010

4. Results and discussions

4.1. Inferences from AWS atmospheric pressure data

Whenever a TC forms in the sea, the variability in m.s.l.p. of inland and coastal stations in the vicinity of the TC is closely monitored as the atmospheric pressure starts falling gradually in the beginning. The 24 hours m.s.l.p. tendency also provides crucial information about the likely direction in which a TC could move. In the case of Jal, the 24 hours m.s.l.p. tendency obtained from the hourly m.s.l.p. values of six coastal AWS in TN for the period 4-8 November, 2010 has been depicted in Fig. 3(a). The stations are Chennai-Nungambakkam (NBK), Madhavaram (MVM), Ennore Port (EPT), Chidambaram (CDM), Karaikal (KKL) and Puducherry (PND). MVM recorded a 24 hours fall of 9.7 hPa in pressure tendency at 0400 UTC of 7th November, followed by NBK with a fall of 9.5 hPa and EPT with 8.8 hPa at the same time. PND, KKL and CDM recorded comparatively less fall in pressure as is evident from Fig. 3(a). The 24 hours m.s.l.p. tendency recorded by AWS of CAP are depicted in Fig. 3(b). The AWS are Sriharikota (SHR), Nellore (NLR), Kavali (KVL), Narasapur (NSR) and Bapatla (BPT) out of which SHR recorded maximum 24 hours pressure fall of 8 hPa at 0500 UTC of 7th November during the passage of the cloud mass which got sheared to the west and 7.2 hPa at 1800 UTC during landfall of the cloud-free cyclonic vortex Jal. NLR reported a fall of 6.7 hPa at 0600 UTC on 7th. The 24 hours pressure fall at EPT AWS was 8 hPa at 0400 UTC and 8.3 hPa at 1000 UTC. Fig. 4 provides the variation in hourly m.s.l.p. of eight AWS (NBK, EPT, MVM, SHR, KVL, NLR, BPT and NSR) located in the neighbourhood of the landfall

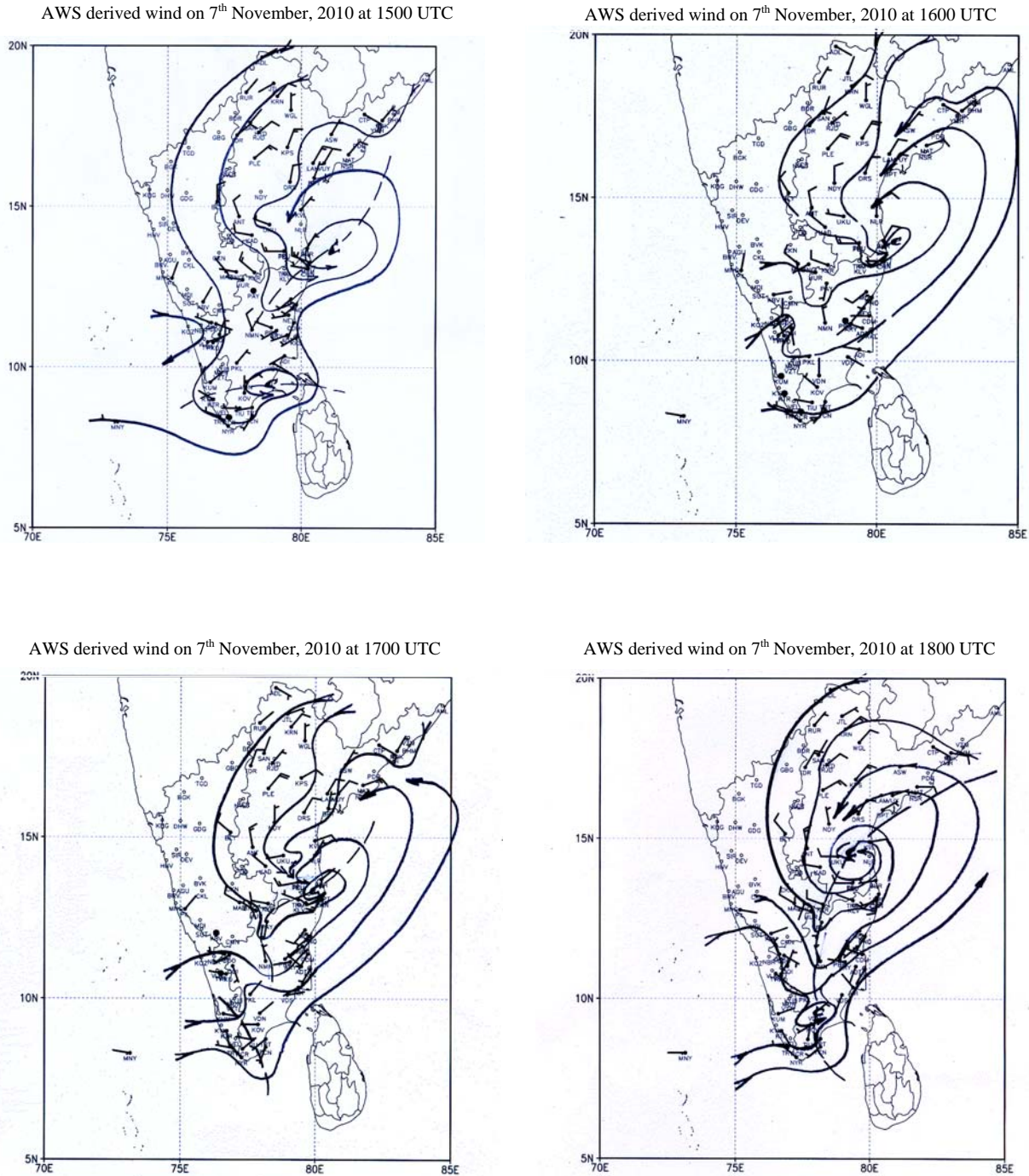


Fig. 5. Cyclonic circulation in the surface level wind pattern as per the wind data of AWS 1500 to 1800 UTCs, 7th November 2010

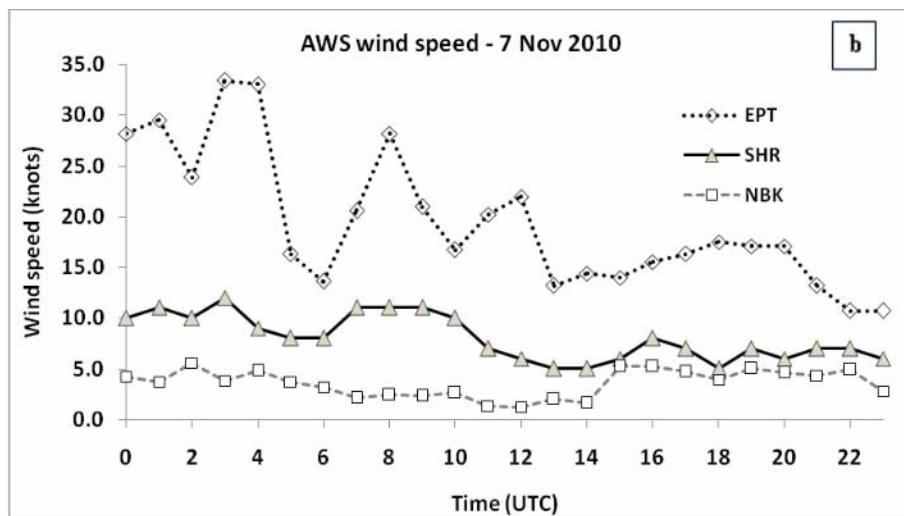
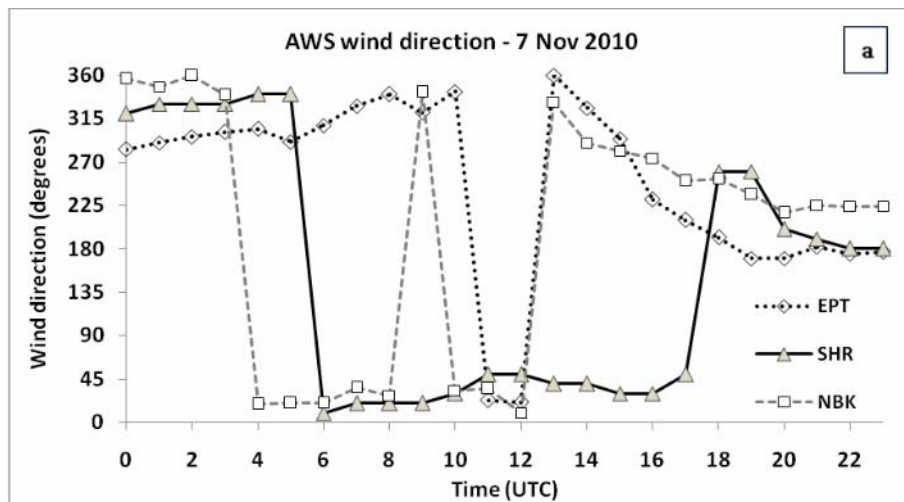
point of Jal which clearly shows that the pressure minimum of 1000.7 hPa occurred at SHR at 1800 UTC of 7th November at the time of landfall. The landfall point

