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Signatures of northeast monsoon activity and passage of tropical cyclones in the integrated precipitable water vapour estimated through GPS technique

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सार – वायुमंडलीय क्रियाओं में जल वाष्प का महत्वपूर्ण स्थान है। वायुमंडल में मौजूद जल वाष्प निर्धारण के महत्व को वर्तमान समय में काफी मात्रा में लगाई गई प्रेक्षण प्रणालियों की संख्या से समझा जा सकता है जो स्थान विशेष पर स्थापित हैं और दूर संवेदी प्रकार की है जो अंतरिक्ष के बहुत बड़े भाग और निर्धारित समय पर इसके वितरण को शुद्धता के साथ मापते हैं। किसी भी स्टेशन के वायुमंडल में मौजूद कुल वर्षणीय जलवाष्प का माप लेने के लिए धरातल पर स्थापित जी. पी. एस. अभिग्राही पूरे विश्व में उपयोग में लाई जाने वाली तकनीक है। इस प्रकार की एक प्रणाली वर्ष 2007 से चैन्ने में प्रचालन में है। वर्ष 2008 में उत्तरी पूर्वी मानसून ऋतु के दौरान इस प्रणाली से प्राप्त किए गए घंटेवार वर्षणीय कुल जलवाष्प (आई. डब्ल्यू. वी.) के आँकड़ों के विश्लेषण से उत्तरी पूर्वी मानसून सक्रियता और उष्णकटिबंधीय विक्षोभों जैसे–चक्रवातीय तूफानों एवं जी. पी. एस. प्रेक्षण स्थान के निकटवतीय स्थानों में अबदाब की स्थिति का पता चला है। जी. पी. एस. से प्राप्त कमल वर्षणीय जलवाष्प की मात्रा रेडियो सौंदे से प्राप्त कुल वर्षणीय जलवाष्प की मात्रा के बहुत हद तक बराबर पाई गई है। इस प्रकार यह दोनों के बीच में सही सहसंबद्ध को दर्शाता है। वर्ष 2008 के उत्तरी पूर्वी मानसून के सक्रिय (कमजोर) चरण के दौरान जी. पी. एस. पर आधारित प्रणाली से प्राप्त की गई कुल वर्षणीय जलवाष्प की मात्रा उत्तरी पूर्वी मानसून की सक्रियता के कारण कुल वर्षणीय जलवाष्प की मात्रा की बढ़ोतरी (कमी) के अनुरूप पाई गई है। सामान्य रूप से देखा गया है कि जी. पी. एस. स्टेशन के निकटवर्ती क्षेत्र में उष्णकटिबंधीय सिस्टम के आगमन से कुल वर्षणीय जलवाष्प की मात्रा में वृद्धि की प्रवृत्ति रहती है और स्टेशन के बहुत समीप पहुँचने पर यह अधिकतम हो जाती है और जैसे जैसे स्टेशन से इसकी दूरी बढ़ती जाती है यह कम होती जाती है। वर्ष 2008 में उत्तरी पूर्वी मानसून ऋतु के दौरान जी. पी. एस. पर आधारित कुल वर्षणीय जलवाष्प की आकलित मात्रा में दैनिक भिन्नता सटीक नहीं लगती है।

ABSTRACT. Water vapour represents a key variable in the atmospheric processes. The importance of assessing water vapour availability in the atmosphere is indicated by the currently prevalent use of vast number of observing systems, both of *in-situ* and remote sensing types, designed to measure its distribution accurately over wide ranges of space and time scales. One of the widely used techniques world over is use of ground based GPS receivers for measurement of total precipitable water vapour in the atmosphere over the station. One such system is being operated at Chennai since 2007. An analysis of hourly Integrated Precipitable Water Vapour (IWV) data received from this system during Northeast Monsoon (NEM) season of 2008 shows the signatures of NEM activity and the passage of tropical disturbances like cyclonic storms and depressions in the vicinity of the GPS observation site. The GPS based IWV values are found to agree fairly well with radiosonde based IWV values and a good correlation exists between them. The IWV values obtained from GPS based system are found to be consistent with activity of Northeast monsoon with increase (decrease) of IWV during active (weak) phase of NEM 2008. The general expected trend of increase in IWV with approach of tropical systems in the vicinity of GPS station, reaching maximum during closest approach and again its decrease with increase of distance from the station is noticed. The diurnal variation of GPS based IWV estimates during NEM 2008 does not appear to be significant.

Key words – Global positioning system, Water vapour, Northeast monsoon, Tropical cyclones.

1. Introduction

Presence of water vapour in the atmosphere is one of the most important features responsible for occurrence of various weather events. It is the key parameter which plays vital role in most of the atmospheric processes. Although comprising less than 1% of the atmospheric mass, water vapour is the dominant gaseous absorber of thermal radiation in the atmosphere. Relative absorption of thermal radiation by water vapour and its re-emission, determines the atmospheric 'greenhouse effect'. Hence, scientists involved in weather forecasting have shown keen interest in understanding the distribution of water vapour in the atmosphere. Various parameters, known as moisture variables, have been defined based on water vapour content of the atmosphere to describe the state of the atmosphere at any given place and time. The importance of accurate and precise measurements of water vapour is evident from the currently prevailing use of a wide variety of observing systems, both in-situ and remote sensing types, designed to measure its distribution over wide range of space and time scales with varying degrees of accuracies. But, due to high variability of water vapour in the atmosphere and also due to lack of adequate observations, description of various atmospheric moisture fields accurately has remained a difficult problem for a long time. Significant efforts have been made over the years to develop new and improved remote sensing systems to mitigate this problem. One such effort is the use of ground based Global Positioning System (GPS) receivers to estimate the amount of integrated precipitable water vapour (IWV) in the atmosphere over a given place.

