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# Quality control issues in atmospheric motion vectors

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**Abstract**

Currently, atmospheric motion vectors (AMVs) are hourly generated satellite derived product on operational basis at India Meteorological Department (IMD), New Delhi. These wind vectors are associated with errors and difficult to use in mesoscale models without considering the quality issues**.** Quality control is an integral part of the AMVs retrieval from geo-stationary satellites. Present paper deals with various quality indicator or flags used in Automatic Quality Control (AQC) scheme of European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) with new coefficients and Auto Editor (AE) criterion at Cooperative Institute for Meteorological Satellite Studies (CIMSS) on Kalpana -1 satellite data. The results obtained from the new parameters in AQC and with height adjustment made with AE are more realistic and free from spurious winds in both Infrared (IR) and Water Vapour (WV) channels. Collocation with radiosonde during one month period shows an average decrease (decrease) of RMSE in CMVs (WVWs) is of the order of 4 % (3 %) and increase (decrease) in mean bias is of the order of 3 % (10 %).

**Keywords**: Automatic quality control (AQC), Atmosphere Motion Vector (AMV), IR, Meteorology, Wind vapour,India

## Introduction

Geostationary satellite has an advantage of getting the images at short time intervals (presently ½ an hour from Kalpana- 1), which provide better temporal resolution than the conventional measurements (6 h or 12 h). Cloud motion vector or broadly we can say atmospheric motion vector, processed globally and operationally on a daily basis from five geostationary meteorological satellites. The sequence of images taken from geo-stationary satellite increases considerably the spatial and temporal coverage over the globe. To fill the data gaps in data void regions, new channels play an important role like, Infrared, Visible and Water Vapour bands. The potential advantage of water vapour winds is that these winds are available in cloud and cloud free regions both. Water vapour winds are very useful during the seasons when clouds are not available specially mid and upper troposphere region.

The automatic extraction algorithm of AMVs from the sequence of satellite images (usually triplet) at India Meteorological Department (IMD) in both Infrared (IR) and Water Vapour (WV) bands provides the valuable information especially regarding the movement of the mesoscale or convective scale systems and better insight of the physical processes involved in their formation, persistence and dissipation. Authors in this paper, deals with the quality mark associated during the AMV extraction process. Tracers are identified (in CMVs maximum brightness or entropy over the specified area, say 12 pixel) and moisture gradients in WVW are identified by bi-directional gradients in specified template with empirically determined threshold and with features of sufficient variability (Velden *et al*., 1997). So in the first initial steps to maintain the quality in the wind extraction process one should identify the entropy and normalized tracer size in target area. Standard deviation, minimum and maximum gradients, correlation coefficient value of the corresponding peak. During the comparison process of two (or more) components new quality marks have been generated based on the wind components direction, speed, correlation and height consistency. The raw AMV product with the above quality flags now tested with neighboring segments or model forecast information corresponding to the same location, pressure level and time by forecast, spatial, temporal and height consistency marks. The final quality mark or AMV flag is generated by weighted average of the individual checks. The final product is then distributed on GTS in SATOB and BUFR format with quality flags to the end users and numerical model assimilation purpose. There are several other parameters which influence the number and quality of consistent AMVs, like size of the target and search area windows and height assignment of the wind vectors. The tracking algorithm used in deriving the CMV is the minimization of Euclidean distance and in WVWs maximization of correlation between the target and search area by recognizing the similar structure on two images. The optimum target and search area should be specified based on the concept that the winds in the troposphere rarely exceed 200 km /hour (Szantai *et al*., 2002)**.** Keeping in view, we have selected the tracer and search window size 20 X 20 and 32 X 32 pixels respectively. In a very small target window, small cloud elements, which are likely to travel with the same (small scale) velocity as the surrounding air, are tracked but are sensitive to noise. On the other hand, large target size reduce the noise but in this case we are dealing an 'average' kind of motion in which several elements move with different velocities and it will increase the computation time also. Similarly, in the height assignment also semi-transparent clouds plays an important role and are the main sources of slow bias in upper level winds. Because the tracking of the high level cloud motion vector because cirrus clouds are thin, single layer clouds which acts as suitable tracer but very difficult to assign the height. Other main centers of the world like National Centre for Environmental Prediction (NCEP), European Centre for Medium Range Weather Forecast (ECMWF) and U.K Met Office etc. restricted the use of high level CMV due to slow speed bias at High level CMVs and Global Data Assimilation Forecast System (GDAFS) faces some problems in real time utilization (Sasaki, 1993)**.** The problems associated with INSAT CMV data is carried out by Kelley (1993). The height assignment errors cause the significant change certain meteorological parameters like vertical wind shear in the vicinity of the significant weather phenomena. To overcome this problem $H_2O$ intercept method is used. Quality control is essential as these winds are assimilated globally in Numerical Weather Prediction (NWP) models. Despite their inherent errors and uncertainties, satellite derived CMVs are very useful as they are the only source of upper wind data over the vast data sparse oceanic areas of the globe (Prasad *et al*., 2003). Significant improvements in regard to the quality control system of CMV have shown (Uchida, 1991; Holmlund, 1993**;** Kelkar *et al*., 1993; Takata, 1993). The data used in the paper is based on the cloud tracking by cross correlation method (Green, 1975). The symmetry check for the corresponding vectors for quality control should be agreed within certain limit of threshold of speed and direction (Schmetz & Nuret, 1987, Schmetz *et al*., 1993). Quality control procedures tend to favor winds that are consistent with their neighbors (Holmlund, 1998)**.** The collocation criteria are for one AMV and one sonde observation if they are less than 150 km apart, have less than 25-hPa separation in the vertical, and are separated less than 1.5 h in time. These criteria follow recommendations of the Coordination Group for Meteorological Satellites (CGMS) (Velden & Holmlund, 1998) and have been found a useful compromise between too large spatial separations (which limit the accuracy of the spatial characterization of the error structure) and too tight criteria (which limit the sample size). The increase of spatial and temporal coverage of the wind observations the quality estimates threshold also modified (Hayden & Purser 1995; Holmlund 1998; Velden & Holmlund, 1998). The new data stream from EUMETSAT contains all observations that pass a very weak quality threshold of QI = 0.3 together with the final quality indicator (QI) assigned during the quality control at the Meteorological Product Extraction Facility (MPEF).

