

OPERATIONAL SYSTEM FOR EXTRACTING CLOUD MOTION AND WATER VAPOR MOTION WINDS FROM GMS-5 IMAGE DATA

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ABSTRACT

Taking an advantage of WV absorption channel on board GMS-5, the Meteorological Satellite Center (MSC) has produced Cloud Motion Winds (CMWs) and Water Vapor Motion Winds (WVMWs) from GMS-5 image data four times a day, e.g. at 00,06,12, and 18 UTC since June 13, 1995. The CMW extraction scheme has been improved in the height assignment and target selection for high level CMW extraction by using water vapor channel data. That is, the procedure to exclude the area containing cumulonimbus using the difference between IR and WV brightness temperatures is newly introduced in the target selection. In the height assignment, the IR and WV intercept technique is also introduced to correct the brightness temperature of non-black body cloud. The WVMW extraction scheme is basically the same as that of CMW, however quality check of WVMWs is performed only through automatic procedure, which check homogeneity of speed, direction and height. CMWs of GMS-5 are distributed to national Meteorological Services in the world via GTS in succession GMS-4, but WVMWs are operationally distributed via GTS since March 28, 1996, after the evaluation of their quality in Numerical Prediction Division of JMA.

This paper describes the methodology and the results of CMW and WVMW extraction from GMS-5 image data in MSC.

1. Introduction

The Meteorological Satellite Center (MSC) of the Japan Meteorological Agency (JMA) has produced cloud motion wind (CMW) since 1978 using visible (VIS) and infrared(IR) channels. GMS series satellites preceding the GMS-4 have only one IR channel and it is therefore difficult to determine the cloud top height of semi-transparent cirrus accurately. Therefore, intensive efforts have been made to improve to certain extent the height assignment to the extracted high-level CMW (Uchida 1991; Takata 1993).

The GMS-5 is equipped with water vapor (WV) absorption channel which improves the height assignment and target selection for high-level CMW extraction and also makes it possible to calculate water vapor motion wind (WVMW).

Taking an advantage of WV absorption channel on board GMS-5, MSC has produced CMWs and WVMWs from GMS-5 image data four times a day, e.g. at 00, 06, 12, and 18 UTC since June 13, 1995.

The general process flow of MSC Cloud and water vapor motion Winds Estimation System (CWES) is shown in Fig. 1. Two types of cloud motion winds are calculated from the CWES system. One is low-level cloud motion wind and the other is high-level cloud motion wind, which are derived through combined processes: automatic process and man-machine interactive process. Both types of winds are assigned to certain levels and their quality is checked manually and automatically. WVMW is also calculated from the CWES system. The WVMW extraction scheme is basically the same as that of CMW, but its quality check is performed only through automatic procedure.

MSC distributes CMWs of GMS-5 to national Meteorological Services in the world via GTS in succession from GMS-4 for an operational numerical analysis and prediction. Also MSC started transmission of WVMWs via GTS since March 28, 1996, after the evaluation of their quality in Numerical Prediction Division of JMA.

In the following sections, the procedures of the CWES system are introduced. Also the results of CMW and WVMW extraction from GMS-5 image data are described.

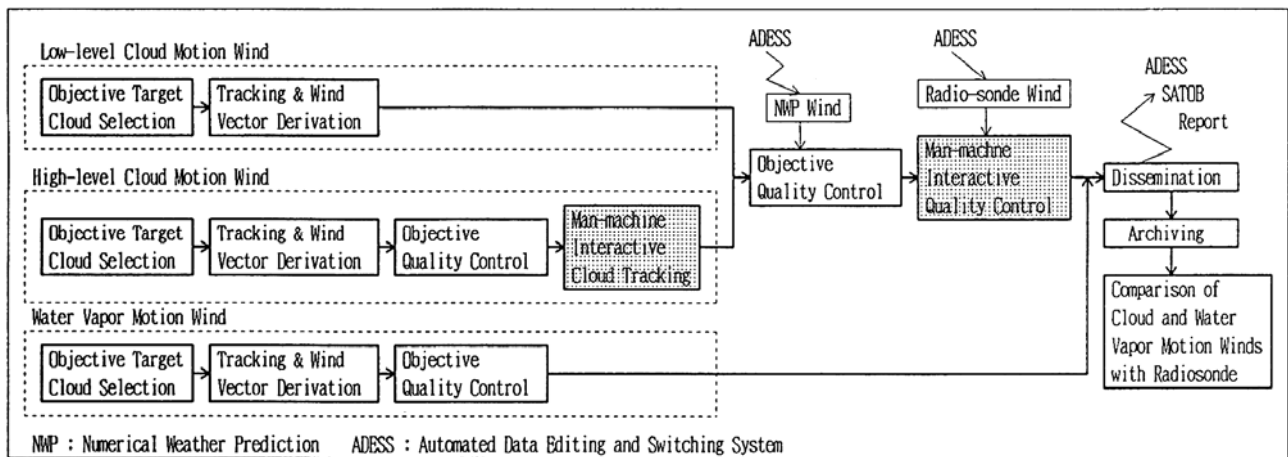


Fig. 1 The general process flow of MSC Cloud and water vapor motion Winds Estimation System.