GPS is a satellite based system being used for locating any ground based object precisely in terms of latitude, longitude and height. GPS receiver measures the time taken by a signal transmitted from an orbiting GPS satellite to reach a ground based receiver and converts this time to distance. The system consists of a network of 24 satellites that transmit radio signals which are delayed and refracted by the atmosphere as they propagate from GPS satellites to earth-based receivers. The time taken for signal propagation, in the absence of water vapour, is referred as Zenith Hydrostatic Delay (ZHD). Presence of water vapour in the atmosphere causes variations in the atmospheric refractivity that leads to an additional time delay, known as Zenith Wet Delay (ZWD), in the reception of the signal at the ground based receiver. Thus, the ground based GPS receiver system inherently taps the signature of the amount of water vapour present in the atmosphere in the form of ZWD. The total time delay, referred as Zenith Total Delay (ZTD) caused by the atmosphere is the sum of ZHD and ZWD. ZTD is then converted to IWV at the site by using GPS data processing software (Bevis *et al*., 1992) and local meteorological observations. Lots of developments have taken place in this field during last ten years and GPS derived IWV has proved to be useful for many applications (Duan *et al*., 1996 and Businger *et al*., 1996).

It has also been shown that GPS based IWV data can be effectively used in subjective Weather Forecasting and also in Numerical Weather Prediction (NWP). To date, most countries have shown great interests in application of GPS technology for meteorological purposes [Takiguchi *et al.* (2000), Iwabuchi *et al*. (2000)]. India Meteorological Department has established a network of five ground based GPS stations for estimation of IWV. A few results on usefulness of GPS based IWV over Indian region are also available in the literature [Jade *et al.* (2005), Giri *et al.* (2007)]. In the present work, the results of analysis of IWV obtained through GPS technique over Chennai during the Northeast monsoon (NEM) season of the year 2008 are presented.

Fig. 1. Photograph of GPS equipment Leica GPS Spider with Met3A meteorological sensors installed at Chennai (Nungambakkam)

2. Data and methodology

Recently, ground based GPS receivers have been installed by the India Meteorological Department (IMD) at New Delhi, Guwahati, Kolkata, Mumbai and Chennai for estimation of IWV. Fig. 1 presents the photograph of the equipment Leica GPS Spider with Met3A meteorological sensors installed at Chennai (Nungambakkam). For the present study, the hourly data of GPS based estimates of IWV over Chennai for the period October-December 2008 were downloaded from the website of IMD (www.imd.gov.in). Also the IWV values based on the 0000 UTC & 1200 UTC radiosonde (RS) observations taken at Chennai (Meenambakkam) (located at about 15 km from the GPS site) were downloaded from the website of University of Wyoming (http:/weather.uwyo.edu/upperair/sounding.html). First, the GPS based IWV are validated against those obtained from RS observations. Then, the variations in GPS based

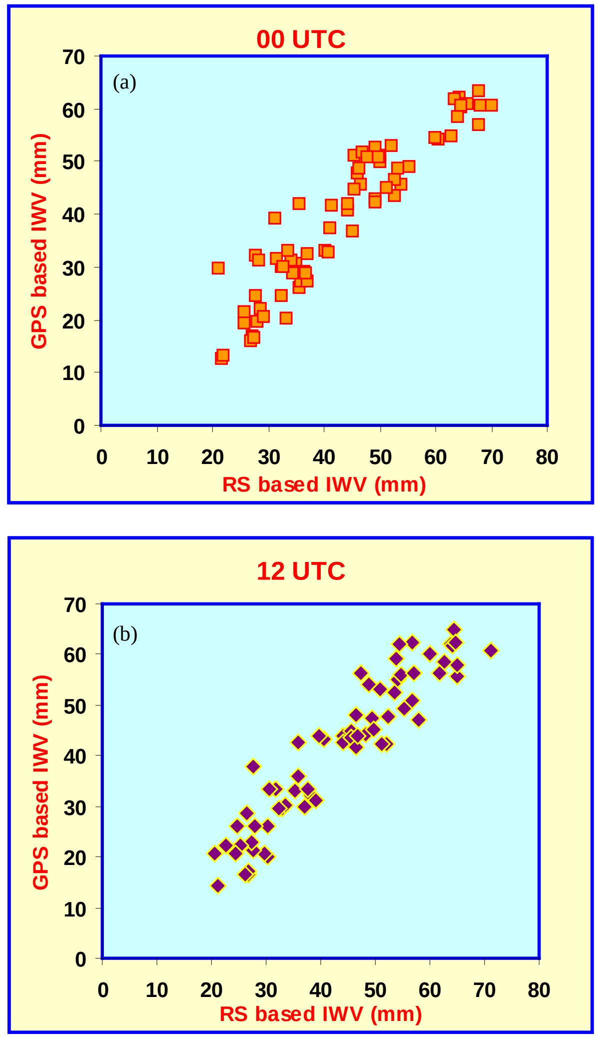
IWV during the onset, active and weak phases of NEM 2008 are analysed by computing the pentad mean of GPS based IWV during October-December 2008 and correlating them with the pentad mean rainfall over Chennai(Nungambakkam) during the same period. Further, existence of any diurnal variation of IWV over Chennai is also examined. Finally, variations in the GPS based IWV during the passage of cyclones and depressions in the vicinity of Chennai during the year 2008 are analysed.

3. Discussions

The Northeast monsoon affects southern parts of the Indian Peninsula during October to December. The state of Tamilnadu is the main beneficiary of the NEM rains and especially over its coastal region, the onset, activity and withdrawal of the NEM are well pronounced. Normal onset date of NEM over Tamilnadu is 20th October with a standard deviation of 7 days (Raj, 2003). During the year 2008, the onset of easterlies occurred by the second week of October, with a trough in easterlies extending from south Tamilnadu to coastal Karnataka across south Interior Karnataka. The easterlies existed up to 0.9 km a.s.l. With active phase of rainfall activity realised from 12th October onwards, the onset of NEM was declared on 15th. After the onset, active NEM conditions prevailed for the subsequent 10 days after which a prolonged dry spell occurred until the second week of November. During the second half of November the NEM was quite active with two cyclonic storms occurring over the Bay of Bengal. During December, the monsoon started receding out in the northern parts of southern peninsula and rainfall occurred in spells over south Tamil Nadu. The cessation of NEM was declared on 31st December. The realised rainfall over Chennai during October and November was in excess by 32% and 60% respectively and during December, it was 85% deficient. We bring out the signatures of these features of NEM 2008 in the GPS based IWV over Chennai in the following sections.