**Data and methodology:**

The Kalpana-1 satellite data used has been taken from national satellite datacenter of India Meteorological Department (IMD), Lodi Road, New Delhi-3. Because the error estimate is probabilistic and the probability for the simultaneous occurrence of '**n**' independent tests $A_j$ can be expressed as (Holmlund, 1996) - Eq-1

$$P\left(A_1 \cap A_2 \cap ---\cap A_n\right) = \prod_{i=1}^{n} P\left(A_i\right) \qquad (1)$$

Assume that all the observations follow the Gaussian distribution function $f\left(x\right)$ which is given below in Eq-2:

$$f\left(x\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{1}{2}\right)\left(\frac{x-\mu}{\sigma}\right)^2} \qquad (2)$$

The cumulative distribution function (CDF) of the test is defined as:

$$\Phi\left(x\right) = \int_{-\infty}^{x} f\left(t\right)dt \qquad (3)$$

EUMETSAT, suggest a quality indicator, which is based on a simple empirical function (Eq-4), based on the tanh function, which has been used to normalize the individual quality tests $\left(f\left(x\right)\right)$ to provide an estimate to the Cumulative distribution function (CDF):

$$\Phi_e\left(x\right) = \tanh\left(f\left(x\right)\right)^D \qquad (4)$$

The various functions utilized in Automatic quality control (AQC) procedure are given below in Eqs-5 (a-e)

**Direction Consistency Function:**

$$DCF = 1.0 - \left[\tanh\left(\frac{\Delta\theta}{\mathrm{A}_1 \exp\left(-S/B_1\right) + C_1}\right)\right]^{D_1} \qquad (5a)$$

**Speed Consistency Function:**

$$SCF = 1.0 - \left[\tanh\left(\frac{\Delta S}{MAX\left(A_2 S, B_2\right) + C_2}\right)\right]^{D_2} \qquad (5b)$$

**Vector Consistency Function:**

$$VCF = 1.0 - \left[\tanh\left(\frac{\Delta V}{MAX\left(A_3 S, B_3\right) + C_3}\right)\right]^{D_3} \qquad (5c)$$

**Spatial Consistency Function:**

$$SCF = 1.0 - \left[\tanh\left(\frac{\Delta V_m}{MAX\left(A_4 S, B_4\right) + C_4}\right)\right]^{D_4} \qquad (5d)$$

**Forecast Consistency Function:**

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$$FCF = 1.0 - \left[ \tanh \left( \frac{\Delta V_F}{MAX\left(A_5 S, B_5\right) + C_5} \right) \right]^{D_5} \quad (5e)$$

Where, $\Delta\theta$, $\Delta S$, $\Delta V$ represent the difference of direction (degrees), difference of speed and the length of difference vector between first and second satellite wind component. $\Delta V_m$ is the length of difference vector between satellite wind component and its best neighbor. The best neighbor is determined by the smallest vector difference. $\Delta V_F$ is the difference of satellite wind component and the forecast vector interpolated to the same location and pressure level. The coefficients of $A_i, B_i, C_i$ and $D_i$ ($i$ = 1 to 5) for old and new set up are defined in Table 1.

The final quality indicator (QI) is a linear weighted average (Eq-6) of the individual results (Φ).

$$QI = \frac{1}{\sum W_i} \sum W_i \left\{ 1 - \left[ \tanh\left(\Phi_i\right)\right]^{D_i} \right\} \quad (6)$$

Where, $W_i$ are the individual test weights and $D_i$ are the exponents. The weight factors are 2.0 for the spatial consistency (Wsp), and 1.0 for the other consistencies. If the final QI of Eq-6, is less than 0.6 then the corresponding wind vector will be rejected.

Another approach of Auto Editor (AE) using at CIMSS is based on three dimensional objective analysis of wind field (Hayden & Purser, 1995) using the background information from the numerical forecast objectively is determined by the following Penalty function (Eq-7):

$$B_{m,k} = \left( \frac{V_m - V_{i,j,k}}{F_v} \right)^2 + \left( \frac{T_m - T_{i,j,k}}{F_t} \right)^2 + \left( \frac{P_m - P_{i,j,k}}{F_p} \right)^2 + \left( \frac{dd_m - dd_{i,j,k}}{F_{dd}} \right)^2 + \left( \frac{s_m - s_{i,j,k}}{F_s} \right)^2 \quad (7)$$

Where, V= velocity, T= temperature, P =Pressure, dd =direction and s=speed. Subscript m refers to the measurement. i,j are the horizontal dimension and k is the vertical level.

The $F$ are weighting factors given to velocity, temperature, pressure, direction, and speed; default values are 2 $\left(m/\mathrm{sec}\right)$, 10°C, 100 hPa, 1000°, and 1000 $\left(m/\mathrm{sec}\right)$ respectively.

