WATER VAPOR WINDS FROM KALPANA VHRR: A NEW APPROACH

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ABSTRACT

The information of tropospheric wind is extremely necessary for numerical weather prediction. A significant contribution of upper air wind information is derived from satellite observations that use the movement of cloud and water vapor tracers to determine winds operationally several times a day. The use of geo-stationary water vapor imagery has allowed the determination of both upper-level moisture content and the wind fields that correspond to the water vapor layers. Water vapor images from geostationary satellite allow the determination of winds in cloud-free regions also. The main aim of this study is to derive upper tropospheric winds operationally from the observations from Indian geostationary satellites. With the availability of water vapor channel (6.3 –7.1 μm) on-board KALPANA VHRR; the first attempt has been made in India to derive water vapor winds (500-100 hPa) from Indian geo-stationary satellites. The algorithms of water vapor wind retrieval techniques basically depend upon the proper selection of appropriate water vapor tracers that are generally in the locations of maximum bidirectional gradients in the image and corresponding tracking of these tracers in the subsequent image. In the present work, upper-level atmospheric motion is derived from the water vapor images by considering 1) fast and efficient tracer selection procedure based on local image anomaly, 2) tracking procedure of the selected tracer in the subsequent image based on Nash-Sutcliffe efficiency coefficient, 3) quality check based on spatial and directional consistency and 4) an empirically derived height assignment technique based on genetic algorithm. For validation of the algorithm, it is applied to METEOSAT5 VHRR images and validated with radiosonde data. Some improvement in mean vector difference and biases are noticed, during independent validation of water vapor winds derived by the present algorithm from METEOSAT5 VHRR and corresponding to EUMETSAT derived product, when both compared with radiosonde data. The present algorithm when applied to KALPANA VHRR shows high degree of agreement with the corresponding EUMETSAT derived product from METEOSAT5, and in the average sense, the KALPANA derived water vapor winds show higher accuracy compared to EUMETSAT products when collocated radiosonde observations were used as ground-truth.

1. Introduction

In any operational meteorological centre numerical weather prediction (NWP) is a daily routine work. The upper tropospheric atmospheric wind estimated from water vapor images of any geo-stationary platform is a very crucial parameter because of their use in data assimilation technique of NWP. In late eighties or early nineties, the synoptic forecasters of operational agencies were using satellite images only for visual interpretation. However, with the ability of automated wind extraction from Water Vapor images in series of GOES, METEOSAT and GMS satellites (*Laurent 1993, Holmlund 1993, Tokuno 1998, Veldon et al. 1997*) have shown some insight in to this area. The water vapor images from geo-stationary satellites have allowed the estimation of both upper-level moisture and the flow that correspond to a water vapor layers. These images can also be used to generate atmospheric flows in cloud-free regions as well. The pattern matching technique (*Merrill, 1989*) is the most common procedure for automatic generation of winds from sequence of satellite images. Two very frequently used techniques to match a pattern between a pair of images are the Maximum Cross-Correlation (MCC) and Minimum of Sum of Squared Difference (MSSD, also known as Euclidean distance method) with a common goal to find the best agreement between an initial target scene and a corresponding matching area in the subsequent images. At National Environmental Satellite Data and Information Service (NESDIS), the tracers in the water vapor images are selected by calculating the bi-directional gradients surrounding each pixel in the target array and then selecting their maximum (*Velden et al. 1997*). During tracking, to estimate where to begin the search operation for computing the sum of squared differences for all possible scenes in the search box, a short-range (6-12 hour) numerical model forecast is used. The scene representing the smallest sum is then selected as the best match. The process is repeated forward and backward in time before a final average vector is computed from the two individual estimates. At European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) water vapor winds (from First generation METEOSAT satellites) are extracted operationally (*Holmlund 1995*) on an equidistant grid (baseline 32 x 32 pixels) with a target size equivalent to the grid size. The target size and extraction grid are controlled separately in this scheme. Moreover, the exact location of the target is centered at the grid location, optimized in a search area around the grid-location. The cross-correlation technique is used operationally for tracking water vapor winds at EUMETSAT (*Rattenborg 2000)*. However, as research and development mode following three basic matching methods had been investigated viz. 1) Cross-correlation in the spatial domain, 2) Cross-correlation in the Fourier domain and 3) Sum of Squared Distances or Euclidean Distances (*Dew and Holmlund, 2000*). The relative quality of the wind vectors produced by the two Cross-Correlation methods using real water vapor imagery (*Dew and Holmlund, 1998*) showed that the performance benefit of Fourier domain compared to the spatial domain Cross-Correlation method is more significant. Moreover, another study by Dew (*Dew 2004)* had shown that Euclidean distance tracking is most effective procedure as compared to both the cross-correlation techniques for water vapor (6.2 μm) channel in cloud free regions. This technique produces a relatively larger number of high quality wind vectors compared to Cross Correlation even in the low-contrast regions of the images. Australian Bureau of Meteorology generates water vapor winds four times a day by using specific gradient criteria for tracer selection and tracking is done automatically using a model forecast to initiate the search for selected targets on sequential images (*Le Marshall et al. 1999*). A lag correlation technique is used to estimate the vector displacement. In China Meteorological Administration (CMA) cross correlation technique is used for tracking tracers, but this method is unable to cover the movement of high-speed tracers. In dark areas on water vapor image, cross correlation often failed in tracing. For those areas in water vapor images, Euclidean distance is used for tracing (*Dew & Holmlund 2000*). The Meteorological Satellite Center (MSC) of Japan Meteorological Agency (JMA) has started retrieving and dissemination of water vapor winds since 1995 from GMS series satellite and uses the traditional cross-correlation technique for tracking procedure (*Tokuno 1996*).