3.1. *Validation of GPS based IWV during NEM 2008*

First we carryout a comparison of the estimates of IWV from ground based GPS observation with that obtained from RS data. Both the data sets of GPS and RS obtained at 0000 UTC and 1200 UTC, were examined for the presence of any outliers using the statistical method of schematic plots (Wilks, 1995). All the data members of both the sets were within their respective outer fences and hence none of them were removed. But, when the difference between the GPS and RS based data were examined and the standard error of difference between the two computed, it was noticed from the 0000 UTC and 1200 UTC data that there were 10 and 14 cases respectively when their differences were greater than three times the standard error which had to be excluded from comparison as required by the sampling theory. After removing these data, further statistical evaluation was carried out. Figs. 2(a&b) show scatter plots of IWV based on GPS and RS during October to December, 2008 at 0000 UTC and 1200 UTC respectively. These plots show that there exists good correlation between the two data sets (Correlation coefficients are about 0.9 for both 0000 and 1200 UTC datasets). The bias and RMS error values of GPS based IWV with reference to that based on RS are (-4.1 mm, 6.4 mm) and (-2.4 mm, 5.5 mm) respectively for 0000 and 1200 UTC data. The distance between the GPS and RS observations sites (about 15 km), error components in GPS processing software as well as the



Figs. 2(a&b). Scatter plot of GPS based IWV against RS based IWV based on (a) 0000 UTC and (b) 1200 UTC observations at Chennai

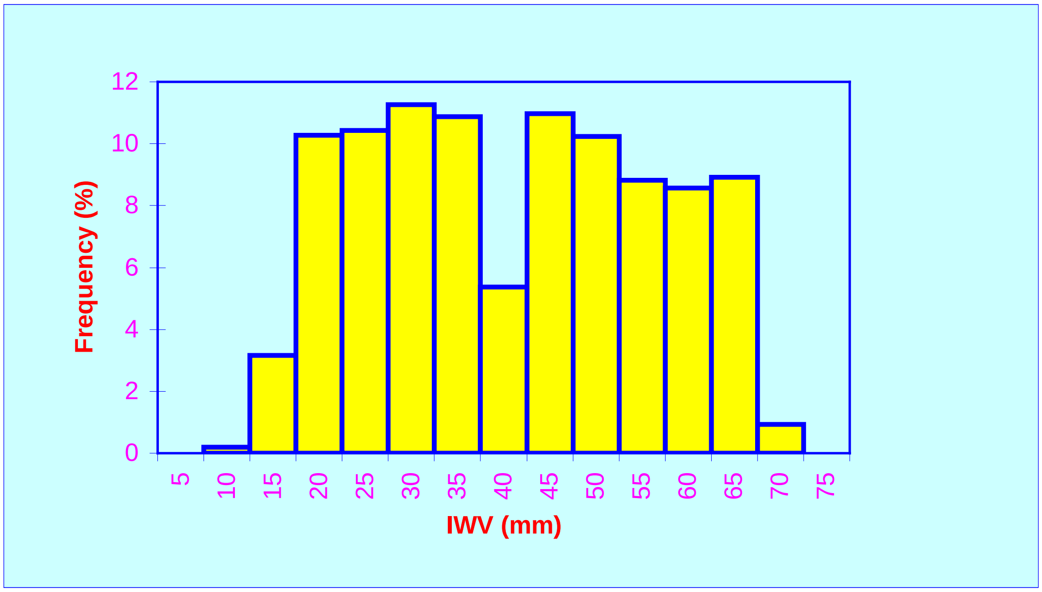


Fig. 3. Frequency distribution (in %) of GPS based hourly IWV over Chennai during October-December 2008

uncertainty in RS measurements are some of reasons for the differences between the two data sets. In this connection, it may be mentioned that Suresh *et al*. (2005) observed, based on one year data from Bangalore, that a deviation of GPS derived IWV from that derived from RS observation was ~5 mm which comes to 15% of change in IWV during the monsoon period where as during December to March this is less than 3 mm (~12%). Thus, by and large, the GPS based IWV data agrees fairly well with RS based IWV. However, it may be mentioned here that only 0000 UTC and 1200 UTC data of GPS based IWV could be validated against RS based IWV and not for each hourly observations due to availability of conventional RS data at these two hours. As such, for the sake of uniformity we use the entire dataset of GPS based IWV including those excluded for comparison against RS for further analysis. Hereafter, the term IWV would generally refer to the IWV values obtained through GPS technique unless mentioned otherwise.