The above two checks are internal quality checks of AMVs. The external quality of the wind is determined by the Radisosonde or rawinsonde observations. The external quality check means the quality control of final set of winds generated after processing the internal checks of the algorithm. The collocation box with the satellite wind vector should be constrained to the nearest match only when satisfy the following criteria (Velden, Report of WGIII, 1998):

$$Collocationmatch_{RS} = \min\left[ \left(\frac{dx}{x_l}\right)^2 + \left(\frac{dp}{p_l}\right)^2 + \left(\frac{dt}{t_l}\right)^2 \right] \quad (8)$$

Where, $x_l$ =150 Km, $p_l$ =25 hPa and $t_l$ =90 minute.

The mean vector difference (MVD) is given by

$$\left(MVD\right) = \frac{1}{N}\sum_{i=1}^{N}\left(VD_i\right) \quad (9)$$

Where, the vector difference, $\left(VD_i\right)$ between individual CMV report $\left(i\right)$ and collocated rawinsonde $\left(r\right)$ are given below Eq-10:

$$\left(VD\right)_i = \sqrt{\left(U_i - U_r\right)^2 + \left(V_i - V_r\right)^2} \quad (10)$$

The Root Mean Square (RMSE) is reported as the square root of the sum of the squares of mean vector difference and standard deviation about the mean vector difference (Eq-11)

$$\left(RMSE\right) = \sqrt{\left(MVD\right)^2 + \left(SD\right)^2} \quad (11)$$

Where,the standard deviation about the mean vector difference is given by Eq-12 below:

$$\left(SD\right) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\left(VD_i\right) - \left(MVD\right)\right)^2} \quad (12)$$

The speed bias is given by Eq-13:

$$\left(BIAS\right)_i = \frac{1}{N}\sum_{i=1}^{N}\left( \sqrt{U_i^2 + V_i^2} - \sqrt{U_r^2 + V_r^2} \right) \quad (13)$$

Normalized RMS vector difference is given by Eq-14

$$NRMSVD = \left( \frac{BIAS}{RMSE} \right) \quad (14)$$

**Results and discussion**

The AQC test scheme used at EUMETSAT for old and new parameters are shown graphically in the figures 1 (a-e). The old and new parameters used in the Eqs 5 (a-e) are described in Table (1). The forecast consistency test is performed using the forecast wind vector of IMD, GFS (T382) model forecast, Figs 2 (i,j).

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*Fig 1 (a). Direction consistency test*