2. Wind Vector Extraction

The procedures of wind vector extraction in the MSC CWES are composed four procedures, i.e., 1) objective Automatic target cloud Selection (AS), 2) objective tracking and wind vector derivation (including height assignment), 3) objective quality control, 4) man-machine interactive procedure as shown in Fig.1.

2.1 Objective Automatic Target Cloud Selection

Firstly the candidate grid point (1 degree latitude/longitude box) for automatic target selection is selected in accordance with a certain regulation to get wind data uniformly in the GMS coverage. Next, the grid area is judged by the following screening steps, and in case the wind vectors obtained number in the fix number in the region where they are included, this procedure is stopped. The following steps are performed in alphabetical order.

a) Screening step 1 : Ocean/land discrimination

This screening step is used only for the low-level wind extraction. The grid point which include slightly land area is rejected from the candidates of the AS point, thus low-level winds are not extracted over land area.

b) Screening step 2 : Zenith angle of the satellite and the sun

When the zenith angle of the satellite in the center of the grid area is greater than 85 degrees, the grid point is rejected from the candidates. In addition, in low-wind motion vectors, when zenith angle of the sun in the center of the grid area is greater than 60 degrees, the grid point is rejected.

c) Screening step 3 : Histogram analysis

Histogram analysis is performed only in CMW extraction. In the grid area, a histogram of the

infrared brightness level is made and the features of the histogram are analyzed to obtain parameters concerning the cloud amount, the cloud top height (CTH), and the thickness of the cloud. The parameters are compared with threshold values and in case the conditions are not satisfied, the grid point is rejected.

In WVMW extraction, histogram analysis is not performed as the feature of WV image is smooth and vague. Therefore the lowest WV brightness temperature in the target area is used in place of parameters from histogram analysis. That is, if the lowest WV brightness temperature is warmer than the threshold temperature, the grid point is rejected.

d) Screening step 4 Cumulonimbus check

This step is newly added in high-level wind extraction scheme. The purpose of this procedure is to exclude the area containing cumulonimbus since the cumulonimbus is not good tracer for high-level wind extraction. This procedure is based on the idea that the cumulonimbus is identified by the difference between IR and WV brightness temperatures (Tokuno and Tsuchiya 1994) as mentioned here-under.

Firstly Brightness Temperature Difference (BTD) (IR1 - WV) of each small box averaged every 2 lines by 2 pixels in the grid area (32 lines by 32 pixels) is calculated and if BTD is lower than the cumulonimbus threshold value (3 K at present), the box is regarded as a cumulonimbus pixel. When the ratio of the total number of cumulonimbus pixels to the total number of pixels in the grid area is higher than the threshold value (10% at present), the grid area is regarded as the area containing cumulonimbus and the grid point is rejected.

2.2 Tracking and Wind Vector Derivation

a) Tracking and wind vector derivation

The corresponding cloud pattern of the same target cloud selected in the AS procedure is searched on another image taken 30 minutes before or latter using cross-correlation technique. On the first picture, digital image data of 32 pixels by 32 lines, centered at a selected point, are used as template data. On the second picture taken 30 minutes before or later, image data of 64 by 64 are used as search area data. The correlation values between the brightness of the template area and the search area are calculated for each lag point and a cross-correlation coefficient matrix called a matching surface is obtained. The biggest value of the correlation coefficients is adopted as the best matched position.

Double matching method is adopted in tracking target clouds to reduce the processing time and the amount of memory. At first, on spatially sampled images the AS target cloud is tracked and a coarse vector of the displacement is derived, which is called coarse matching. Next, on original spatial resolution images, a correction vector is derived for fine tuning of the displacement in similar procedure of coarse matching, which is called fine matching. Sum of the coarse vector and the correction vector is a resultant cloud displacement or motion. The sampling rate in the coarse matching are given as preset values.

Tracking AS targets is performed using three time-sequential images (A,B,C). Target clouds are selected on the image B and target cloud displacement between B and C is derived. The inverse displacement vector from image B to C is used as a coarse vector between images B and A. Consequently two time-sequential vectors, V_{BC} and V_{AB} are decided and the former is regarded as the final wind, and the latter is used for quality control of the wind vector.

b) Height assignment

In the low-level wind, it is widely accepted that the velocity of low-level cloud agrees with that of the environmental wind at the altitude of the cloud base. In MSC, we made some statistical investigation (Hamada, 1982) on comparing the low-level CMW with the velocity observed by a radiosonde, which revealed that the velocity of the low-level CMW well represents the atmospheric wind at the altitude of 850 hPa. The fixed wind representative height, 850 hPa, is assigned to all resultant winds from low-level target cloud with the CTH lower than the limitation height, 700 hPa.

In the high-level wind, two steps are available to estimate the height of the high-level wind. One is the estimation using only IR data (method 1). The other is the estimation using IR data and WV data for correction of semi-transparent cirrus height (method 2) based on the theory described by Bowen and Saunders (1984). We had used only method 1 until August 1995 in high-level CMW height assignment. As from September, we have selected the higher cloud height for the high-level wind, comparing cloud height estimated in method 1 and 2.

— method 1 —

The lowest black body temperature, TBB, is extracted from a histogram of infrared brightness level in a grid area selected in target cloud selection or at a matching point determined in the matching procedure. TBB is converted into a Temperature of Cloud top (TC), taking account of the effect of atmospheric attenuation. Then, TC is transformed into CTH both in pressure level and in geo-potential height, using vertical temperature profiles obtained from the 6-hourly forecast of JMA numerical weather prediction.