and time based on the variation in hourly m.s.l.p. and 24 hours m.s.l.p. tendency of AWS is observed to be at 1800 UTC of 7th November.

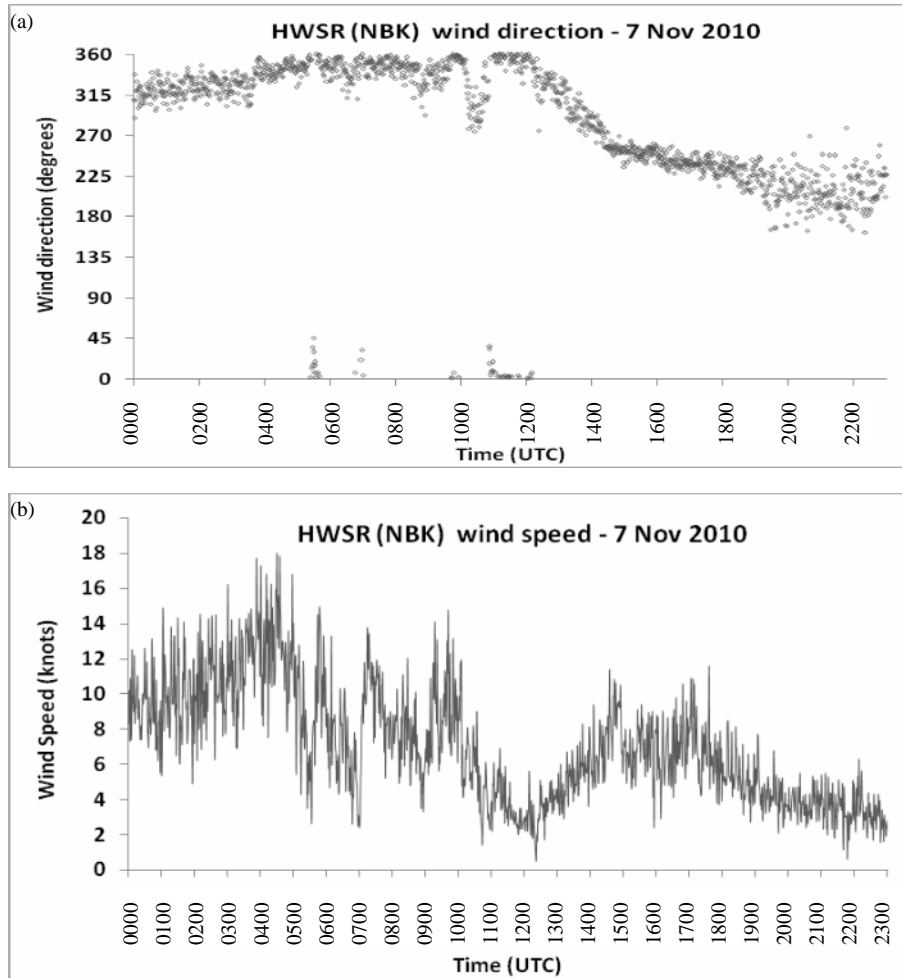
SCS – JAL over Bay of Bengal on 7 November 2010

Date →	7 November 2010						
Time (UTC) → AWS Stations ↓	1400	1500	1600	1700	1800	1900	2000
Sriharikota (SHR)							
Ennore (EPT)							
Chennai Nungambakkam (NBK)							
Madhavaram (MVM)							

Fig. 6. Variation in wind direction recorded by AWS close to landfall point of Jal



Figs. 7(a&b). Wind direction and speed recorded by AWS at Ennore Port, Nungambakkam and Sriharikota on 7th November

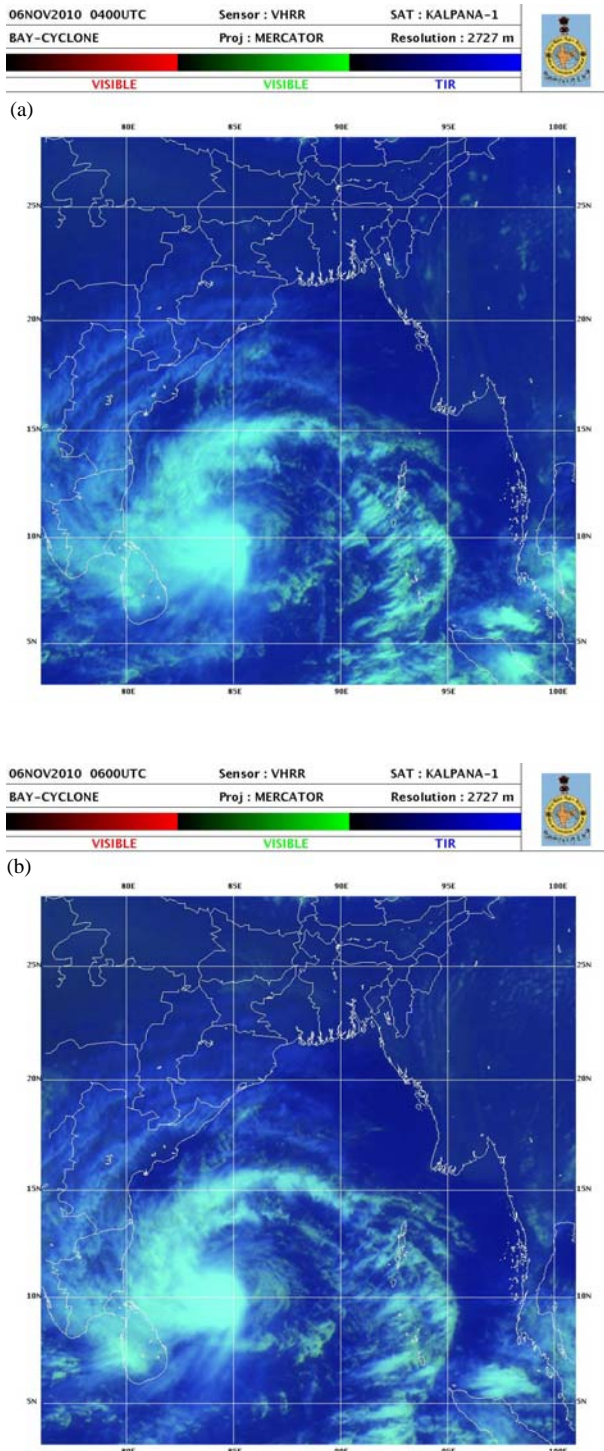


Figs. 8(a&b). Variation in wind direction and wind speed recorded by High Wind Speed Recorder at Chennai on 7th November, 2010