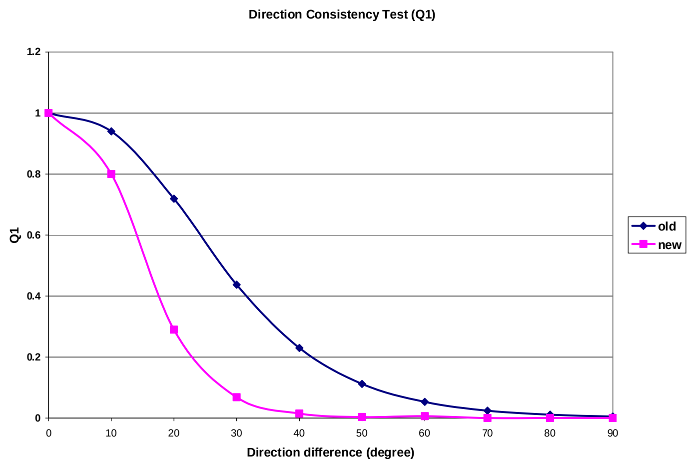


*Fig1 (b). Speed consistency test*

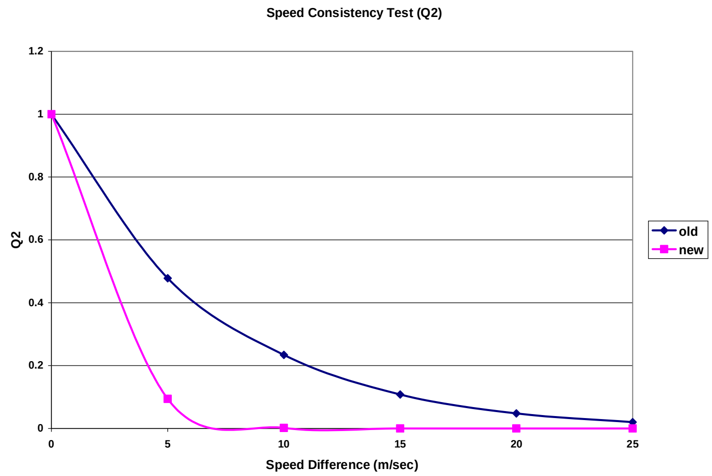


*Fig. 1 (c). Vector consistency test*

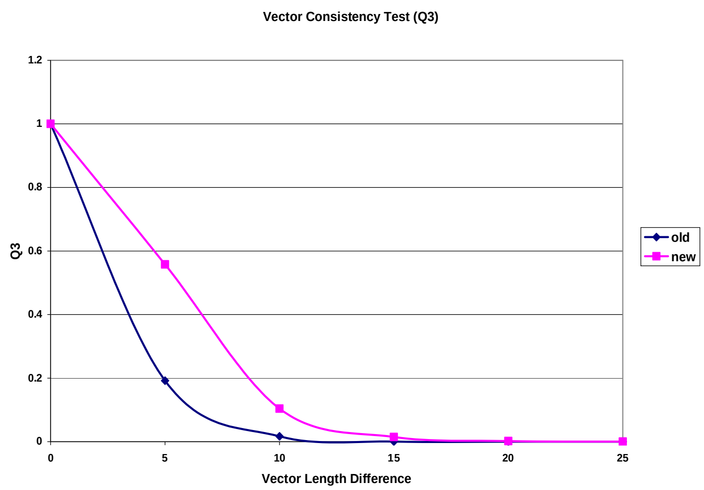


*Fig.1 (d). Spatial consistency test*

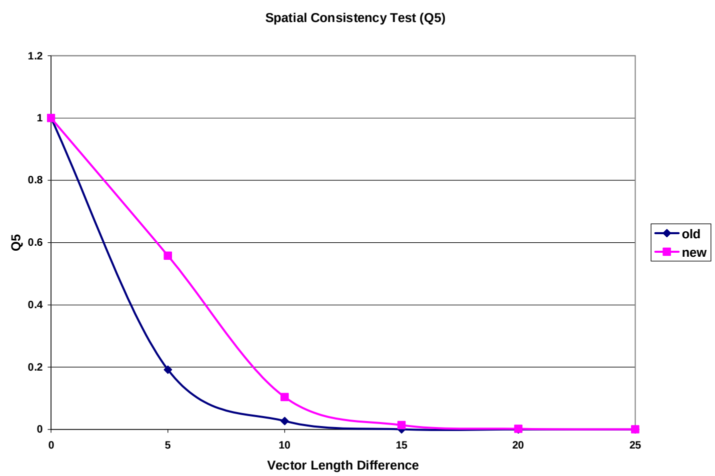


*Fig.1 (e). Forecast consistency test*

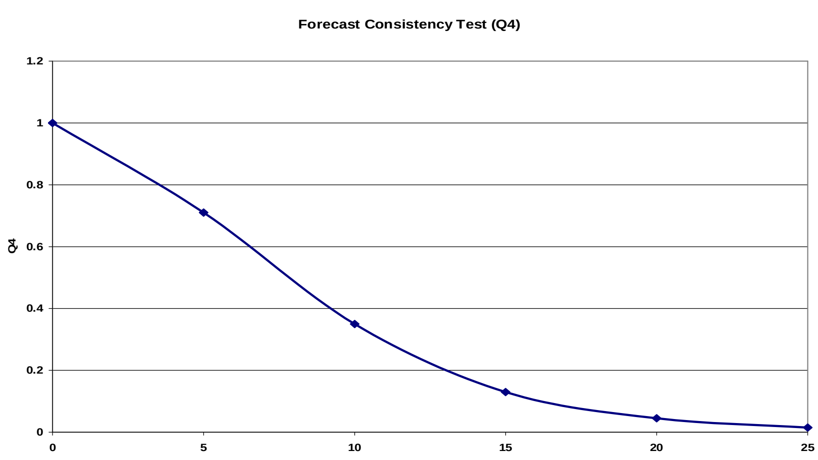

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*Fig.2(b). CMV of 0330 UTC of Kalpana-1 after new AQC: dated 06-01-2011*