— method 2 —

Concept of this method is shown in Fig.2.

Firstly pixels for non-black body cloud in a target area are classified from both infrared and WV image data in a grid area centered at a selected point in target cloud selection using an IR and WV clustering technique. Then, the brightness level of the pixels for non-black body cloud is corrected using an IR and WV intercept technique. The lowest TBB is extracted from an histogram produced by reprocessing corrected pixels. The procedure of transforming TBB into CTH is the same as that of the method 1.

In the WVMW, we adopted the height corresponding to the lowest 1.0 % of the WV brightness temperature in a grid area in the method 1 and had used only method 1 until August 1995. As from September, we adopted lowest 10.0 % of WV brightness level in the method 1 and we have used both method 1 and 2 as the same as the high-level wind height assignment procedure.

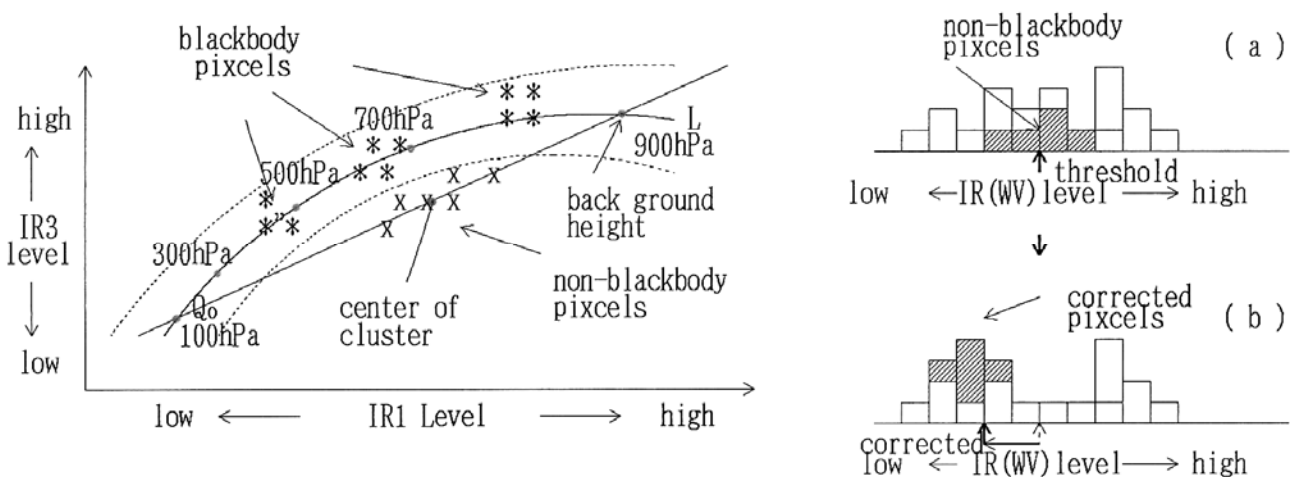


Fig.2 Concept to correct non-black body cloud height

2.3 Automatic Assessment and Objective Quality Control

The CWES has been the following three stages of quality control,

- the automatic assessment on matching surface, wind velocity, cloud top height and missing lines (line drops).
- the objective Quality Control (QC) which consists of horizontal consistency check, vertical shear check and comparison with numerical weather prediction (NWP) winds.
- the man-machine interactive quality control of the resultant winds, which is performed by using graphic display and TV-display on workstations, which is shown in the following sub-section 2.4.

a) Automatic Assessment

The resultant vectors are assessed automatically by checking the following items in accordance with threshold values, and unreliable vectors are rejected from the resultant vectors.

· The feature of matching surface

In case values of parameters of a matching surface don't satisfy the conditions, the vector is rejected.

· Wind velocity

The difference between two time-sequential vectors, V_{AB} and V_{BC} is automatically checked and in

case the difference exceeds the preset threshold value (10.0 m/s for high-level CMW and WVMW, 5.0 m/s for low-level CMW at present), the vector is rejected.

- Missing line check on the images

In case two/five lines or more are missing in infrared and water vapor/visible template or search area, the derived vector is immediately rejected.

b) Objective Quality Control

Objective QC consists of the following three steps. Through these procedures unreliable data may be automatically rejected or flagged, and the flagged data are assessed in the process of man-machine interactive QC.

- Horizontal consistency check

CMW (WVMW) is compared with the mean vector of the neighboring same-level CMWs (WVMWs) within a certain distance. In case the difference between them is larger than a threshold value (8.0 m/s for low-level CMW, 15.0 m/s for high level CMW and WVMW), the wind is flagged. In addition, in case the difference between the WVMW height and the mean height of the neighboring WVMWs within a certain distance is larger than threshold value (50hPa), the wind is flagged.

- Vertical shear check

A low/high-level CMW is respectively compared with the mean vector of the neighboring different level (high/low) cloud motion winds within a certain distance. When the difference defined as vertical shear of the winds is smaller than a preset value (8.0 m/s at present), the very wind is flagged. This check is very effective when thin cirrus clouds are tracked as low-level winds in automatical process.