4.2. Wind data from AWS and HWSR

Since the objective is to utilise AWS data to the maximum possible extent in cyclone track monitoring, the surface level wind available from 66 AWS on 7th November has been utilised to depict the wind circulation during 1500, 1600, 1700 & 1800 UTCs. (Fig. 5). In spite of the fact that the surface level is a friction layer, the streamlines reveal interesting features of the variation in wind direction characteristic of the DD which had landfall around 1800 UTC. The centre of the cyclonic wind circulation of Jal at 1500 & 1600 UTC is still at sea, but very close to TC NBK coast, as per the winds recorded by NBK, MVM, SHR and EPT shown separately for more clarity in Fig. 6. At 1700 UTC the centre is between EPT and SHR and at 1800 UTC, the centre has entered the interior parts of extreme south Andhra Pradesh. Hourly wind speed recorded by AWS at EPT showed an

increasing trend with highest maximum of 33.4 and 33 knots at 0300 and 0400 UTCs of 7th. Graphical representation of the wind direction and speed recorded by the three coastal AWS at NBK, EPT and SHR on 7th are shown in Figs. 7(a&b). The wind direction recorded by NBK is northwesterly (NWly) up to 0300 UTC of 7th, which veered to easterlies (Ely) till 1200 UTC, thereafter the winds backed to westerlies (Wly) till the landfall and subsequently to southerlies (Sly). The wind pattern of EPT depicted in Fig. 7(a) shows veering, *i.e.*, Wly up to 1000 UTC; Ely at 1100 & 1200 UTC and backing of winds thereafter. SHR recorded NWly winds up to 0500 UTC and then only Ely up to 1700 UTC which became Wly at 1800 UTC indicating the landfall at SHR around that time. The AWS at EPT which is located very close to the sea is an ideal site with no obstructions and hence has been able to capture the signatures of the TC Jal in terms of wind speed and direction, in particular. A gusty wind



Figs. 9 (a&b). Kalpana-1 satellite VHRR pictures of 0400 and 0600 UTCs of 6th November 2010

speed of 32 knots was recorded by the conventional Dines Pressure Tube (DPT) Anemograph at Chennai Nungambakkam (NBK) at 0353 UTC. The High Wind Speed Recorder (HWSR) which was installed in Chennai

NBK during Oct 2009 (Amudha & Raj, 2010), records wind direction and speed at every minute interval and showed a maximum wind of 17.7 knots during the same time. The variation in wind direction and wind speed as recorded by the HWSR is shown in Figs. 8 (a&b). Distinct pattern of veering of winds from NWly to northerly (Nly) up to 0930 UTC was observed. Winds became Wly between 0930 and 1000 UTC, then to Nly for a short duration and oscillated from Ely to Nly between 1100 & 1200 UTC. Backing of winds from Nly to southwesterlies (SWly) from 1200 UTC onwards has been recorded by the HWSR at NBK. Wind speed of around 18 knots was recorded at 0430 UTC. The fact that the landfall of Jal occurred between EPT and SHR at 1800 UTC is proven from the wind analysis coupled with the variability in m.s.l.p. of AWS.

4.3. Analysis with satellite pictures of TC Jal

Satellite cloud imageries serve as crucial inputs while monitoring the movement of TCs. In the case of Jal, as early as 2nd November, the genesis of the TC in the Bay of Bengal could be captured by satellites and monitored continuously. The satellite-estimated sea surface temperature (SST) obtained from the NOAA high resolution blended analysis data (www.esrl.noaa.gov/psd/cgi-bin/GraDS) for 6-7 November was in the range 28-29 °C in the BoB in the vicinity of the track of the cyclone Jal which was conducive for the further development of TC Jal. During its journey over sea, it was observed from the Kalpana-1 VHRR satellite images shown in Figs. 9(a&b) of 0400 and 0600 UTC of 6th November that the rain-bearing cloud mass was sheared westward. The rain-bearing cloud mass and the cyclonic vortex with a doughnut shape are visible in the figures as two parts of the same system.

Adem & Lezama (1960) had in his analytical study on cyclones shown that a cyclone initially embedded in a uniform flow moves with the velocity of the flow and there exists a northwestward translation due to the variation of the coriolis parameter which contributes to the total displacement of the cyclone. Gray (1988) had concluded that under the influence of the environment, TCs move poleward into strong baroclinic currents and the upper portions get detached from the lower circulation. Similar feature was observed in the case of Jal. Asnani (2005) has also documented that a cyclone is steered by the middle and upper tropospheric currents. Miller and Moore (1960) had found that the 700 and 500 hPa geostrophic wind components are well correlated with the motion of TCs. For operational forecasting steering level is considered to be 200 hPa winds and vertical shear is calculated between 200 and 850 hPa and followed in this study of Jal as well.

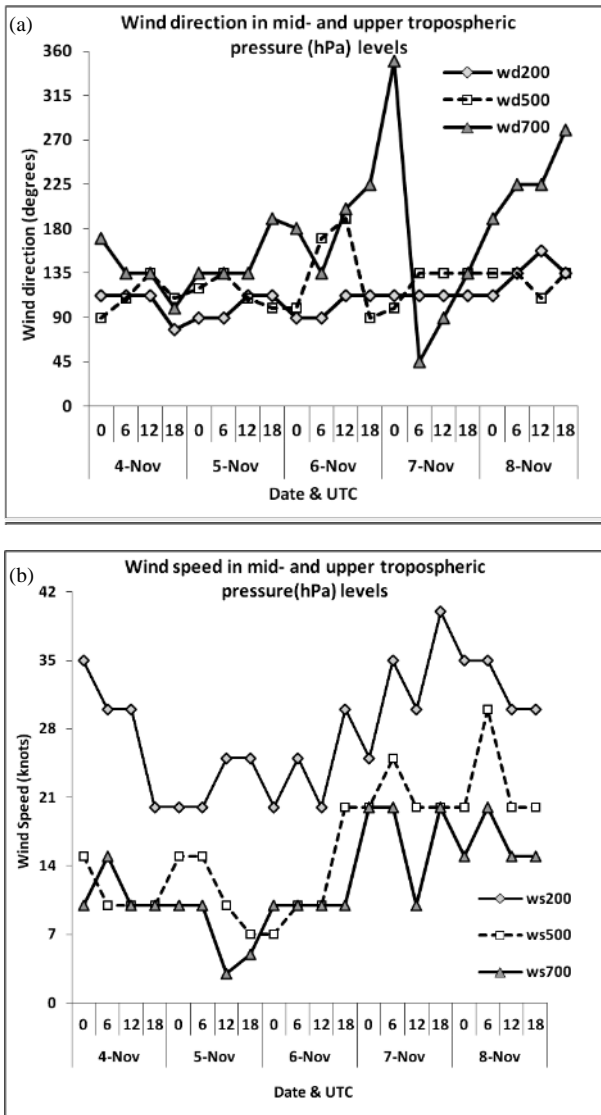


Fig. 10 (a&b). Wind direction and speed in mid and upper tropospheric levels during 4-8 November, 2010