3.2. *Descriptive Statistics of IWV during NEM 2008*

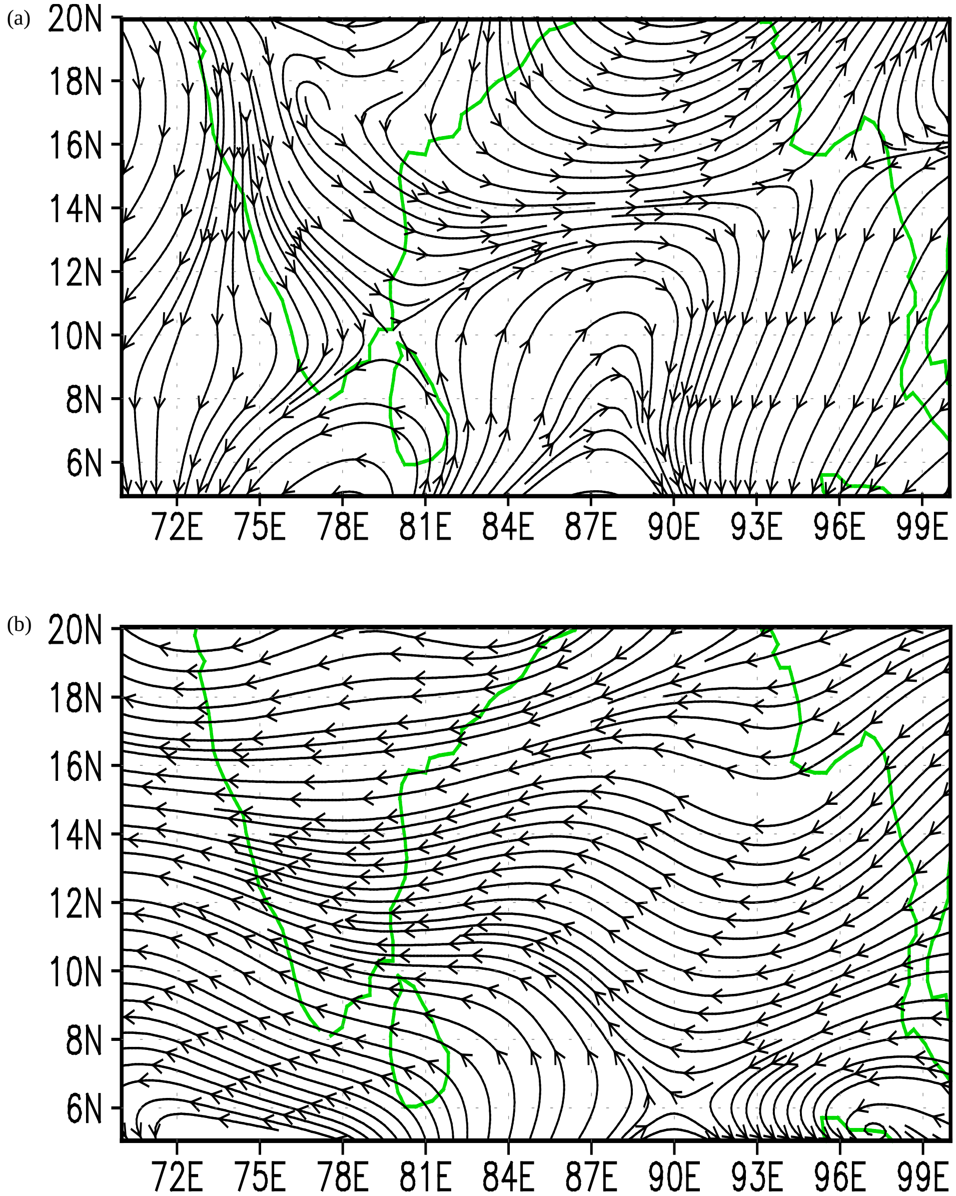
Hourly data of IWV over Chennai during the period 1 October to 31 December comprised of 2052 values excluding 156 missing data. The seasonal mean IWV for NEM 2008 computed with the 2052 values is 38.5mm. Fig. 3 presents the frequency distribution in percentage. It can be seen that the distribution of most of the data values are not concentrated around the mean. They are deviated from the mean on either side and are somewhat evenly dispersed around the two modal classes which suggests that IWV values could be linked with two distinct features of NEM activity, presumably, active and weak phases.

TABLE 1

Statistical parameters of GPS based hourly IWV during October – December 2008

Statistical parameter	Oct	Nov	Dec
Sample size	623	713	716
Mean (mm)	45.30	43.11	27.93
Mode (mm)	43.64	23.50	32.46
Standard Deviation (mm)	14.67	14.81	8.89
Maximum (mm)	67.77	68.24	54.15
Minimum (mm)	12.53	11.78	8.14
Range (mm)	55.24	56.46	46.01

The NEM activity is generally not uniform throughout the season but occurs in spells; normally onset of NEM occurs during the second half of October and it recedes out by the third week of December. As such, to bring out any possible link between IWV and NEM activity during different phases of the season we have analysed the data of each month separately. Table 1 presents the sample size, mean, standard deviation, maximum, minimum and range of the available data for all the three months during the year 2008. The monthly mean of IWV values are 45.3 mm, 43.1 mm and 27.9 mm



Figs. 4(a&b). Streamline flow pattern at 850 hPa on (a) 11 Oct 2008 and (b) 15 Oct 2008 depicting the change of westerlies in to easterlies during the onset of NEM-2008. (*Source*: http://www.esrl.noaa.gov/psd/data)

(with standard deviations of 14.7 mm, 14.8 mm and 8.9 mm) for October, November and December - 2008 respectively. The percentage of data above the seasonal mean during October, November and December are about 79%, 68% and 18% respectively. This pattern of moisture distribution during the three months agrees fairly well with the extent of rainfall activity that occurred during these months (+32%, +60% and -85% as mentioned earlier).

3.3. *Pentad variation of IWV in relation to NEM activity*

In tropical regions, pentad scale variations in meteorological parameters are one of the well known oscillations studied in detail (Asnani, 2005). As mentioned in Section 2, we have carried out an analysis of IWV during different phases of NEM 2008 by studying the corresponding pentad variation of IWV and rainfall. From

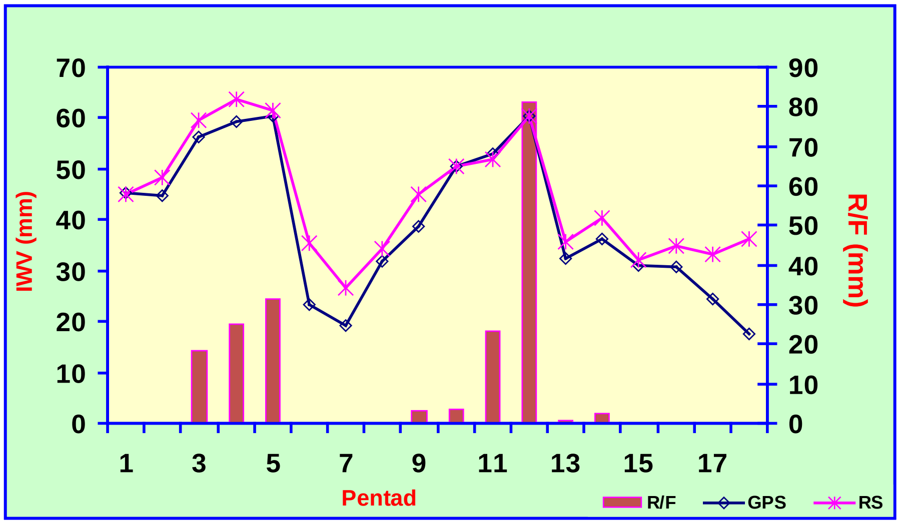


Fig. 5. Pentad variation of GPS and RS based mean IWV, and realised rainfall over Chennai during October - December 2008

the averages of hourly values, the daily mean values are obtained which are, in turn, averaged over corresponding pentad period to get pentad mean values of IWV. The pentad mean values of IWV based on RS observations and the pentad mean rainfall at the GPS site were also computed. In this averaging process, the time convention followed by IMD with respect to rainfall measurements were taken care of.