- Comparison with Numerical Weather Prediction (NWP) wind data

CMWs and WVMWs are compared with NWP wind data (wind height and wind vector) which are obtained from the 6 hourly forecasts of NWP at the Numerical Prediction Division, JMA. In case the difference between them is larger than a preset value (12.0 m/s (low-level CMW - NWP wind), 18.0 m/s (high-level CMW or WVMW - NWP wind)), the very wind is flagged.

2.4 Man-machine Interactive Procedure

This procedure is performed for the following purposes;

- to derive CMWs in data sparse areas or important area around disturbance, in addition to winds calculated automatically.
- to perform quality check including reassignment of wind height.

a) CMWs derivation

The operator can derive CMWs in the two methods using time-sequential images on TV display. One is called MM-1 method, in which a suitable target is manually selected on the second image and a cloud motion vector is derived by tracking the target automatically in the same method as the automatical process. The other is called MM-2 method, in which a suitable target is manually selected on the first image and a cloud motion vector is derived by tracking the target manually to the third image.

b) Quality check including reassignment of wind height

Quality check of the resultant winds is performed using the graphic display and TV display of the image processing console on workstations. The operator checks the resultant CMWs, comparing them with the movement of the target cloud in the animation on the TV display, radio-sonde winds and NWP winds on the graphic display. In case CMW's height is judged to be unreliable, the operator reassigns the target a suitable wind height at 50 hPa intervals.

3. Accuracy

To evaluate the accuracy of CMWs and WVMWs derived operationally, they are compared with collocated radiosonde winds in the same way as the International Comparison of Satellite Winds (refer to Appendix A). Monthly mean statistics are calculated from July 1994 to April 1996 (except for May and June 1996) to compare results of GMS-4 with GMS-5.

3.1 Low-level Cloud Motion Winds

From a statistical observation of low-level CMW shown in Fig. 3, The following features are outstanding,

- The Root Mean Square Error (RMSE) of vector differences and speed bias of GMS-5 low-level CMWs is respectively about 0.5 m/s larger than that of GMS-4 for July and August 1995, a brief period since operation of GMS-5 started.
- RMSE of GMS-5 is slightly larger than that of GMS-4 from November 1995 to March 1996.
- BIAS of GMS-5 is generally a little negative (less than -1.0 m/s) as the same as that of GMS-4.

Thus the accuracy of low-level winds since GMS-5 is the same as that of GMS-4 which retained the excellent level.

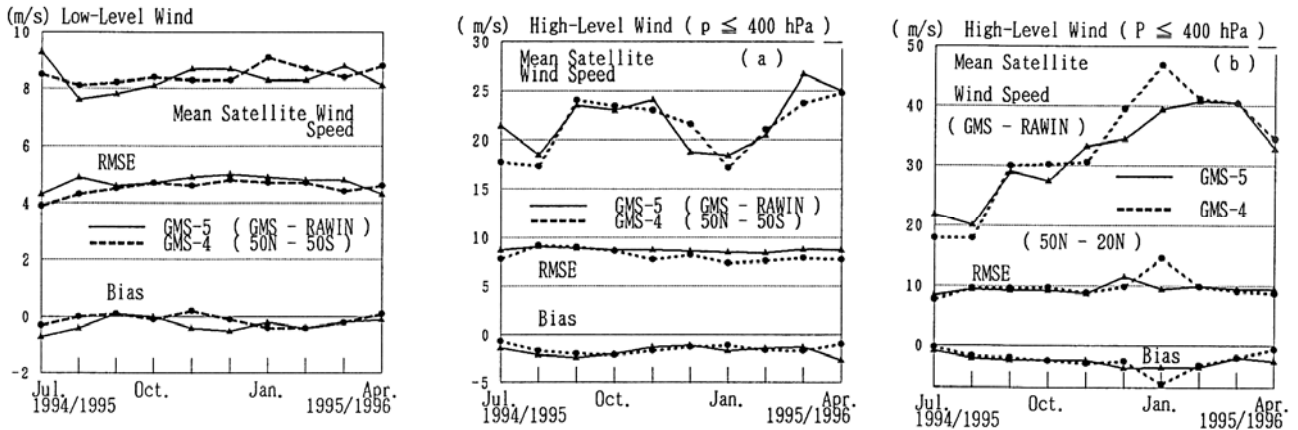
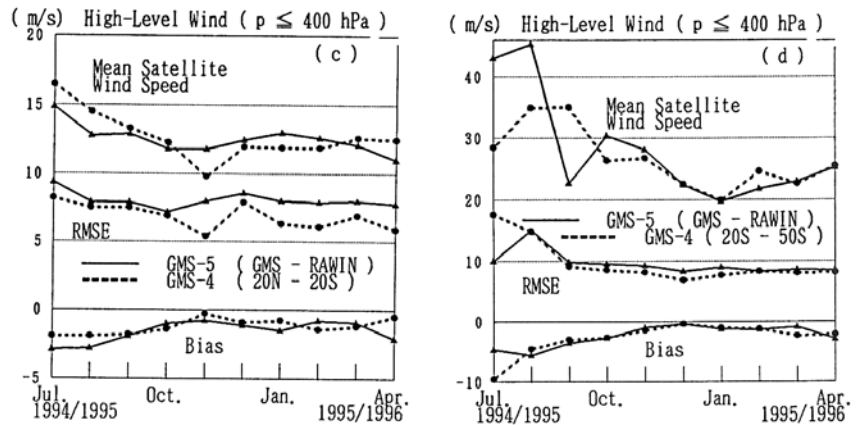


Fig.3 Statical results of low-level CMWs

Fig.4 Statical results of high-level CMWs



3.2 High-level Cloud Motion Winds

To evaluate the accuracy of high-level CMW, high-level CMW ($p \leq 400$ hPa) is investigated and the statistical results are shown in Fig.4.