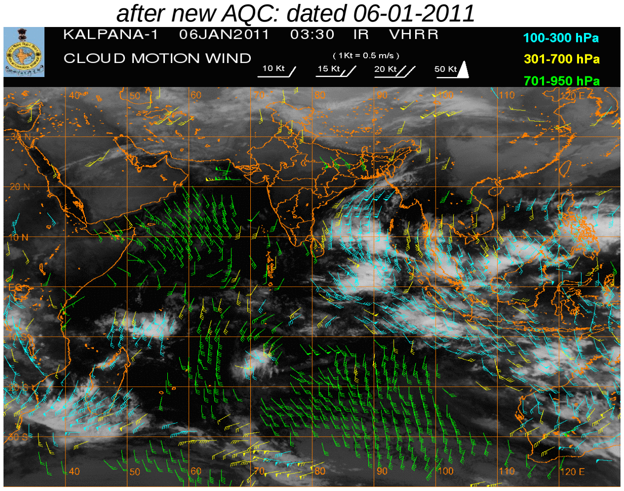


*Fig. 2(b). CMV of 0330 UTC of Kalpana-1 after new AQC: dated 06-01-2011*

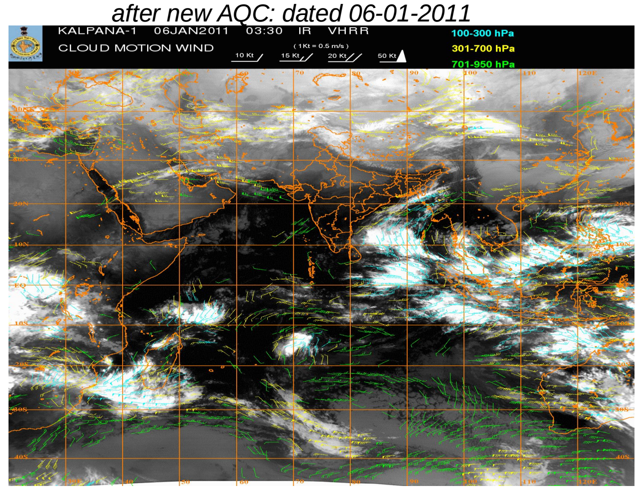


*Fig. 2 (c). CMV of Kalpana -1 (0430UTC) wWith old AQC: dated 06-01-2011*

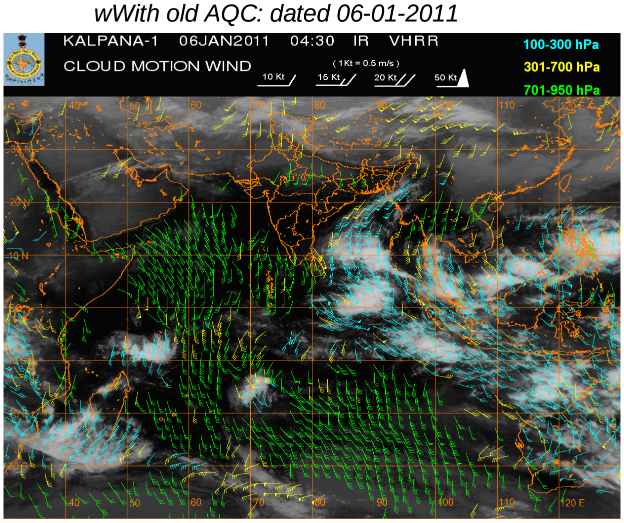


*Fig. 2(d). CMV of 0430 UTC of Kalpana-1 after new AQC: dated 06-01-2011*

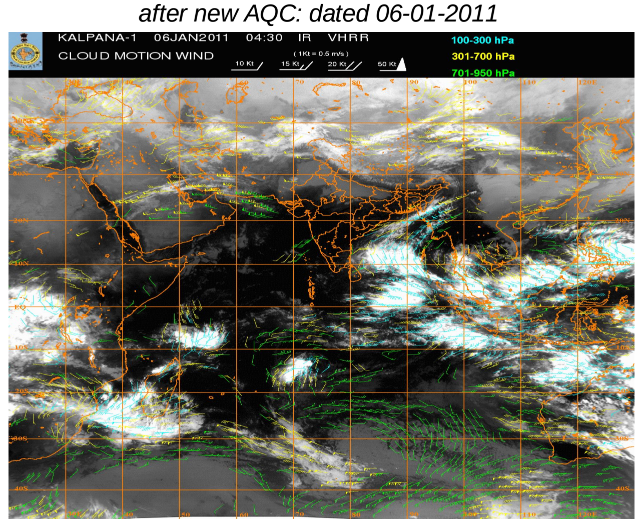


*Fig. 2 (e).WVW of Kalpana -1 (0500UTC) with old AQC: dated 06-01-2011*

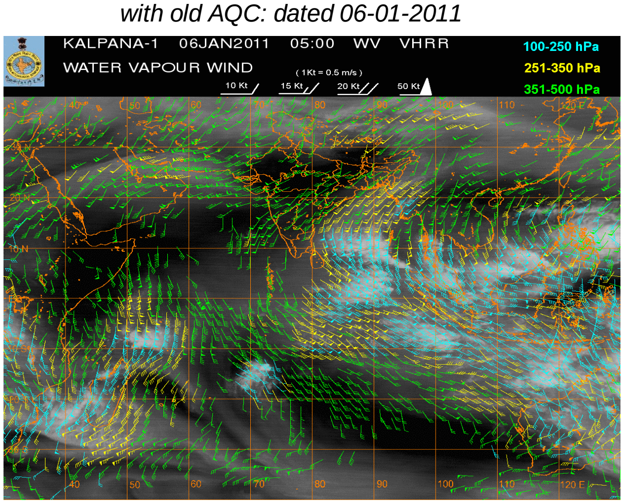


*Fig. 2(f). WVW of 0500 UTC of Kalpana-1 after new AQC: dated 06-01-2011*

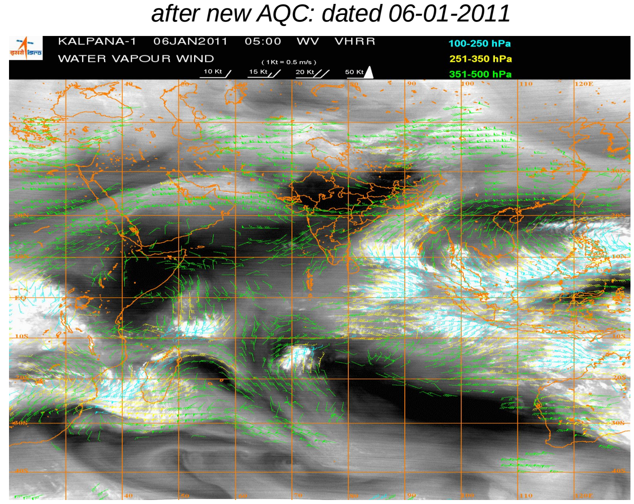



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*Fig. 2 (g). WVW of Kalpana -1 (1200UTC) with old AOC: dated 12-01-2011*