Generally during the onset of NEM, associated with easterly winds, advection of water vapour from oceanic regions into land takes place. During the year 2008, the changing over of circulation pattern from westerlies [Fig. 4(a)] to easterlies [Fig. 4(b)] occurred at lower tropospheric levels almost simultaneously with the withdrawal of southwest monsoon from the southern most parts of India and northeast monsoon rains commenced over Tamil Nadu and adjoining areas of Andhra Pradesh, Karnataka and Kerala on 15 October in association with a trough in easterlies (IMD, 2009).

The pentad variation of IWV and rainfall are shown in Fig. 5. It is observed that from the pentad (2nd) prior to the onset of NEM to the pentad during onset (3rd), the IWV changed by about 12 mm (about 23%). This notable increase in IWV is quite appreciable especially when the pentad prior to the onset pentad was not dry but associated with southwest monsoon activity. Over Chennai, the onset phase of rainfall activity commenced on 12th and continued till 25th of October (*i.e.*) during 3rd to 5th pentads.

From the climatology point of view, it is well known that the NEM season is a season of cyclonic disturbances (Depressions and cyclones) in the North Indian Ocean. During NEM 2008, there were 3 cyclones (RASHMI, KHAI-MUK and NISHA) and one deep depression whose positions during some part of their life time were in the vicinity of the Chennai GPS station (Fig. 6).

From Fig. 5 it can be seen that the IWV decreased by about 42% between 5th and 6th pentad. During the 6th pentad, cyclonic storm RASHMI (25-27 October 2008) formed as a depression on 25th/0300 UTC with its centre near 16.5° N / 86.5° E. It intensified and moved Northwards/Northnortheastwards (away from the GPS site), crossed Bangladesh coast between 2200 & 2300 UTC of 26th and subsequently weakened. Correspondingly, the rainfall activity over Chennai decreased to zero during the 6th pentad and the lull period continued during the 7th and 8th pentads also. On the other hand, the IWV increased by about 34% between 9th pentad and 12th pentad. During the 9th pentad, cyclonic storm KHAI-MUK (13-16 November 2008) formed as a depression over the southeast and adjoining southwest Bay on 13th. It intensified into a CS moving Northnorthwestwards to Northwestwards upto 15th/0300 UTC. Subsequently, it remained practically stationary for some time and then gradually moving Westnorthwestwards weakened into deep depression crossing south Andhra coast north of Kavali between 2200 and 2300 UTC of 15th. Widespread rainfall activity with isolated heavy to very heavy falls occurred coastal Andhra

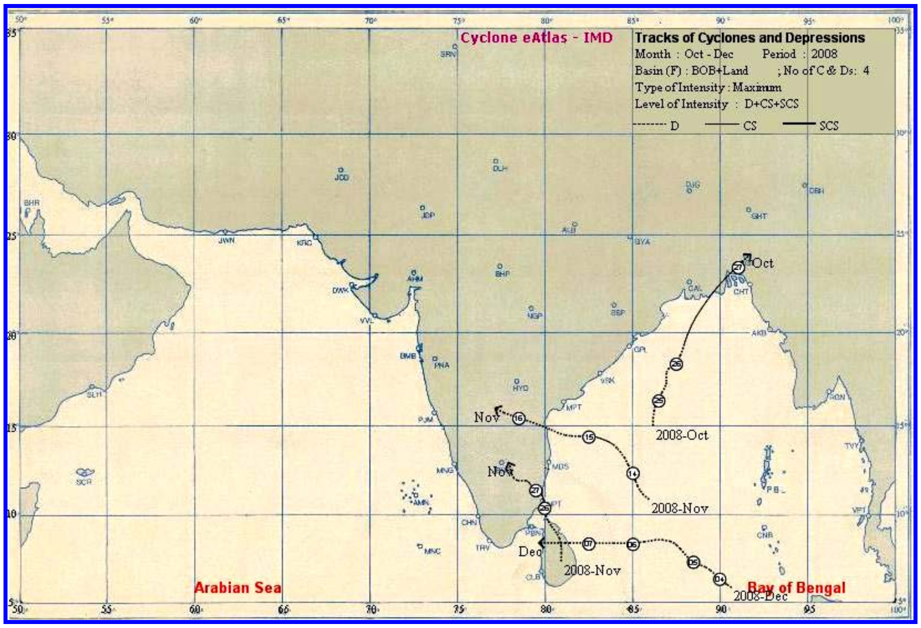


Fig. 6. Tracks of cyclonic storms RASHMI, KHAI-MUK, NISHA and the deep depression (DD) that occurred over Bay of Bengal during October-December 2008 (*Source* : Cyclone eAtlas – IMD)

Pradesh on 16th and 17th. Over Chennai also some rainfall activity prevailed during the period (9th to 10th pentads) which picked up during 11th pentad. During the 12th pentad, cyclonic storm NISHA (25-27 November 2008) formed as a depression over Sri Lanka, intensified and moved Northwestwards crossing north Tamil Nadu coast north of Karaikal between 0000 and 0300 UTC of 27th and then gradually weakened. Associated with the passage of this cyclone fairly widespread rainfall activity with very heavy fall to extremely heavy falls at scattered places occurred over Tamil Nadu from 25th to 29th November. Over Chennai also heavy rainfall activity occurred during the 12th pentad (Fig. 5).

During the 13th to 14th pentads a deep depression formed over the Bay affecting Sri Lanka and neighbourhood and some light rainfall activity occurred over Chennai. After this, the NEM started receding and there was no appreciable rainfall during last four pentads.