The average values of RMSE of vector differences and speed bias after September 1995 are 8.6 m/s and -1.5 m/s respectively. Thus the accuracy of GMS-5 is generally the same as that of GMS-4 using height assignment table except RMSE of vector difference is slightly larger than that of GMS-4 from November 1995 to April 1996 (Fig.4 (a)).

In addition to these facts, it is founded that RMSE of vector differences of GMS-5 in the equator area (20N - 20S, Fig.4(c)) is 1-2 m/s larger than that of GMS-4 from November 1995 and negative speed bias has a tendency to increase as wind speed increases.

Then, to investigate the efficiency of height assignment method 2 and manual reassignment, We evaluated the accuracy in the following five cases, 1) method 1 in AS, 2) method 2 in AS, 3) manual height reassignment in AS, 4) manual height reassignment in MM-1, 5) manual height reassignment in MM-2. The results in two seasons are tabulated in the Table-1, and the notable point from the table are summarized as follows,

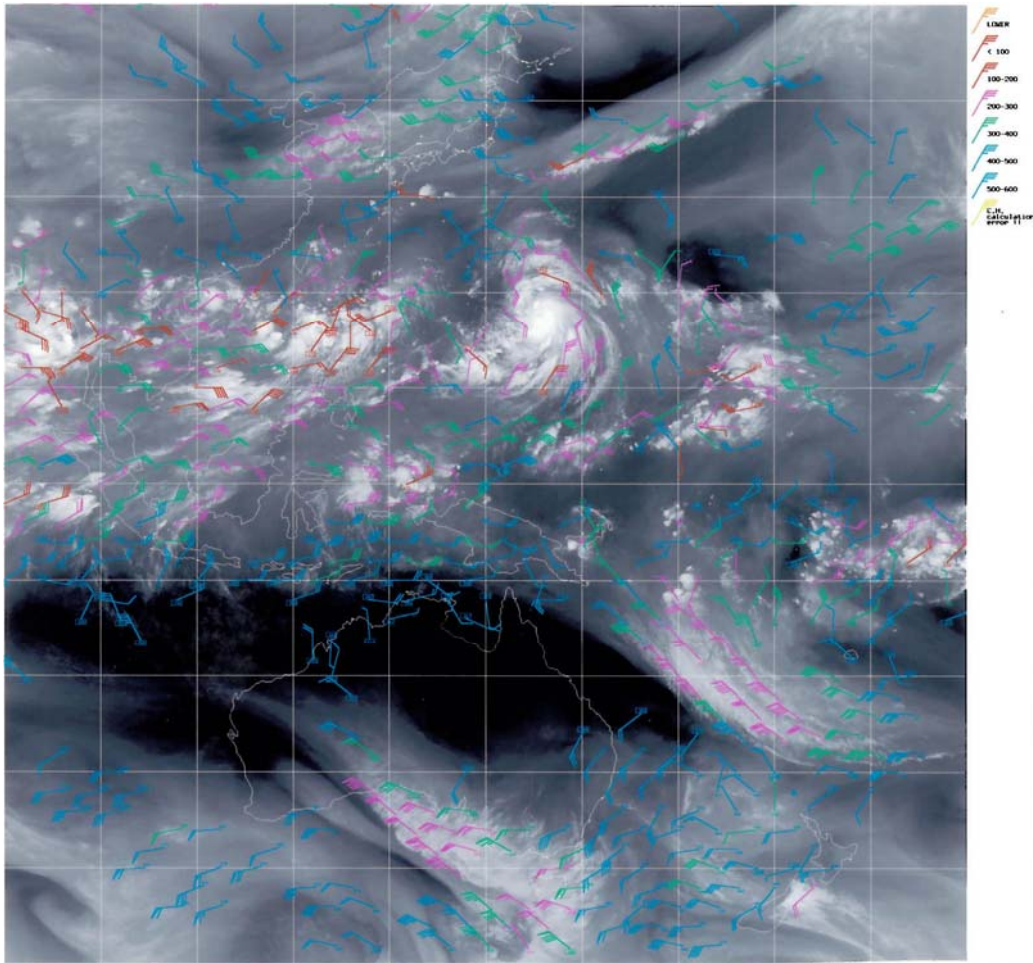


Fig.5 WV image with WVMWs extracted in AS at 00 UTC Sep. 13, 1995

- height assignment by method 2 (case 2) is mainly applied to clouds over 300 hPa in equator area (20N - 20S).
- manual height reassignment is mainly applied to clouds over 300 hPa.
- the case 5 (manual height reassignment in MM2) has the fastest wind speed in the cases.
- negative speed bias is larger than that of manual height reassignment.

Thus the efficiency of manual height reassignment is confirmed, but further investigation is inquired to confirm the efficiency of height assignment method 2.