The analysis of zonal (u) and meridional (v) wind components at the mid and upper tropospheric levels [Figs. 10(a&b)] during 4-8 November, 2010 downloaded from the web site www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html provides clear-cut signals of the strong easterlies prevalent in the 500, 700 and 200 hPa levels. The wind direction and wind speed at the Lat./Long. values of the location of TC Jal have been computed from the 'u' and 'v' components at the specific UTCs. Comparison of the wind direction at 700, 500 & 200 hPa levels shown in Fig. 10(a) shows the dominant prevalence of easterlies at 200 hPa. The strength of the easterlies gradually increasing from around 20 knots at

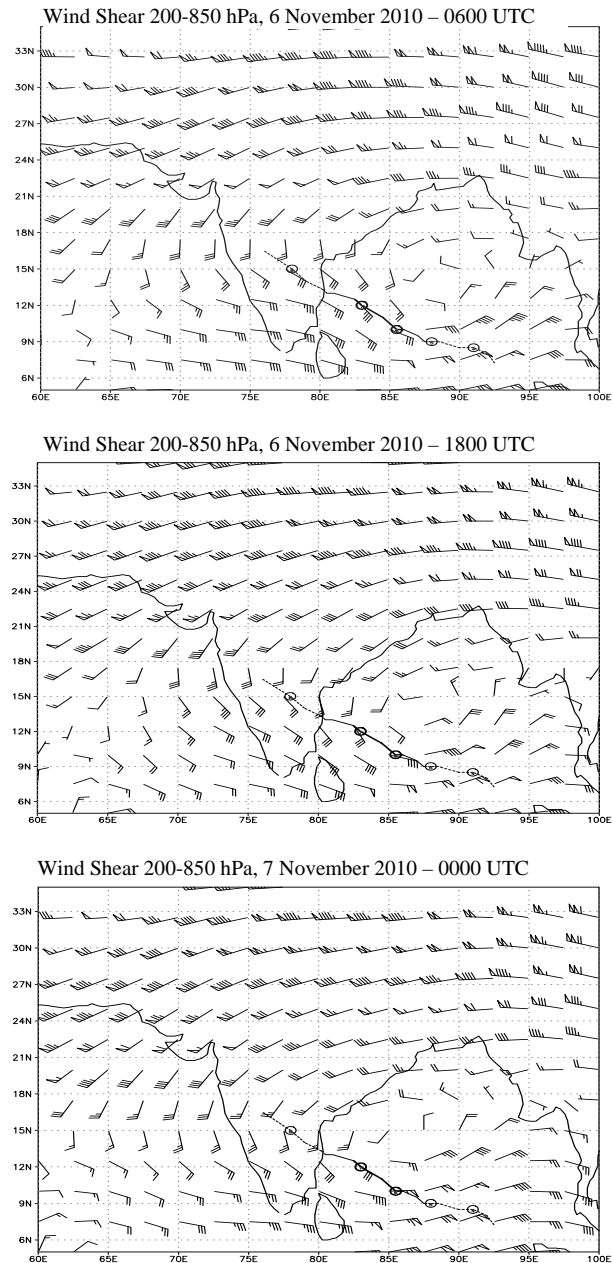
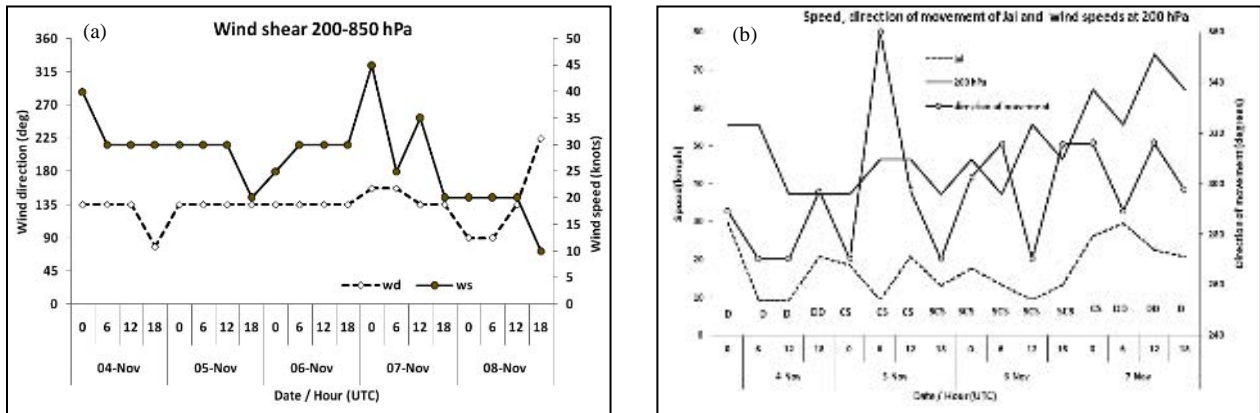
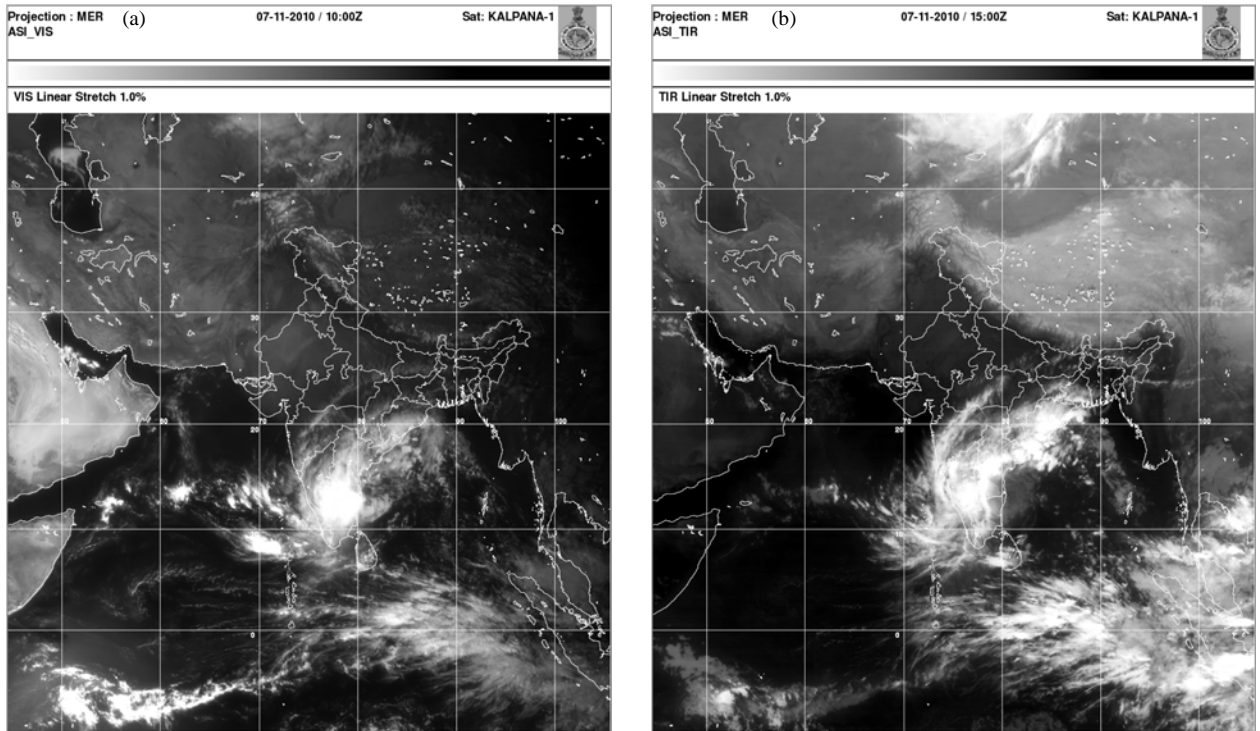