The main components for the estimation of water vapor winds are: a) Tracer selection and Tracking, b) Use of image-triplet and basic quality control and c) Height Assignment. The present study focuses on a re-look on the techniques of derivation of upper tropospheric atmospheric winds from the observations from Indian geo-stationary satellites. Indian geo-stationary satellite KALPANA is stationed over the Indian Ocean (74^{o}E) since 2002 with a spatial resolution of 8 Km. The main aim of this study is to estimate water vapor winds using an alternate approach for tracer selection and tracking procedure from water vapor channel (6.3 –7.1 μm) of KALPANA, which is looking at Indian Ocean region. This method is applied to three-months (September, October and November 2007) KALPANA water vapor imager triplets acquisition either at 2330, 0000 and 0030 UTC or at 0700, 0730 and 0800 UTC respectively. The corresponding EUMETSAT derived water vapor winds from METEOSAT7 are also acquired for comparative validation. Both the products were validated independently with radiosonde data over the Indian Ocean region covering the area 30^{o}E – 130^{o}E, 50^{o}S-50^{o}N. Further application and verification of this technique will be carried out using observations from the future Indian geo-stationary satellites INSAT-3D, which will have data with horizontal resolution of 5 Km.

2. Algorithm for Water Vapor Winds retrieval

Water Vapor Wind Vector (WVWV) is generated for all the available half hourly triplets in normal mode. Water Vapor images are used for detection and movement of moisture for estimation of winds at upper levels. A procedure for the detection of WVWV using KALPANA/INSAT WV data is being presented here. Detection of motion vectors is based on the assumption that moisture at different levels follows the atmospheric motion as rigid bodies. This assumption can be applied over a short interval of time, say, 30 minutes. Three consecutive KALPANA/INSAT-WV images at 30-minute interval are needed to determine the WVWVs. Following steps are involved in these estimations: i) Feature Selection and Tracking for WVWV extraction, ii) Use of image-triplet and basic quality control and iii) Height assignment. These steps along with the description of algorithm is described below:

2.1 Tracer Selection & Tracking for WVWV extraction

In this step the original water vapor triplet images are filtered to isolate frequencies that are of physical interest from those that are not. The filtered images are reconstructed by using the equation

$I_j = \frac{\left(I^o{}_{j+1} + 2I^o{}_j + I^o{}_{j-1}\right)}{4}$. Here I^0 represents the old grey values of the images. This is called triangular One-Two-One filtering function. This filtering function is used to remove high frequency noise or low frequency trends from the images. The tracers are selected by computing local anomaly in a 20 x 20 pixels window (called 'template'), both in cloudy and cloud free regions. The local anomaly is calculated using the following formula: $ana = \sum_i \sum_j \left(I(i,j) - \bar{I}\right)$. Here $I(i,j)$ represent the grey value for *(i, j)* pixel of a template window and bar represents the mean of grey values within that template. The features and their motion in two consecutive KALPANA/INSAT images are determined sequentially in 20 X 20 template windows. The match of this template is searched in second filtered image within a "search window" of 40X40 pixels, centered at the same point as the template window. The 20X20 template in the second filtered image, which lies within the search window, should have the same class as the template in first filtered image; otherwise the template in second window is rejected as a potential match. The degrees of matching between two successive images are calculated by the Nash-Sutcliffe model efficiency (*Nash and Sutcliffe 1970*) coefficient (*E*). The Nash-Sutcliffe model efficiency has been reported in scientific literature for model simulations of discharge, and water quality constituents such as sediment, nitrogen, and phosphorous loadings to find the match between modeled dishcharge to the observed data (*Moriasi 2007*). Here an attempt has been to investigate this technique for tracking tracers between two successive images. It is defined as:

$$E = 1 - \frac{\sum_{i=1}^{n}\left(I_s - I_t\right)^2}{\sum_{i=1}^{n}\left(I_s - \bar{I}_s\right)^2}$$

Where I_s and I_t are the variance of the grey values for search and target window and $\bar{I}_s$ is the average of variance of search window. *n* is the window size of both search and target box. The coefficient *E* is normalized to values between $-\infty$ and +1. An efficiency *E* = 1 corresponds to a perfect match between the search and target window, *E* = 0 means that search window is as accurate as mean of the target window and *E* < 0 implies the lack of matching between search and target window. Essentially, the closer the model efficiency to 1, the more accurate the matching between search and target window. The bar indicates the average of the grey values of the pixels. The center of the template with maximum value of *E* is considered to be the location of feature in second image. This is the first set of the motion vector for the given template location. Sequentially the template is shifted in x and y directions and the motion vectors are determined using the procedure given above.

2.2 Use of image-triplet and basic quality control

Previous step is repeated for second and third WV images, and a second set of motion vectors is generated. In both the above sets of WVWVs there are several vectors that are spurious. This may occur due to several factors. For example, moistures does not act as rigid bodies. Also, with atmospheric motion, moisture may change shape, and maximum correlation may appear at some false location. Some rectification of this problem can be done using basic quality control measures. These are:

- WVWV magnitude should not exceed a threshold that is predetermined for each level using climatology.
- Any vector should not deviate by more that 60^o from the average direction in a 3 X 3 neighborhood.
- Any vector magnitude should not exceed by more that 10 m/s from the average magnitude in a 3 X 3 neighborhood.
- Any vector direction should not deviate by more that 60^o from the direction of corresponding vector in second set of WVWV.
- Any vector magnitude should not exceed by more that 10 m/s from the magnitude of corresponding vector in second set of WVWV.
- If an image location produces 2 vectors in 2 sets and satisfies conditions (iv) and (v), both the vectors are averaged to produce the WVWV at that location. If only one set contains a vector at the above location, that is retained, but has to pass tests (i),(ii), and (iii).

Theoretically the maximum accuracy that can be attributed to the WVWV is equivalent to the error of 1 pixel/30 minutes. This is 4-5 m/s for KALPANA/INSAT. There are several other sources of error, for example uncertainties about water vapor thickness, and the validity of assumptions of rigidity of moisture shapes within a short time span.

2.3 Height assignment

In this section the height assignment of derived water vapor wind vector is done. The Genetic Algorithm (GA) is one of the best empirical techniques to determine best relationship between the independent and dependent parameters. The GA is used here to find the height of the corresponding vector. In this step, a function is generated for cloudy and non-cloudy pixels using three image variables like coldest, warmest and cosine of latitude from randomly selected 95 METEOSAT5 images and corresponding product of EUMETSAT from one month data as training data sets. Later a mapping is defined between METEOSAT5 and KALPANA, so that the function generated using METEOSAT5 can be used in KALPANA WVWV. Finally the functions for cloudy and non-cloudy regions are used to find the WVWV height in KALPANA through the mapping.