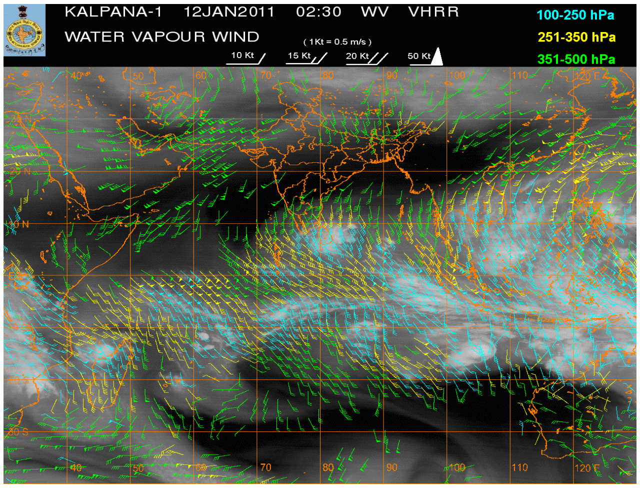


*Fig. 2(h). WVW of 1200 UTC of Kalpana-1 after new AQC: dated 12-01-2011*

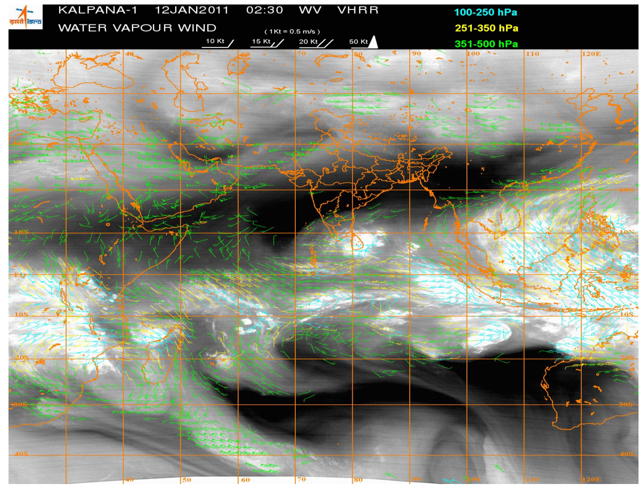


*Fig. 2(j). IMD GFS (T382) forecast based on 12-01-2011(300 hPa)*

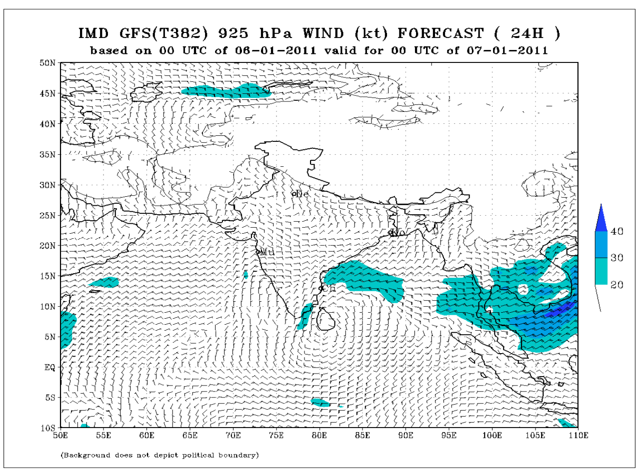


*Fig. 2 (i).IMD GFS (T382) forecast based on 06-01-2011 (925 hPa)*

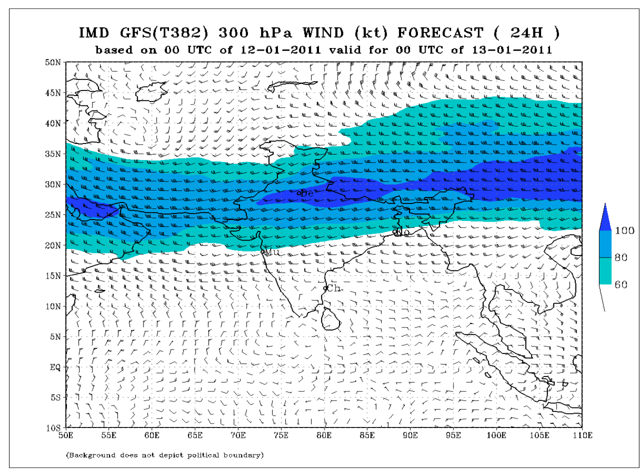


*Fig. 3. NRMSVD versus collocation (RS) of water vapour winds*

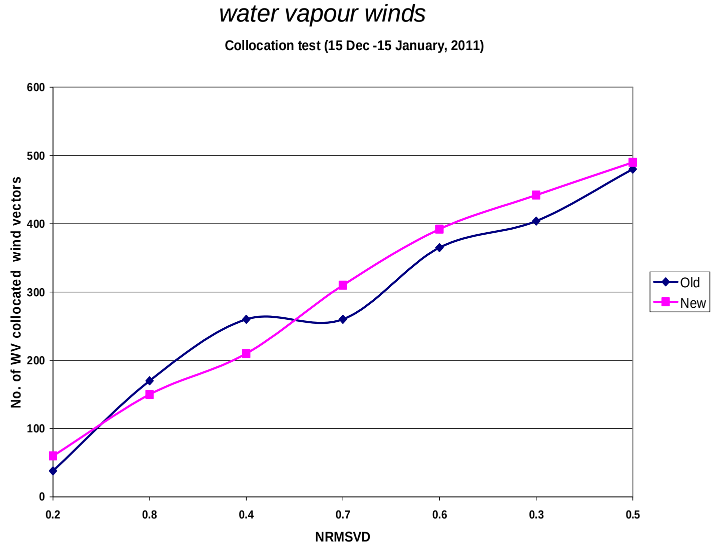


*Fig. 4. NRMSVD versus collocation (RS) of cloud motion winds*

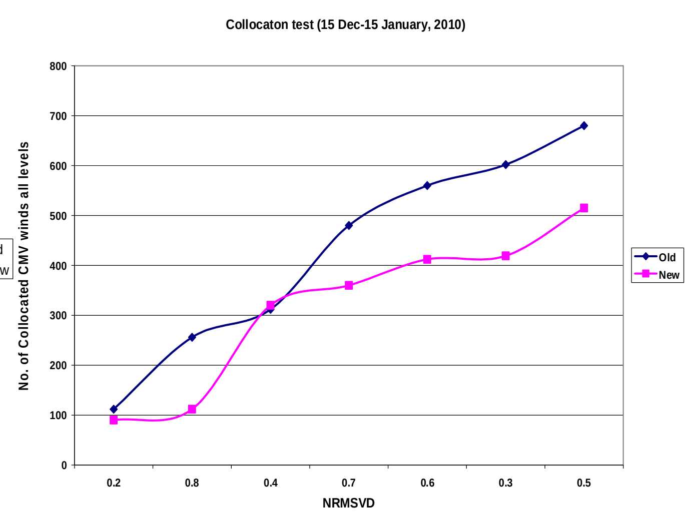

*Table 1. AQC Parameter Summary*

| Name of the Test | Parameter | Old set up | New Set up (Impact) |
|---|---|---|---|
| Direction consistency test | $A_1$ | 40 | 20 |
| | $B_1$ | 15 | 10 (harder) |
| | $C_1$ | 15 | 10 |
| | $D_1$ | 3 | 4 |
| Speed Consistency test | $A_2$ | 0.5 | 0.1 (softer for good winds) |
| | $B_2$ | 0.01 | 0.01 (harder for bad winds) |
| | $C_2$ | 2 | 1 |
| | $D_2$ | 0.7 | 2.5 |
| Vector Consistency test | $A_3$ | 0.1 | 0.2 (sofer) |
| | $B_3$ | 0.01 | 0.01 |
| | $C_3$ | 1 | 1 |
| | $D_3$ | 3 | 3 |
| Spatial Consistency Test | $A_4$ | 0.1 | 0.2 (sofer) |
| | $B_4$ | 0.01 | 0.01 |
| | $C_4$ | 1 | 1 |
| | $D_4$ | 3 | 3 |
| Forecast Consistency Test | $A_5$ | 0.4 | 0.4 |
| | $B_5$ | 0.01 | 0.01 (unchanged) |
| | $C_5$ | 1 | 1 |
| | $D_5$ | 2 | 2 |

This test is desirable in tropics; because there is valuable forecast information is available in tropics. The final height adjustment is determined by the Penalty function defined by Eq-7 and used in AE technique. Because the wind vectors qualitatively prone to so many inconsistencies like vectors which have no displacement at all and having very small speed (arbitrary set to 0.3 m/sec) or large change in speed , $0 < \frac{V_{\max}}{V_{\min}} < R_s$ (threshold =0.5) and if there is a large change in directions (threshold $\Delta dir_{\max}$ =45$^0$). So when two wind vectors are computed using the images at time t, t +Δt and t-Δt. The difference between these two vectors cannot exceed a threshold. This threshold increases as the velocity increases (Schmetz & Nuret, 1987). Besides this there are some inherent problems are also present like tracking of similar structure and formation of new clouds and dissipation of tracking cloud in ½ hour duration, tracking of cloudless regions (in case of CMVs) and presence of permanent features like orography etc. are considered before finalizing the quality flag to each vector. Figs 2 (a-h) for both Infrared (IR) and Water Vapour (WV) images motion winds shows significant difference between the old AQC scheme and new AQC scheme. The new parameter based scheme is more consistent and appropriate as compared to old one which is also justified by the 2 (i,j) of the IMD,GFS (T382) model forecast. In Fig.2(a, c) shows some erroneous winds in cloudless areas which are having inconsistent wind direction also (Southerly, SEasterly) with old AQC parameters, which totally contradicts the model forecast fields, which is almost northwesterly at lower levels (>700 