Table -1 Statical results of high-level CMWs in different height assignment method

September 1995														
50N - 20N					20N - 20S					20S - 50S				
400 - 300 hPa					400 - 300 hPa					400 - 300 hPa				
CASE	N	BIAS	MEAN	RMSE	CASE	N	BIAS	MEAN	RMSE	CASE	N	BIAS	MEAN	RMSE
1	356	-6.0	13.9	17.7	1	76	-1.5	6.8	13.3	1	43	-12.7	17.3	17.2
2	1	-4.6	20.8	9.4	2	—	—	—	—	2	—	—	—	—
3	—	—	—	—	3	—	—	—	—	3	22	0.1	17.5	12.7
4	—	—	—	—	4	—	—	—	—	4	2	0.4	17.9	3.0
5	8	2.8	30.3	12.7	5	3	2.8	8.1	10.6	5	5	-3.1	25.0	5.4
300 - 200 hPa					300 - 200 hPa					300 - 200 hPa				
1	469	-5.2	15.1	17.7	1	241	-3.5	7.7	10.2	1	17	-14.3	17.8	10.2
2	23	-1.7	14.7	8.5	2	54	-3.9	9.7	12.3	2	—	—	—	—
3	125	-2.0	24.2	7.8	3	3	-4.5	20.5	8.0	3	3	3.3	16.2	8.0
4	14	-2.2	27.4	6.7	4	4	-1.1	6.4	3.8	4	—	—	—	—
5	79	-1.8	31.4	9.2	5	6	0.6	14.8	4.2	5	2	0.6	17.5	2.6
200 - 100 hPa					200 - 100 hPa					200 - 100 hPa				
1	13	-4.8	9.0	10.5	1	202	-7.1	8.2	12.5	1	—	—	—	—
2	8	-3.7	12.2	25.4	2	40	-5.8	11.9	11.8	2	—	—	—	—
3	31	-1.4	16.1	9.1	3	134	-2.7	11.2	7.6	3	—	—	—	—
4	15	-0.8	13.8	6.2	4	18	-1.5	13.1	6.4	4	—	—	—	—
5	13	-3.4	25.2	11.1	5	31	-1.1	13.0	8.1	5	—	—	—	—

January 1996														
50N - 20N					20N - 20S					20S - 50S				
400 - 300 hPa					400 - 300 hPa					400 - 300 hPa				
CASE	N	BIAS	MEAN	RMSE	CASE	N	BIAS	MEAN	RMSE	CASE	N	BIAS	MEAN	RMSE
1	150	-6.0	13.9	17.7	1	129	-0.5	6.9	11.3	1	103	-3.9	10.5	16.0
2	—	—	—	—	2	—	—	—	—	2	—	—	—	—
3	15	-2.6	30.7	7.5	3	4	-2.2	9.5	6.9	3	3	-2.3	19.6	3.9
4	3	-1.8	19.6	3.1	4	—	—	—	—	4	—	—	—	—
5	47	-2.1	37.5	11.5	5	—	—	—	—	5	1	7.3	12.4	9.1
300 - 200 hPa					300 - 200 hPa					300 - 200 hPa				
1	35	-5.2	15.1	17.7	1	283	-3.0	7.7	10.2	1	99	-5.9	13.4	14.0
2	—	—	—	—	2	77	-2.4	9.7	12.3	2	1	-0.4	17.0	6.7
3	13	-6.9	31.8	10.3	3	1	2.1	20.5	8.0	3	51	-1.9	15.2	6.5
4	2	-5.7	15.3	6.3	4	—	—	—	—	4	—	—	—	—
5	16	-8.9	37.4	17.8	5	6	2.4	17.1	9.0	5	4	1.2	16.7	7.4
200 - 100 hPa					200 - 100 hPa					200 - 100 hPa				
1	3	-29.0	30.1	42.6	1	238	-6.4	7.4	10.9	1	21	-7.9	9.6	14.1
2	—	—	—	—	2	53	-6.5	9.7	11.9	2	—	—	—	—
3	—	—	—	—	3	197	-2.6	11.3	6.9	3	18	-6.0	12.7	11.3
4	—	—	—	—	4	28	-1.6	10.1	5.7	4	—	—	—	—
5	—	—	—	—	5	71	2.6	14.6	8.6	5	6	0.2	12.5	4.7