3. Verification procedure

The quantitative evaluation of derived atmospheric motion vectors are calculated according to the CGMS guidelines, where derived cloud motion and water vapor winds are validated with collocated radiosonde data. According to CGMS guidelines, the vector Difference (VD) between an individual wind (i) and the collocated Rawinsonde wind (r) used for verification is given by

$$VD = \left[(U_i - U_r)^2 + (V_i - V_r)^2\right]^{1/2}.$$

The speed bias (BIAS) is calculated as

$$BIAS = 1/N \sum_{i=1}^{N}\left[\left(U_i^2 + V_i^2\right)^{1/2} - \left(U_r^2 + V_r^2\right)^{1/2}\right]$$

Finally the mean vector difference (MVD) is reported as

$$MVD = 1/N \sum_{i=1}^{N}(VD)_i .$$

These statistics can provide a fixed measure of product quality over time and can be employed in determining the observation weight in objective data assimilation. And the standard deviation (SD) about the mean vector difference traditionally reported is

$$SD = \left[\frac{1}{N}\sum_{i=1}^{N}(VD - MVD)^2\right]^{\frac{1}{2}}$$

The root-mean-square error (RMSVD) traditionally reported is the square root of the sum of the squares of the mean vector difference and the standard deviation about the mean vector difference,

$$RMSVD = \left[MVD^2 + SD^2\right]^{\frac{1}{2}}.$$

It is suggested to report mean vector difference (MVD) and standard deviation (SD), along with mean radiosonde speed (SPD) and number of collocation with radiosonde data (NC). Here the unit of MVD, RMSVD, SD, SPD and BIAS is m/s. A typical example of water vapor winds derived from KALPANA VHRR for 2nd January 2008 valid at 0730 UTC using the present technique is shown in the Fig. 1a and the corresponding EUMETSAT derived water vapor winds from METEOSAT7 is also shown in Fig. 1b. It shows that the present technique is able to produce the wind with uniform coverage, large-scale and synoptic-scale features are well captured and vertical distribution of information is in between 100-500-hPa portion of the troposphere.

3.1 Validation with Radiosonde and Meteosat data

The water vapor winds derived two times (00Z and 0730Z) a day at Space Applications Centre (SAC) Ahmedabad. The winds derived at SAC with all available acquisitions are validated with radiosonde data for the period of September, October and November 2007. To know the performance of the product generated at SAC from KALPANA, the EUMETSAT derived METEOSAT7 winds for September, October and November 2007 are also acquired and compared with radiosonde data for the same time when KALPANA winds are also derived at SAC. The validation is done for each day by calculating different statistical parameters as discussed above for the region 50^{o}N to 50^{o}S and 30^{o}E to 130^{o}E and making the average to get the monthly mean. During collocation 1.0 x 1.0 degree latitude/longitude grid point is considered, with speed and direction differences more than 30 m/s and 90 degree respectively are filtered out.

The water vapor winds derived from Kalpana and Meteosat7 are validated with radiosonde data for the months of September, October and November 2007. Unlike in cloud motion winds, where validation is done for three different levels, here validation is done for high level only (according to CGMS guidelines) as derived water vapor winds lies in between 100-500 hPa. Table 1(a-b) shows the values of different statistical parameters calculated for water winds for the month of September 2007 as derived from Meteosat7 and Kalpana, when both the sets are compared with radiosonde separately. The parameters are calculated in three cases viz. i) by considering all acquisitions together, ii) considering all 00Z acquisitions and iii) all 0730 acquisitions respectively. During the validation of 00Z acquisitions all available 00Z radiosonde data are used, while for 0730Z acquisitions all available radiosonde data between 06Z and 09Z are used. It is seen from the Table 2(a-b) that the statistical parameters for Meteosat7 and Kalpana are very close to each other in all the three cases. As similar to Table 4, the different statistical parameters calculated for water vapor winds for the month of October 2007 is shown in Table 3(a-b). Similar to the month of September 2007, the statistical parameters for Meteosat7 and Kalpana are very close to each other, when both are collocated separately with radiosonde. Similar trends are also observed in the month of November 2007 (Table 7) for both Meteosat7 and Kalpana. One interesting feature is that total number of collocations (NC) in Kalpana is higher than the corresponding Meteosat7 derived winds in all the cases. Another set of validation is also carried out by collocating Meteosat7, Kalpana and radiosonde data together. In this case, since the number of collocations for a single month is not very high, winds from all the three months are considered together. Table 4 shows the statistical parameters calculated in this collocation for three different cases viz. i) Meteosat7 vs. Radiosonde, ii) Kalpana vs. Radiosonde and iii) Kalpana vs. Meteosat7 respectively. It is also seen from the Table 8 that Meteosat7 and Kalpana values are very close to each other when both are compared with radiosonde data. However, when Kalpana and Meteosat7 are compared RMSVD is 6.5 m/s.