hPa). The derived wind vector data for both IR and WV wind vectors, said above is further reanalyzed with AE penalty function (Eq-7) with the background GFS model forecast field. In this way most of the erroneous winds have been removed, those having inconsistent wind direction. Later, the new AQC parameter (Table 1) scheme is applied to the wind data set and the winds are shown in the Fig.2(b,d,f,h). It is clear from the figures that the winds generated by the new scheme are more realistic. Holmlund *et al.* (2002), presented the combined scheme of AE and AQC procedure which is used operationally at different numerical weather prediction centers.

*Collocation and validation strategy*

Berger *et al*. (2007) used new quality indicator in which EUMETSAT quality indicator is taken along with Numerical Weather Prediction (NWP) information and showed higher skill than individual with collocated radiosonde observations. Cherubini *et al*. (2006) showed that high quality of AMV data are found to influence the cyclone's development, improving the prediction of the cyclone's central pressure and the track of the low's center. The collocation box and validation formulae are defined by the equations (8-14) above. Fig. 3 and 4 shows the collocated water vapour wind and CMV observations and NRMSVD (Eq-14). The result shows the monotonous curve indicating the NRMS error increase continuously with decreasing Quality Index (Higher collocated observations). Fig 3 shows 12 % increase of collocations with RS observations, while in case of IR winds there is a decrease of 14 %. The possible reason may be that most of the winds removed with the new AQC parameters and AE height

*Table 2 (a). External quality check CMVs Statistics (Satellite - Radiosonde) during 15 December-15 January, 2011*

| Pressure (hPa) | MVD (m/sec) | RMSE (m/sec) | SD (m/sec) | BIAS (Satellite - Radiosonde) (m/sec) |
|---|---|---|---|---|
| 700 - 1000 | 3.6 (4.2) | 5.1 (5.1) | 1.8 (2.1) | 2.8 (2.7) |
| 400-700 | 5.3 (5.1) | 4.2 (3.2) | 2.6 (2.2) | 2.6 (3.1) |
| 100- 400 | 6.4 (5.8) | 7.6 (6.8) | 3.8 (3.6) | 2.3 (2.2) |

*Table 2 (b). External quality check WVWs Statistics (Satellite - Radiosonde) during 15 December-15 January, 2011*

| Pressure (hPa) | MVD (m/sec) | RMSE (m/sec) | SD (m/sec) | BIAS (Satellite - Radiosonde)(m/sec) |
|---|---|---|---|---|
| 100 - 250 | 9.4 (6.8) | 8. 2 (7.8) | 5.4 (4.2) | -2.1 (-1.1) |
| 251 - 350 | 6.2 (5.7) | 7.2 (6.5) | 3.2 (2.3) | -3.2 (-2.5) |
| 351 - 500 | 7.3 (7.6) | 7.4 (7.5) | 4.4 (6.3) | -3.3 (-2.6) |

*(New AQC parameter with AE values are given in brackets)*

optimization. Results of external quality of winds compared with available radiosonde winds ($40^0$ N-$40^0$ S and $30^0$E -$129^0$E) for the period of 15 December, 2011 to 15 January, 2011) are given in Table 2 (a,b), brackets figures are for new parameters of AQC with AE penalty function. It is clear from the table that the results show an average decrease (decrease) of RMSE in CMVs (WVWs) is of the order of 4 % (3 %) and increase (decrease) in mean bias is of the order of 3 % (10 %).