Fig. 11. Wind shear (200-850 hPa) on 6th (0600 & 1800 UTCs) and 7th (0000 UTC) November. Track of Jal is also shown

0000 UTC / 6th to around 40 knots at 1800 UTC / 7th is a cause for the shearing of the cloud mass. The gradually increasing magnitude of the vertical wind shear between 200 and 850 hPa levels is shown in Fig. 11 with the track of TC Jal superimposed in the wind field. Fig. 12(a) brings out the temporal increase of wind speed between 200 & 850 hPa levels with 45 knots at 0000 UTC of 7th. Fig.12(b) is a depiction of the speed, direction of



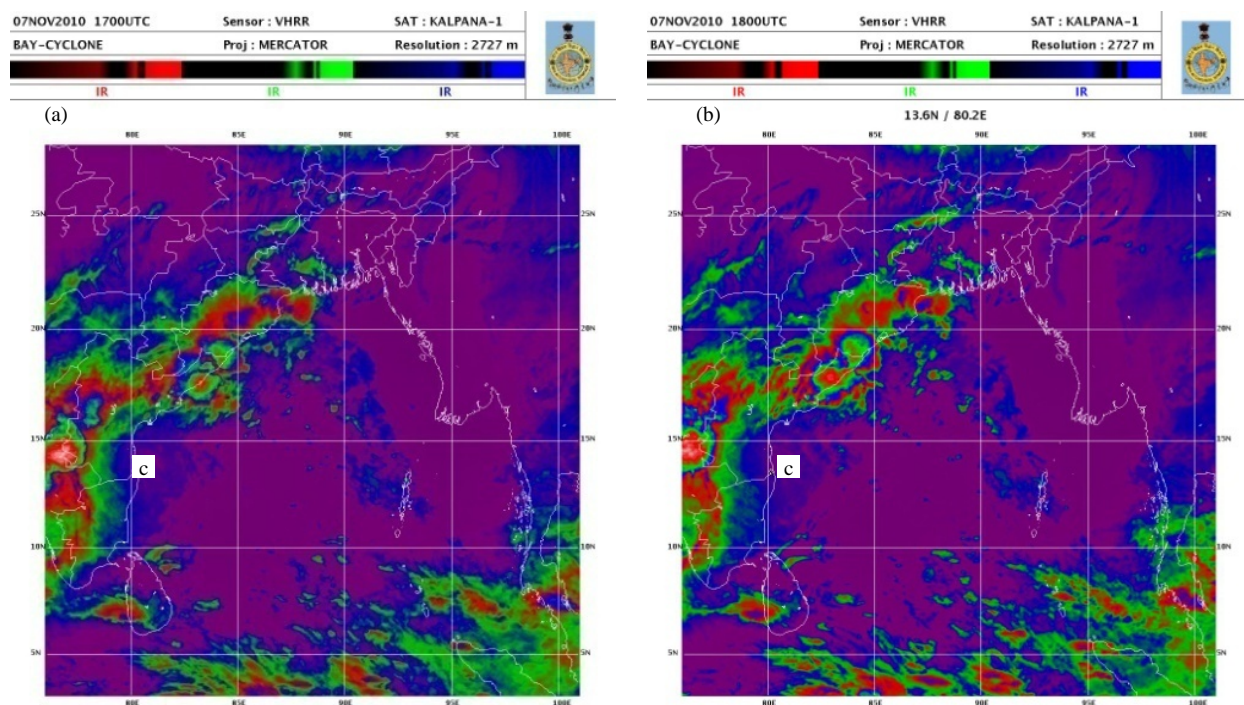
Figs. 12 (a&b). (a) Vertical wind shear between 200 and 850 hPa during 4-8 November, 2010 and (b) Speed, direction of movement of Jal and wind speeds at 200 hPa



Figs. 13(a&b). Kalpana-1 satellite pictures of (a) 1000 UTC (Visible) and (b) 1500 UTC (Thermal Infrared - TIR) of 7th November, 2010

movement of TC Jal (in kmph) and the prevailing wind speeds at 200 hPa. The correlation $r = 0.44$ between speed of Jal and prevailing wind speeds indicates that in the case of TC Jal, the wind speeds of 200 hPa explain only 19% of the variability in the speed of movement. It is clear that due to the easterlies at the upper levels, the rain-bearing cloud mass was sheared off inland, by 0700 UTC

of 7th and Visible / Thermal Infrared (TIR) satellite pictures as shown in Figs. 13(a&b) of 1000 and 1500 UTC which serve as proof for this conclusion. The vortex subsequently lost its shape but was centred at $13.6^\circ \text{ N} / 80.2^\circ \text{ E}$ close to SHR which was evident from the feeble cloud patches in the colour enhanced satellite pictures of 1700 & 1800 UTCs of 7th November provided in



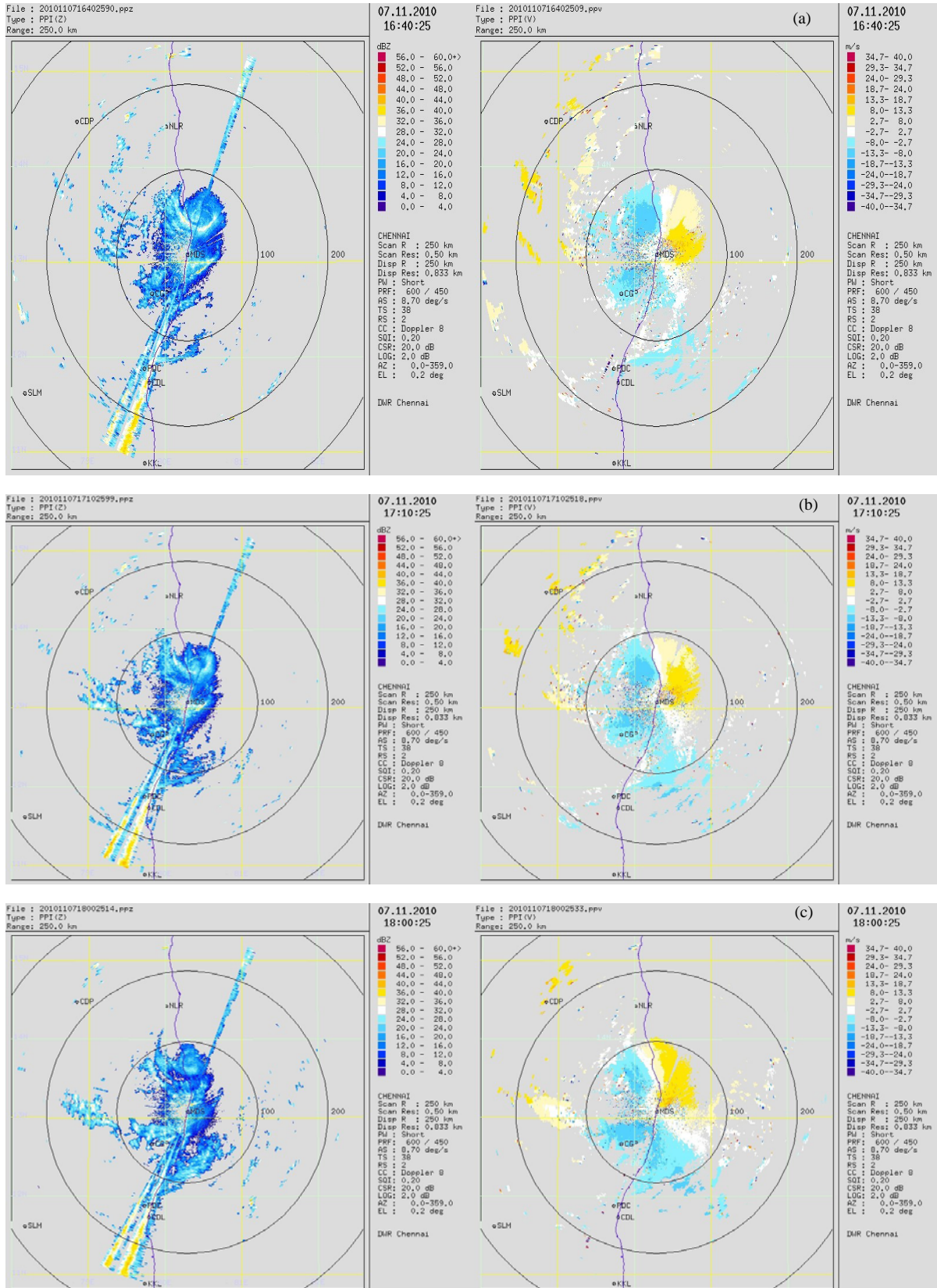
Figs. 14(a&b). Kalpana-1 satellite pictures of 1700 and 1800 UTCs of 7th November, 2010. C (indicated in figure) : Centre at 13.6° N / 80.2° E