4 Conclusions

In this study a brief descriptions of the retrieval algorithm of water vapor winds with an empirically derived height assignment technique is presented. The water vapor winds derived from Kalpana at SAC for September, October and November 2007 are validated against radiosonde data. To know the performance of the derived product from Kalpana, the corresponding water vapor winds derived at EUMETSAT using Meteosat7 are also acquired and validated. The water vapor winds derived from Kalpana has very good resemblance with the corresponding winds from Meteosat7 derived at EUMETSAT. This may be due to the robust tracer selection and tracking procedure used in the derivation of WVWV. Though this technique is working properly in case of water vapor winds, however, this algorithm should be verified by implementing the other existing techniques already running in different operational agencies, related to tracer selection, tracking and height assignment.

5. Acknowledgement

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Table 1: Water Vapor winds, both Meteosat7 and KALPANA: September 2007

a) **Considering both 00Z & 0730Z acquisition together**

Parameters	METEOSAT7 VS RADIOSONDE (ALL)	KALPANA VS RADIOSONDE (ALL)
MVD	8.9	8.7
RMSVD	10.2	9.9
SD	4.8	4.6
BIAS	0.8	1.4
SPD	14.2	15.6
NC	296	360

b) Considering 00Z & 0730Z acquisition separately

PARAMETERS	METEOSAT7 VS RADIOSONDE (00 UTC)	KALPANA VS RADIOSONDE (00 UTC)	METEOSAT7 VS RADIOSONDE (0730 UTC)	KALPANA VS RADIOSONDE (0730 UTC)
MVD	8.4	8.5	9.1	8.8
RMSVD	10.5	9.9	10.3	9.9
SD	5.3	4.7	4.6	4.3
BIAS	1.0	1.1	0.7	1.8
SPD	14.0	16.9	13.4	14.1
NC	157	203	139	157

Table 2: Water Vapor winds, both Meteosat7 and KALPANA: October 2007

a) Considering both 00Z & 0730Z acquisition together

Parameters	METEOSAT7 VS RADIOSONDE (ALL)	KALPANA VS RADIOSONDE (ALL)
MVD	7.9	8.3
RMSVD	9.2	9.5
SD	4.5	4.4
BIAS	1.9	3.6
SPD	14.6	17.8
NC	319	355

b) **Considering 00Z & 0730Z acquisition separately**

PARAMETERS	METEOSAT7 VS RADIOSONDE (00 UTC)	KALPANA VS RADIOSONDE (00 UTC)	METEOSAT7 VS RADIOSONDE (0730 UTC)	KALPANA VS RADIOSONDE (0730 UTC)
MVD	7.1	6.9	8.5	9.6
RMSVD	8.6	8.0	9.7	10.9
SD	4.5	3.7	4.4	5.1
BIAS	1.1	1.8	2.9	5.0
SPD	12.8	13.3	16.6	21.3
NC	172	156	147	199

Table 3: Water Vapor winds, both Meteosat7 and KALPANA: November 2007

a) Considering both 00Z & 0730Z acquisition together

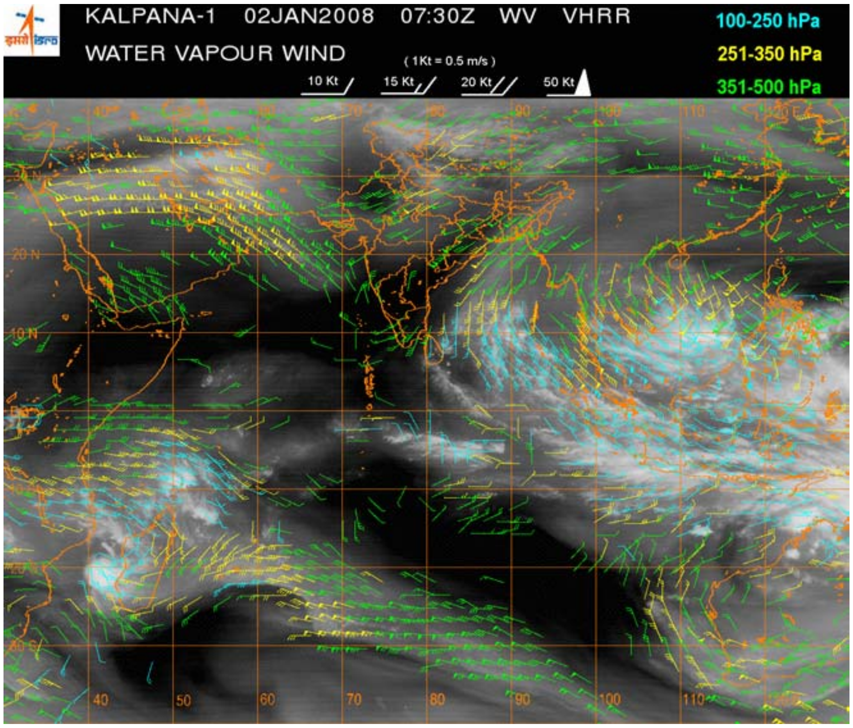
Parameters	METEOSAT7 VS RADIOSONDE (ALL)	KALPANA VS RADIOSONDE (ALL)
MVD	8.4	9.2
RMSVD	9.8	10.4
SD	4.9	4.6
BIAS	3.7	4.9
SPD	18.7	20.6
NC	339	459