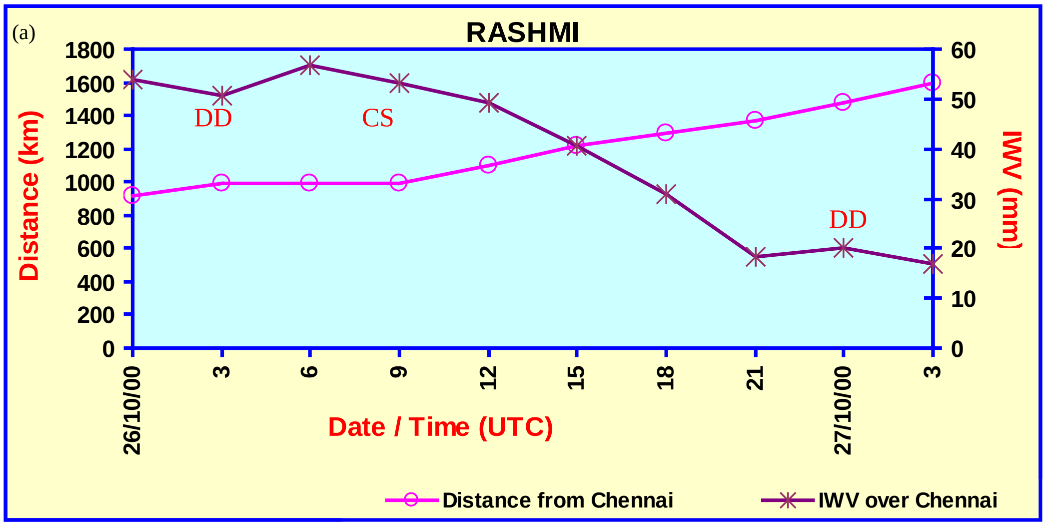
The pentad variation of IWV values based on RS also match well with that obtained through GPS technique as shown in Fig. 5 except towards end of the season. The increase in difference between GPS and RS pentad IWV values towards end of the season may be due to variability in distribution of IWV around these observation sites and/or some other factors which require further examination and are beyond the scope of this paper.

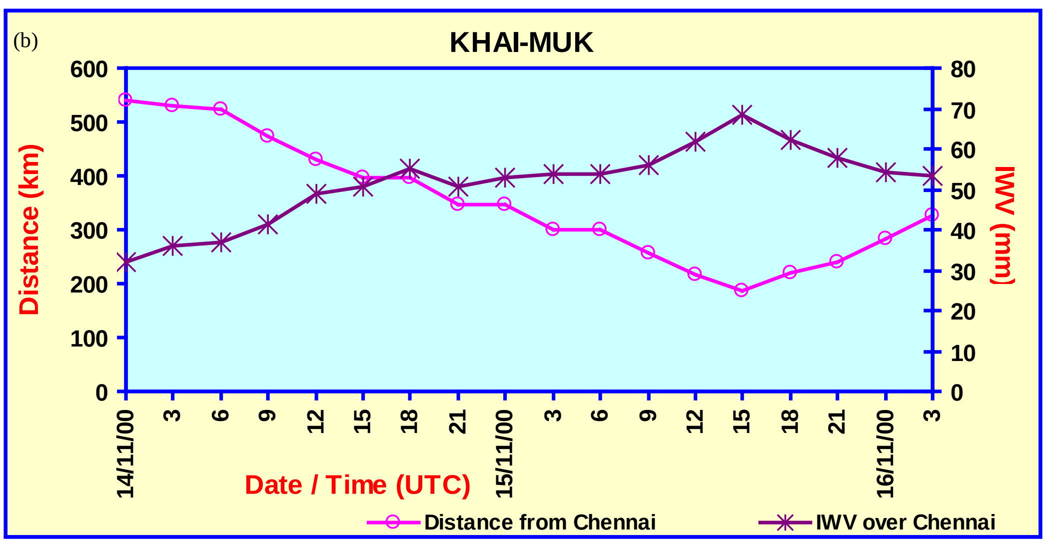
3.4. *Variation of IWV during the passage of cyclonic disturbances*

In the present section, we discuss the variation of IWV in the vicinity of the GPS site with respect to the movement of cyclonic disturbances. The hourly IWV values corresponding to the best track positions of these systems are shown in Figs. 7(a-d). These best track positions were extracted from the RSMC report on the cyclonic disturbances over the North Indian Ocean during 2008 (www.imd.gov.in). The variation of IWV in association with movement of these systems are discussed in the following paragraphs.

In the case of 'RASHMI' system [Fig. 7(a)], the IWV value was 54 mm on 26th October 0000 UTC when the system was in the depression stage and its centre was at about 917 km from the GPS site. Later, this system intensified in to a cyclonic storm and was moving away from the GPS site. The sweeping away of moisture from the region encompassing the GPS site by the system which is intensifying and moving away is depicted by the decrease of IWV value to a low of 18.3 mm, a decrease of 66%, on 26th October 2100 UTC (when system has moved away with its centre at about 1370 km from GPS site).

In the case of 'KHAI-MUK' cyclonic storm [Fig. 7(b)], the IWV value was 32 mm when the system