Figs. 14(a&b). Jal crossed as DD at 1800 UTC of 7th near SHR. The observations from satellite-based analysis of Jal support the corresponding changes discussed in Paras 4.1 & 4.2 above in the meteorological parameters like m.s.l.p. and wind recorded at surface level by the AWS.

4.4. Analysis based on Doppler weather radar data

Variability in wind and maximum winds observed in AWS, DWR and satellite have been compared and analysed here. As elucidated in Para 4.3 above, the vertical wind shear had a detrimental effect on the TC Jal choking and weakening Jal at sea level (IMD, 2011). The DWR track of Jal could not be fixed firmly due to inconclusiveness about the centre of the system in view of the shearing of the cloud mass which took place in the morning hours of 7th. The cloud-free vortex of Jal could be tracked through the DWR at Chennai continuously up to 1800 UTC of 7th. The PPI (V) (Plan Position Indicator, Velocity) products of DWR, Chennai are shown in Figs. 15 (a-c). The observations taken at 1640, 1710 and 1800 UTCs show the gradual movement and subsequent crossing of the vortex. Negative Doppler radial velocities (blue) are toward the radar and positive (yellow-red) are away from the radar indicating the movement of the vortex during landfall. Interpretation of the PPI (V) product from the radar observations of 1554 UTC and 1654 UTCs of DWR SHR [Figs. 16(a&b)] along with

the observations from the DWR Chennai of 1640, 1710 and 1800 UTCs allow us to draw the inference that the crossing occurred between 1700 and 1800 UTCs. Further, maximum surface level wind speed of 33 knots and NW'y direction was recorded by AWS at EPT at 0300 and 0400 UTC of 7th (Amudha and Raj, 2010). The Volume Velocity Processing-2 (VVP2) product of DWR Chennai generated at around 0400 UTC indicated winds veering in vertical from NW'y direction with speed of 30 knots to SE'y/45 knots at 6.3 km height. ASCAT Scatterometer satellite-derived surface wind estimates (http://rammb.cira.colostate.edu/products/tc_realtime) during 0000 UTC and 0600 UTC indicate winds in the range 25-30 knots close to the NBK and EPT. At the time of landfall, the winds reported by AWS SHR was ENE/7 knots at 1700 UTC and WSW/5 knots at 1800 UTC. AWS EPT reported SSW/16 knots at 1700 UTC and SSW/17.5 knots at 1800 UTC and AWS NBK recorded WSW/5 knots at 1700 UTC and WSW/4 knots at 1800 UTC. As per the report of DWR Chennai on TC Jal, the surface level wind speed associated with the weak vortex was not more than 25 knots at any time (Thampi, 2011) which agrees well with the winds reported by AWS located at SHR, EPT and NBK near to DWR Chennai. PPI (V) products of DWR Chennai and SHR proved to be valuable supporting evidence and the combined inputs from AWS, satellite and DWR confirm the fact that TC Jal crossed the coast between EPT and SHR.



Figs. 15 (a-c). PPI (V) products of DWR Chennai taken at (a) 1640, (b) 1710 and (c) 1800 UTCs, 7th November, 2010

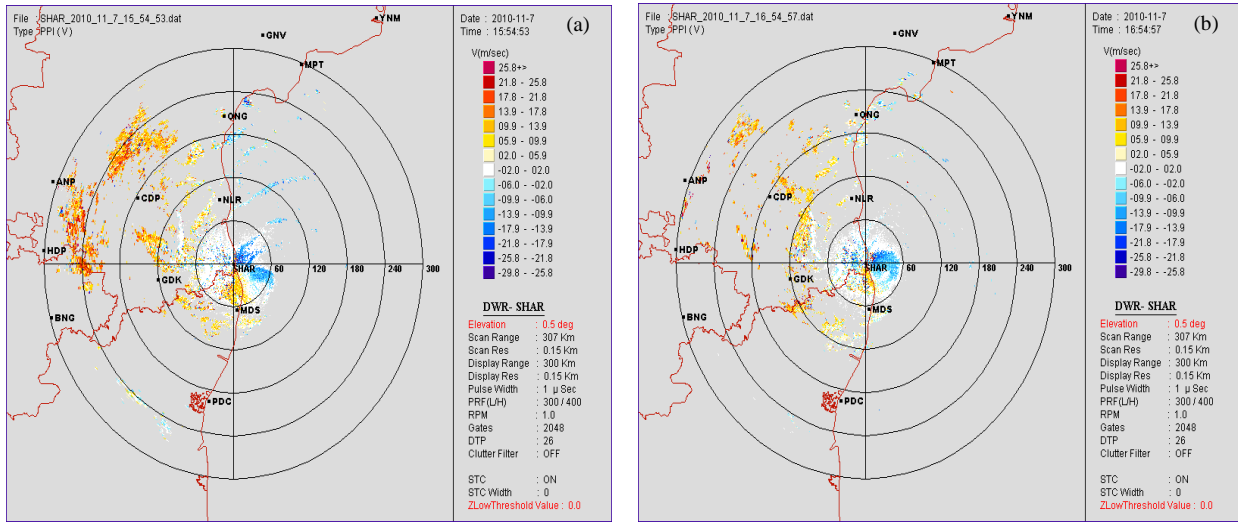


Fig. 16 (a&b). PPI(V) products from DWR Sriharikota, (a) 1554 and (b) 1654 UTCs of 7th November, 2010