b) **Considering 00Z & 0730Z acquisition separately**

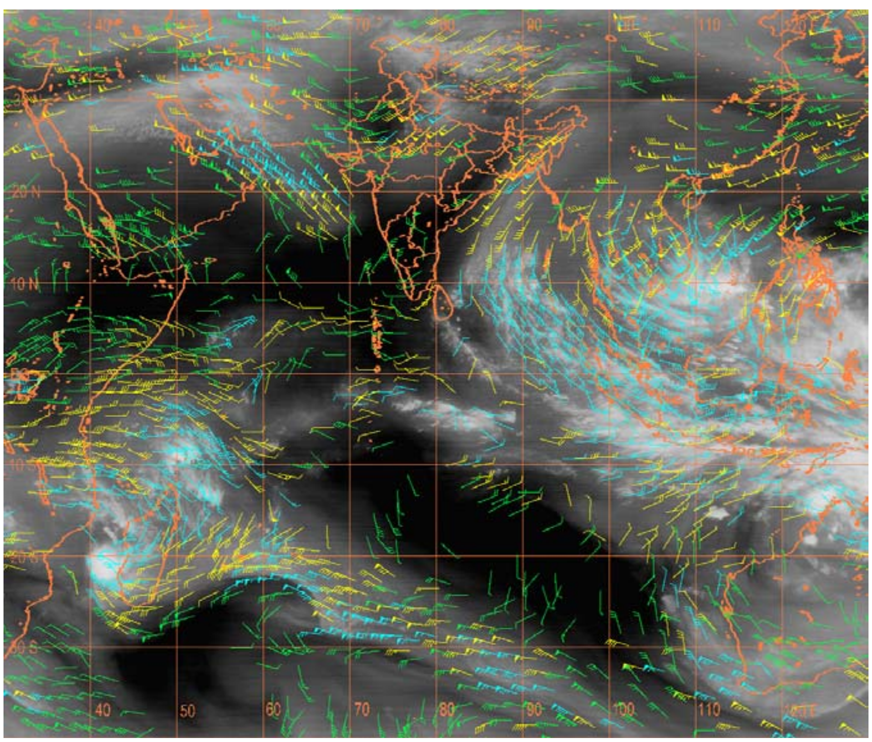
PARAMETERS	METEOSAT7 VS RADIOSONDE (00 UTC)	KALPANA VS RADIOSONDE (00 UTC)	METEOSAT7 VS RADIOSONDE (0730 UTC)	KALPANA VS RADIOSONDE (0730 UTC)
MVD	8.4	8.2	8.4	9.9
RMSVD	10.0	9.3	9.6	11.1
SD	5.3	4.3	4.5	4.9
BIAS	2.7	3.3	4.8	6.2
SPD	16.8	16.9	20.0	23.4
NC	179	200	160	259

Table 4: September, October & November 2007
(when Meteosat7, Kalpana & radiosonde are collocated together)

Parameters	METEOSAT7 VS RADIOSONDE	KALPANA VS RADIOSONDE	KALPANA VS METEOSAT7
MVD	9.0	8.5	6.5
RMSVD	10.4	10.0	7.9
SD	4.1	3.6	3.7
BIAS	1.3	2.2	-0.9
SPD	16.4	16.4	16.4
NC	252	252	252



a)



b)

Figure 1: A typical example of Water Vapor winds over Indian Ocean region (30E-130E, 50S-50N) from: a) KALPANA VHRR derived at SAC using the present algorithm and b) METEOSAT7 derived by EUMETSAT for 2nd January 2008 valid at 0730 UTC.