## Conclusions

AQC scheme for assessing AMVs internal quality with new parameters along with AE penalty function shows reasonable improvement (3-4 %). The new parameter scheme removes most of the spurious winds at lower levels CMVs which are inconsistent with direction and area. The mean bias of high level WVWs winds reduced significantly (~10 %) with radiosonde winds, this enhance the compatibility of the winds in NWP assimilation. This improvement is possibly due to the combined effect of AE penalty and new AQC parameters. The density of CMVs is lesser and can be improved by better height assignment of tracers.

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## References

1. Berger Howard, Velden C, Wanzong Steve and Daniels J (2007) Evaluation of a new quality indicator to estimate satellite-derived atmospheric motion vector observation error. EUMETSAT Meteorological Satellite Conference and Satellite Meteorology and Oceanography Conference, 15th, of the American Meteorological Society, Amsterdam, the Netherlands, Sep. pp:24-28.
2. Cherubini T, Bussinger S, Velden C and Ogasawara R (2006) The impact of satellite-derived atmospheric motion vectors on mesoscale forecasts over Hawaii. *Mon. Wea. Rev*. 134, 2009-2020.
3. Green RG (1975) The automatic extraction of wind estimates from VISSR data. *NOAATech. Mem. NESS*. 64, 94-110.
4. Holmlund K, Velden C, Tokuno M, Le Marshall J, Sarrazin R and Fernandez Serdan J (2002) Automatic quality control with the CIMSS RFF and the EUMETSAT QI Schemes. *Proc. of the 6th Intl. Winds Workshop*, Madison, WI, 121-128. [Available from EUMETSAT, Am Kavalleriesand 31, D-64295, Darmstadt, Germany.]
5. HolmlundK (1996) Normalized quality indicators for EUMETSAT cloud motion winds. Third Intl. Wind Workshop, Ascona Switzerland. pp:155-164.
6. Holmlund K (1998) The utilization of statistical properties of satellite- derived atmospheric motion vectors to derive quality indicators. *Wea. Forecasting.* 13, 1093-1104.
7. Holmlund K (1993) Current system for extraction cloud motion vectors from METEOSAT multi-channel image data. Proc. 2nd Intl. Wind Workshop. pp:45-53.
8. Hayden CM and Purser RJ (1995) Recursive filter objective analysis of meteorological fields–Applications to NESDIS operational processing. *J. Appl. Meteor.* 34, 3-15
9. Kelley G (1993) Numerical experiments using cloud motion winds at ECMWF. In: Proc. Developments in
10. the use of Satellite Derived data in NWP, 6-10 Sep. pp: 331-348.
11. Kelley G and Saunders RW (2001) Impact of a new cloud motion wind product from Meteosat on NWP analyses. *Mon. Wea. Rev*. 129, 2392-2403.
12. Kelkar RR, Rao AVRK and Bhatia RC (1993) Recent improvements in cloud motion vector derivation from INSAT. Proc. 2nd Int. Wind Workshop. pp: 65-70.
13. Prasad SV, Ramesh KJ, Bohra AK and Sant Prasad (2003) Impact of consistent height reassignment method for INSAT derived cloud motion vectors. *Meteor. Atmos. Phys*. 83, 163-172.
14. Schmetz J and Nuret M (1987) Automatic cloud tracking of high level clouds in METEOSAT infrared images with Radiance windowing technique. *Euro Space Agency J*. 11, 275-286.
15. Schmetz J, Holmlund K, Hoffman J, Strauss B, Mason B, Gärtner V, Koch A and Van de Berg L (1993) Operational cloud motion winds from Meteosat infrared images. *J. Appl. Meteor.* 32, 1206-1225.
16. Szantai A, Desalmand F and Desbois M (2002) A method for the construction of cloud trajectories from series of satellite images. *Intl.J. Remote Sensing*. 23, 8, 1699-1732.
17. Sasaki H (1993) The impact of satellite derived wind on the numerical forecast. Proc. 3rd Intl. Workshop. pp: 603-608.
18. Takata S (1993) Current status of GMS wind and operational low-level wind derivation in typhoon vicinity from short-time interval images. Proc. 2nd Int. Workshop. pp: 29-36.
19. Uchida H (1991) Height assignment of GMS high-level cloud motion wind. In: Proc. Workshop of Wind Extraction from Operational Meteorological Satellite Data. pp: 27-32.
20. Velden CS and Holmlund K (1998) Report from the working group on verification and quality indices (WG III). In: Proc. Fourth Int. Winds Workshop, Saanenmo¨ser, Switzerland, EUMETSAT. pp: 19-20.
21. Velden CS, Hayden CM, Nieman SJ, Menzel WP, Wanzong S and Goerss JS (1997) Upper troposphere winds derived from geo-stationary satellite water vapour observations. *Bull. Am. Meteor. Soc*. 78 (2),173-195.