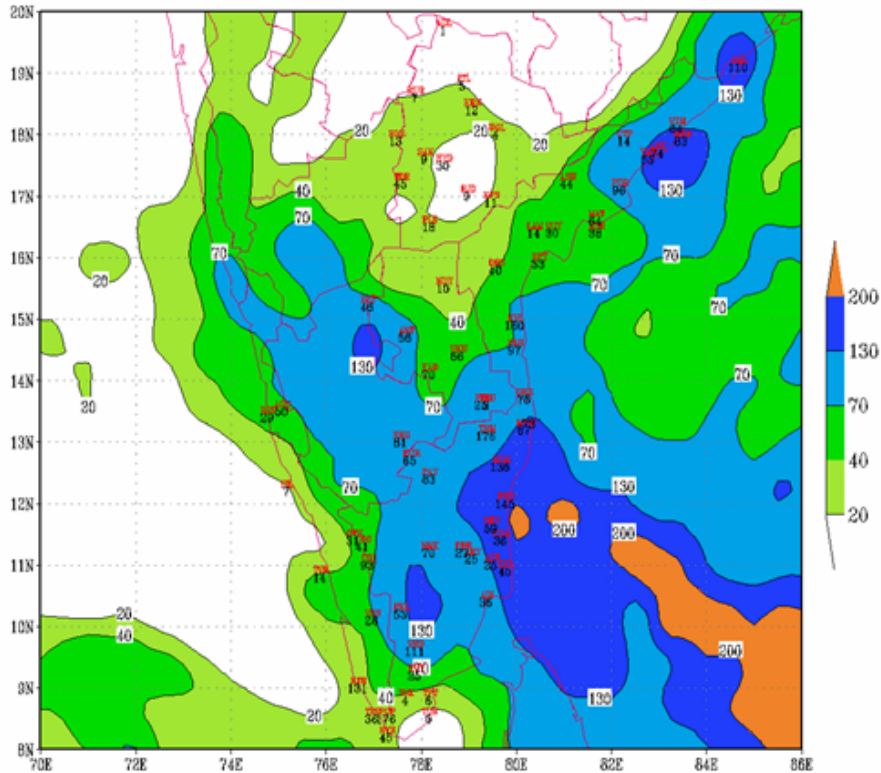


Fig. 17. Comparison of the rainfall distribution as recorded by AWS and TRMM cumulative (2B42V6) rainfall estimates of 4 - 8 November, 2010

4.5. AWS rainfall analysis

The cumulative rainfall recorded by 71 AWS in the southern peninsular Indian region due to the passage of

the TC Jal during 4-9 November, 2010 has been plotted and superimposed with the rainfall estimates (Fig. 17) obtained from 3B42V6 product of the TRMM satellite (<http://www.trmm.gsfc.nasa.gov/>). Validation of the

TABLE 1
Total rainfall recorded during 4-9 November, 2010

S. No.	Name of the station	State	Total rainfall (mm)	
			OBSY	AWS
1.	Ariyalur	Tamil Nadu	25	25
2.	Nungambakkam	Tamil Nadu	79.5	79
3.	Vedasandur	Tamil Nadu	29.8	28
4.	Karaikal	Tamil Nadu	46.2	45
5.	Coonoor	Tamil Nadu	36	41
6.	Pondicherry	Tamil Nadu	139.6	145
7.	Adiramapatnam	Tamil Nadu	36	36
8.	Narsapur	Andhra Pradesh	36.4	38.0
9.	Hyderabad	Andhra Pradesh	32.9	30
10.	Bengaluru	Karnataka	76	77
11.	Thiruvananthapuram	Kerala	38.9	36

OBSY : Observatory; AWS : Automatic Weather Station

rainfall recorded by AWS has been done by a comparison of rainfall of 11 stations which have a manual observatory and an AWS adjacent to each other (Table 1). But TRMM satellite estimates of rainfall are underestimated for few stations and overestimated for many others even in the case of such 11 stations and do not agree one-to-one. Since the grid spacing resolution of TRMM data $0.25^\circ \times 0.25^\circ$, location-specific agreeability in cumulative rainfall data of AWS when compared with TRMM data is not obtained whereas almost exact matching of values is seen in the comparison of AWS and manual observatory data. The rainfall recorded by AWS indicated that stations in the left forward sector of the track of Jal recorded maximum rainfall during 6th and 7th November. The cloud top temperatures in the region of the genesis and landfall of the cyclone Jal during 5-7 November were in the range of -40°C to -70°C and stations in the left sector of Jal received rainfall of the order of 6 to 10 cm under the influence of the passage of the moisture-filled cloud mass over them. Kalpana-1 satellite-derived six hourly Outgoing Long Wave (OLR) data showed OLR values in the range 55-140 W/m^2 at sea on 6th Nov and on 7th OLR values over land varied from 60 to 150 W/m^2 (Fig. 18) indicating the intense convective activity. Kelkar *et al.* (1989) showed that distinct inverse relationship exists between OLR and precipitation. Lower the OLR,

greater the precipitation which has been established from the AWS recorded rainfall values in the case of TC Jal.

4.6. *Assessment of maximum winds and effect of the environment over TC Jal*

The second part of the objective of the study as outlined under Section 3 is to compute the distance traversed and the direction of movement of Jal during 4-8 November, 2010. The maximum winds associated with it has also been computed and discussed in Section 4.6.1. Atkinson and Holliday (1977) had derived an empirical relationship between maximum sustained wind and the pressure defect based on TC data of Western North Pacific, collected over a period of 28 years. An attempt has been made in the forthcoming sections to analyse the actual maximum wind when the cyclone is out at sea by considering the effects of (a) the direction of movement (b) the environmental flow and (c) friction on the winds reported by AWS, EPT.

4.6.1. *Distance traversed, direction of movement and maximum winds*

According to the cyclone eAtlas (IMD, 2008) database, considering the period 1961-2009 which is after