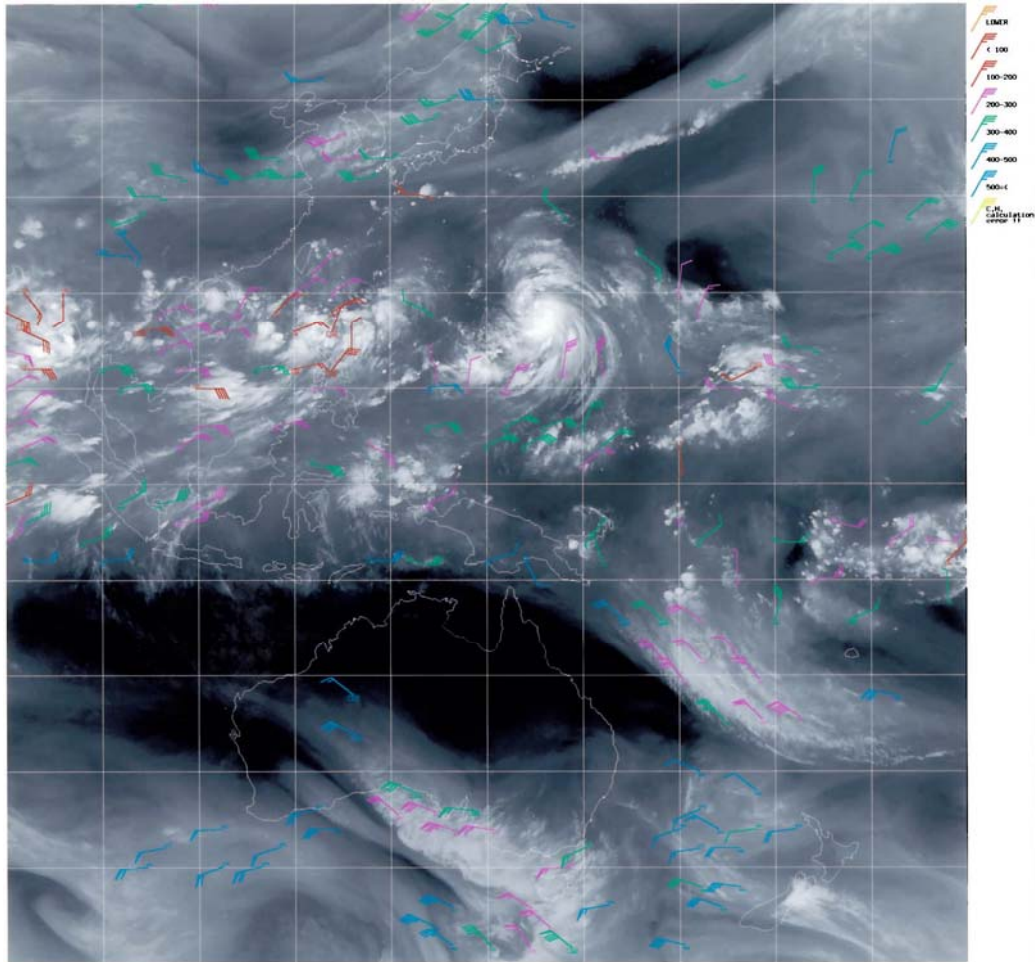


Fig.6 WV image with WVMWs distributed via GTS at 00 UTC Sep. 13, 1995

3.3 Water Vapor Motion Winds

Fig.5 and 6 are respectively an example of WVMWs extracted in AS method (before QC) and distributed via GTS. Fig.5 show large amount of WVMWs extracted in AS method, but large part of WVMW is excluded by automatical QC. For example, there are many WVMWs extracted in AS method around a typhoon, but finally good wind vectors remain a little. Thus it show the difficulty to get good WVMWs in the region where the feature of tracer is changeable.

In addition to the fact, good WVMWs ($p > 400$ hPa) remain a little in the equator area. One of the causes may be that the peak of contribution function of WV channel in GMS-5 wide around 400 - 500 hPa and therefore it is difficult to separate information in the vertical layer below 400 hPa in the equator area (Fig.7).

In middle latitude, there are many WVMWs along air stream around Japan and Australia region where it is difficult to get CMWs. Thus WVMWs are fully extracted along air stream so that WVMWs may become good indicators for weather analysis as well as bocas data of initial value of NWP.

Then we investigate the accuracy of WVMW in the two vertical layers, i.e. WVMW ($P \leq 400$ hPa), WVMW ($p > 400$ hPa), and three latitude zoos in the same manner as high-level CMW. regions as like high-level CMW.

Comparing WVMWs ($P \leq 400$ hPa) with high-level CMWs ($P \leq 400$ hPa), RMSE of vector differences and speed bias are respectively about 9 m/s and less than -1.0 m/s, thus the accuracy of WVMW ($P \leq 400$ hPa) is relatively good. Then comparing WVMW ($P \leq 400$ hPa) with WVMW ($P > 400$ hPa), in the whole GMS coverage RMSE of WVMW ($P > 400$ hPa) is 2-3 m/s larger than that of WVMW ($P \leq 400$ hPa), and positive speed bias of WVMW ($P > 400$ hPa) is outstanding in the region where wind speed is weak.

In addition, in the equator area, WVMW ($P > 400$ hPa) have large positive speed bias and large RMSE of vector differences.

the accuracy of WVMW ($P > 400$ hPa) is poorer than that of WVMW ($P \leq 400$ hPa), and therefore

further investigation is inquired to solve the problem.