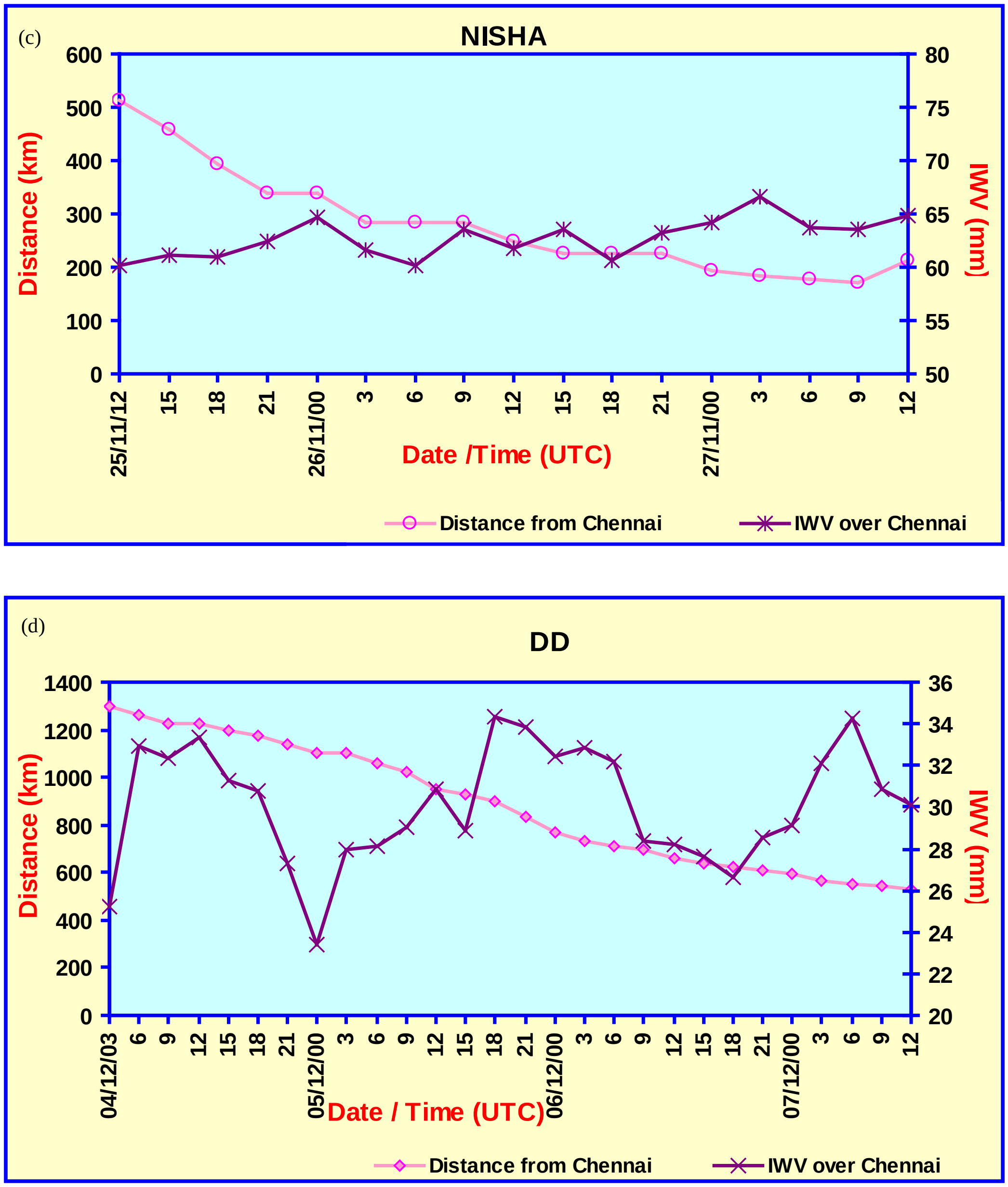




Figs. 7(a&b). Plots of distances of the centres of cyclonic storms (a) RASHMI, (b) KHAI-MUK, corresponding to the best track positions at different times from the GPS site (Chennai) and the corresponding IWV over Chennai. In Fig. 7(a), DD/CS/DD points represent stages of intensification of the system from Depression to Deep Depression, Deep Depression to Cyclonic Storm and then weakening back to Deep Depression stage respectively

centre was at about 540 km from the GPS site at 0000 UTC of 14th November. It increased to 53.8 mm, which is about 64%, as the system moved closer to the GPS site with system centre at about 300 km at 0300 UTC of 15th. The IWV value later reached a maximum of 68.3 mm (about 113% increase) on 15th November/1500 UTC when the system centre was at its closest position with respect to GPS the station (about 186 km). It later started to decrease as the distance of the centre of the system increased from GPS site and finally reduced to 53.3 mm, a decrease of 22%, with respect to the value at the closest position of the system from the GPS site.

In the case of 'NISHA' cyclonic storm [Fig. 7(c)], the GPS based IWV value increased from 60.2 mm to 64.7 mm (about 7%) when the centre of the system moved from about 515 km (25th/1200 UTC) to 340 km (25th/2100 UTC) with respect to the GPS site. Later, this value increased to 66.6 mm (an increase of about 10%) when system centre was at about 185 km (27th/0600 UTC) from the GPS site. In the case of deep depression (DD) of 4th Dec – 7th Dec, [Fig. 7(d)], though there exists an oscillatory variation of IWV, a general tendency of increase of IWV with the approach of the system in the vicinity of GPS site is noticed. However, it may be noted



Figs. 7(c&d). Plots of distances of the centres of cyclonic storms (c) NISHA and that of (d) deep depression (DD) corresponding to the best track positions at different times from the GPS site (Chennai) and the corresponding IWV over Chennai.

that the amplitude of the variation in IWV values in the last two cases are not as high as seen in the case of other two systems discussed earlier. This is due to the consideration given here only for the distance factor for explaining the variability of IWV while other factors like variability of the dynamical and physical conditions with respect to azimuthal and vertical directions also determine the distribution of IWV.

From above discussions, the general trend of increase in IWV with approach of cyclonic systems towards the GPS station, reaching maximum during closest approach and again decreasing with increase in distance of systems from the GPS site is noticed. Similar variations were also observed by Liou *et al.* (2000) who have reported an increase in precipitable water from about 5 cm to nearly 8 cm in four days when a typhoon was