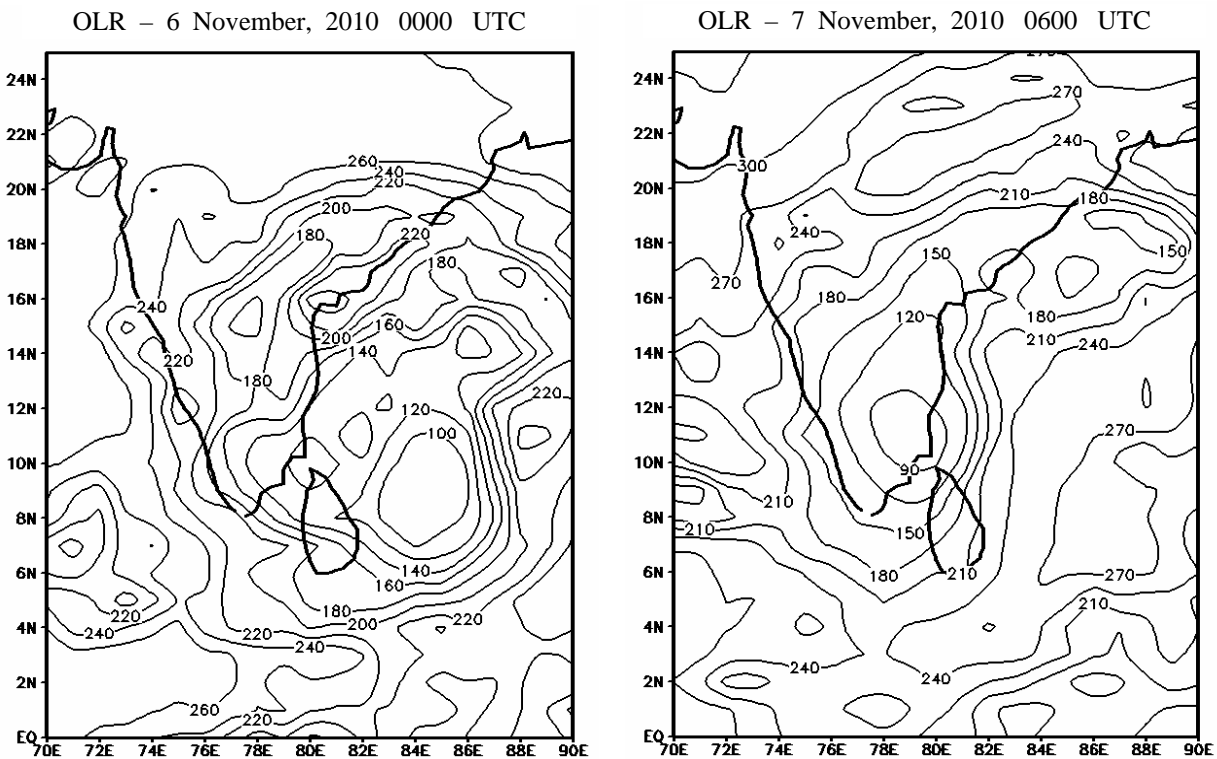


Fig. 18. OLR variability at 0000 UTC / 6th and 0600 UTC / 07th November

the advent of satellite era when the tracks of TCs are more authentic and reliable, the mean direction of movement and vector speed in November for TCs originating in the quadrant where Jal formed is WNWly direction and 17-19 kmph respectively. The established climatological pattern of movement of TCs originating in the quadrant bounded by Lat. 5° to 10° N / Long. 90° to 95° E in the Wly to NWly direction up to landfall has been followed by Jal also [Fig. 12(b)]. Distance travelled by TC Jal during the preceding 24 hours period ending at 0300 UTC on 5th, 6th, 7th Nov is 448, 299, 356 km respectively and that travelled from 0300 to 1800 UTC of 7th Nov is 373 km. The total distance travelled by Jal during the 4-day period commencing from 4th (0300 UTC) to 7th (1800 UTC) is 1477 km covering an average distance of 370 km per day. Speed of movement is 19, 12, 15 and 25 kmph respectively for the same days. Various dynamical factors including the barotropic state of the atmosphere, vorticity factor, divergence from the anticyclone at the upper tropospheric level and influence of the speed of the steering currents at 200 hPa govern the variation in speed of movement.

In the synoptic m.s.l.p. chart of 0300 UTC of 7th November, the outer closed isobar $P(n)$ is 1008 hPa and

$P(o)$ is 992 hPa for the TC Jal. So the pressure defect becomes 16 hPa and when $K = 11$ is used in the equation for V_m , the maximum wind speed becomes 44 knots at 0300 UTC of 7th. During the operational phase of forecasting the movement of Jal, IMD had declared that Jal was a CS between 0300 and 1200 UTC of 7th. A TC is classified as a CS when the wind speeds are in the range 34 to 47 knots and as SCS when wind speeds are 48 to 63 knots according to IMD nomenclature. As per the best track (RSMC, 2011) estimates and DWR data of IMD, TC Jal was an SCS up to 0300 UTC and weakened into a CS after 0300 UTC of 7th. Jal was classified under T-3.5 (SCS) considering the cloud pattern in satellite imagery. It can be inferred that up to 0300 UTC Jal was an SCS and from 0300 UTC it became a CS. Analysis based on wind data of EPT recorded at 0300 and 0400 UTCs as discussed below in Section 4.6.2 fully support that TC Jal was indeed of CS intensity at 0300 UTC of 7th.

4.6.2. Effect of environmental wind, direction of movement and friction

Wind speed recorded by AWS at EPT showed an increasing trend with highest maximum of 33.4 and 33 knots at 0300 and 0400 UTCs on 7th November. With this

TABLE 2

Calculation of the hypothetical maximum wind speed on wind data of AWS at Ennore

Wind	Prevailing wind Ennore (E)		AWS Ennore wind 7 Nov / 0300 UTC (W_r)		Resultant Wind (W_r) + (- E)		Effect due to movement of TC (S)	7% decrease due to friction (F)
	Components (knots)							
	u	v	u	v	u	v		
	2.00	-2.23	28.65	-17.21	26.3	-14.8		
Direction (deg)	318		301		299			
Speed (knots)	3		33.4		30		6.1	2.3
$W_h = W_r + (E + S + F)$								
Wind speed at sea (W_h) = 33.4 + (-3.0 + 6.1 + 2.3) = 38.8 knots, approx around 39 knots								

crucial input, the hypothetical wind speed (knots) W_h when Jal was at sea was calculated by the equation $W_h = W_r + (E + S + F)$ including the effect of three factors, viz., Environmental wind E , Translational speed S of the cyclone and Friction F . Table 2 provides the details about the contribution of these factors to W_h . The resultant wind W_r is the wind speed reported by AWS at EPT at 0300 UTC of 7th November. The 0300 UTC mean environmental wind (E) direction and speed at EPT was 318° (NWly) and 3 knots respectively. Jal was moving in a NWly direction at 0300 UTC of 7th November under the influence of SEly winds (134°) with a speed of 24.7 kmph (12.3 knots). The translational speed S of Jal gets halved while moving in the right sector of the storm (Raj, 2010) and hence the value of $S = 6.1$ knots has been included for the calculation of W_h . The environmental wind speed E is subtracted from W_r to eliminate the contribution to the speed of the system by the environmental wind speed. The environmental flow and the translatory motion increase the wind speed only in certain sectors of the storm whereas the effect of friction is always to reduce the speed. Including the effect of E and S , W_h becomes 36.1 knots. Friction over land reduces the wind speed by nearly 25% whereas over high seas, the reduction is nearly 10% (Raj, 2010). The effect of friction at EPT decreased the speed to 33 knots. Hence, frictional effect needs to be suitably taken into consideration (by adding the percentage contribution) while calculating the wind speed when TC Jal was over sea. Adding a minimum of 7% of the resultant wind as the contributory factor due to friction to W_h yields the wind speed as 39 knots which conforms to the IMD's declaration that JAL as a CS while out at sea during 0300-0400 UTC. Operationally, weakening of SCS Jal into CS was declared at 0600 UTC with centre 12.5° N / 82.5° E (IMD, 2011).

5. Conclusions

- (i) The SCS Jal had landfall between EPT and SHR on 7th November around 1800 UTC, the inference of which is supported by the variability observed in hourly m.s.l.p. and wind data of coastal AWS, DWR and satellite products.
- (ii) Minimum m.s.l.p. was recorded at 1800 UTC of 7th November by AWS at SHR which helped in pinpointing the landfall location supported by DWR data of Chennai.
- (iii) The wind field patterns at surface level plotted for 1500, 1600, 1700 & 1800 UTCs of 7th November using AWS data show precisely the landfall location as SHR by the transition of wind direction from easterlies to westerlies.
- (iv) The wind speed (W_h) that could have prevailed when Jal was out at sea, close to the coast of Chennai was calculated with the wind speed of 33.4 knots recorded at 0300 UTC of 7th November by the AWS EPT located over land, very close to the sea. W_h works out to be around 39 knots which substantiates the downgrading of Jal to CS at 0600 UTC of 7th November.
- (v) AWS rainfall validated with 11 collocated manual observatories indicate the exactness with which automation can provide crucial inputs even from unmanned locations.
- (vi) A comparison of rainfall with TRMM data yielded the conclusion that satellite estimates are underestimated for few locations and overestimated for many others due to the uncertainties involved in terms of spatial resolution

and limitations in the satellite radar based algorithms used to retrieve rainfall data.

(vii) The rain-bearing cloud mass sheared off westward due to the strength of easterlies in mid and upper tropospheric levels and could be understood by an amalgamation of all the inputs from modern observing systems and NCEP reanalysis data.

(viii) The AWSs located along the coast of TN and AP prove to be valuable during adverse weather in obtaining data from unrepresented areas.

(ix) The AWS at EPT, being close to the sea is an ideal site with no obstructions to the wind flow. In future too, such AWS can provide similar inputs while monitoring adverse weather situations in addition to assessing the strength of northeast monsoon winds and in examining various aspects of cyclones.

(x) The winds recorded by AWS at EPT will provide valuable inputs for further studies on sea breeze aspects during the summer season.

(xi) The analysis of TC Jal by meteorological data from AWS supplemented by data of other modern weather observing systems has proven that AWS can be utilised on an operational mode in real time for weather monitoring.

(xii) An important aspect that needs to be given priority in terms of continuous AWS network monitoring and quality control management is the crucial necessity of periodic preventive maintenance and cleaning of rain gauges in AWS which will ensure reliability and dependability of data received from such automated weather observing stations.

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