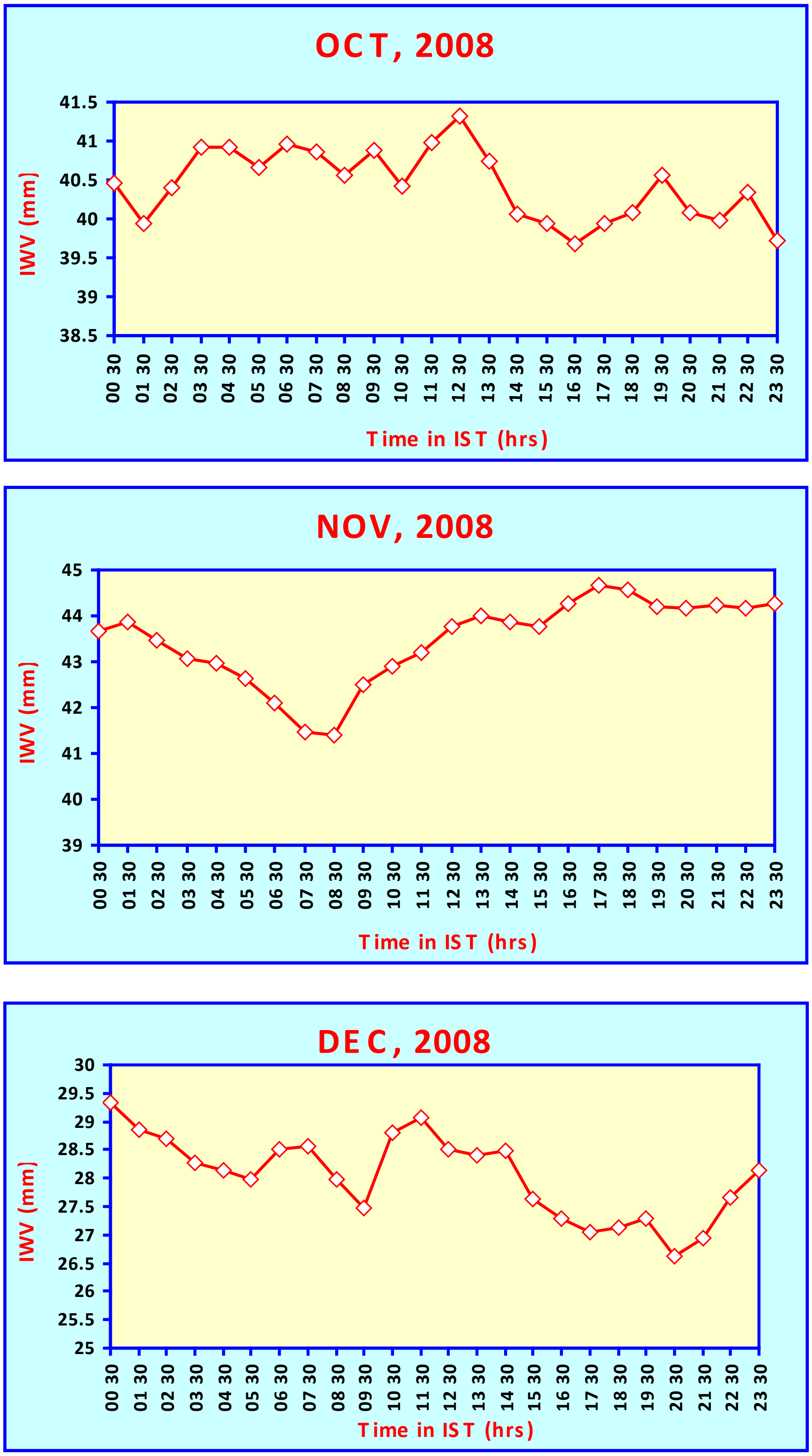


Fig. 8. Diurnal variation of GPS based IWV over Chennai during October-December 2008

striking Taiwan which, then decreased to 2-3 cm after the passage of the typhoon. Thus, by and large, the GPS based IWV reflects variation of atmospheric water vapour in association with respect to movement of cyclonic systems in the vicinity of the GPS site.

3.5. *Diurnal variation of IWV*

Next, the diurnal variations in the IWV over Chennai during NEM 2008 is studied by considering IWV values of all the 24 hours of the day (0030-2330 IST) and averaging the data pertaining to that particular hour for that month. Only those days having data for all the 24 hours are considered for analysis. The diurnal variations during October, November and December 2008 are shown in Fig. 8. It can be seen that the diurnal variations are not well pronounced during all the three months with the range of IWV being only 1.62, 3.26 and 2.73 mm during October, November and December respectively. Based on TOVS data of 0000 and 1200 UTC of three years (1996-1998), Suresh and Raj (2001) observed that, there is no notable diurnal variation of IWV over Chennai and morning IWV values are only 2 to 6 mm higher than those of evening. However, it is interesting to note that in November 2008, there is a small decreasing trend between 0030 hrs (IST) and 0830 hrs (IST) which happen to be the chief rainfall hours during NEM season after which there is a gradual accumulation of moisture as the day progresses. But, in contrast, during December 2008, there is no indication of building up of moisture as the day advances.

Above discussions show that the signatures of NEM activity could be noticed in the IWV values obtained from GPS based techniques. However, it may be mentioned here that the above analysis are based on hourly dataset for one season only and in that too there were some missing data for few hours/days. Similar analysis carried out with more number of seasonal data shall provide more insight in the understanding of variability of atmospheric water vapour on various time scales at local level as well as on regional level with dense GPS network.

4. Conclusions

An analysis of GPS based integrated precipitable water vapour over Chennai during North East Monsoon season of 2008 shows that :

(*i*) The GPS based IWV generally agrees fairly well with radiosonde based IWV and good correlation exists between them. The correlation coefficients are about 0.9 for both 0000 and 1200 UTC datasets. The bias and RMS error values of GPS based IWV with reference to that based on RS are (-4.1 mm, 6.4 mm) and (-2.4 mm, 5.5 mm) respectively for 0000 and 1200 UTC data.

(*ii*) About 79% of the IWV data are above the seasonal mean (38.5 mm) during October, 68% during November but only 18% in December for the year 2008.

(*iii*) The GPS based IWV values are consistent with activity of Northeast monsoon with increase (decrease) of IWV during active (weak) phase of NEM.

(*iv*) GPS based IWV values reflect the variation of IWV values with passage of cyclonic disturbances like cyclonic storms and depressions in the vicinity of the GPS observation site. The general expected trend of increase in IWV with approach of systems towards station, reaching maximum during closest approach and again decreasing to minimum with increase in distance of systems from station is observed in IWV values over Chennai during NEM season of 2008.

(*v*) The diurnal variations of IWV estimates during NEM season of 2008 do not appear to be very significant.

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