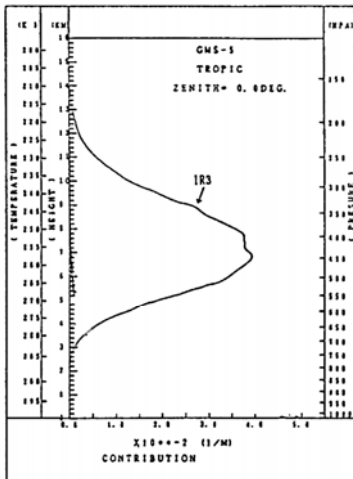


Fig.7 Contribution Function

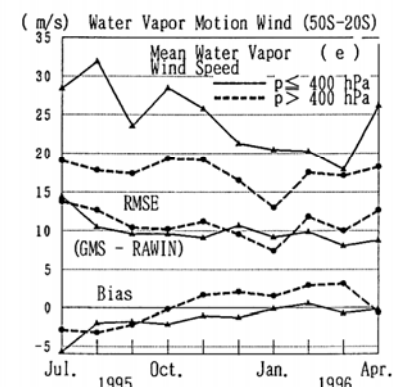
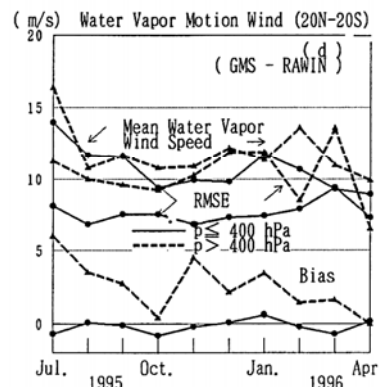
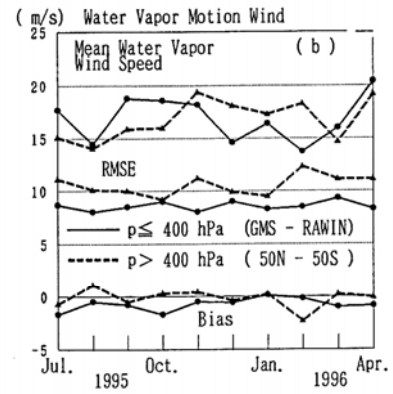
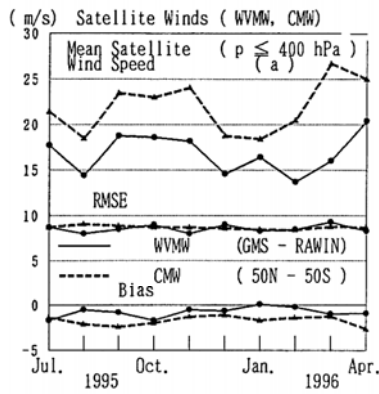
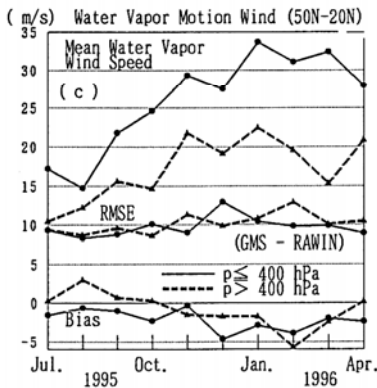


Fig.8 Statistic results of WVMWs

4. Concluding Remark

MSC has produced CMWs and WVMWs from GMS-5 image data since June 13, 1995. The accuracy of GMS-5 CMWs is generally the same as that of GMS-4, however further investigation is inquired to conform the efficiency of height assignment by the IR and WV intercept technique to correct the brightness temperature of non-black body cloud. On the other hand The accuracy of WVMWs ($P \leq 400\text{hPa}$) is relatively good, however The accuracy of WVMWs ($P > 400\text{hPa}$) is poorer than that of WVMWs ($P \leq 400\text{hPa}$), especially in the equator area. Therefore more studies are inquired to solve these problems.

Acknowledgments

The author acknowledges the valuable help of Mr Sachio Takata in the preparation of these water vapor images with WVMWs.

Appendix

International Comparison of Satellite Winds (Type 2 Reports)

In this study, the method is used the same as that of Type 2 Reports-Inter comparison with conventional data. The regulation is the followings.

a) Co-location area for comparison

The area is defined as an elliptical co-location area.

b) Time

Satellite wind and its companion ground truth observation are used within 3 hours.

c) Height

Winds interpolated from rawinsondes are used as ground truth. The following technique is used for interpolation.

· Treatment of vertical sonde profile

Firstly we separate wind speeds of estimated cloud wind vectors and sonde winds into the two components (U-component and V-component) (equation 1). Secondly we calculate the sonde wind which is equivalent to the height of estimated cloud wind vector by interpolating the two sonde winds on special points (equation 2) Finally we calculate statistics for the monthly wind vectors (equation 3).

$$\begin{aligned}
 \text{KCOFF} &= 0.0174532 \text{ (coefficient: convert degree to radian)} \\
 U_e &= \text{VEL}_e \cdot \cos ((270.0 - \text{DEG}_e) \cdot \text{KCOFF}) \\
 V_e &= \text{VEL}_e \cdot \sin ((270.0 - \text{DEG}_e) \cdot \text{KCOFF}) \\
 U_{s,i} &= \text{VEL}_{s,i} \cdot \cos ((270.0 - \text{DEG}_{s,i}) \cdot \text{KCOFF}) \\
 V_{s,i} &= \text{VEL}_{s,i} \cdot \sin ((270.0 - \text{DEG}_{s,i}) \cdot \text{KCOFF}) \\
 U_{s,i+1} &= \text{VEL}_{s,i+1} \cdot \cos ((270.0 - \text{DEG}_{s,i+1}) \cdot \text{KCOFF}) \\
 V_{s,i+1} &= \text{VEL}_{s,i+1} \cdot \sin ((270.0 - \text{DEG}_{s,i+1}) \cdot \text{KCOFF})
 \end{aligned} \tag{1}$$

where, U_e , V_e , DEG_e are respectively U-component, V-component and wind direction of satellite wind. $U_{s,i}$, $V_{s,i}$, $\text{DEG}_{s,i}$ are respectively U-component, V-component and wind direction of sonde wind, i is pressure level.

· Interpolation

$$\begin{aligned}
 \text{RATE} &= (\log_e (\text{CH}_i) - (\log_e (\text{CHT}))) / (\log_e (\text{CH}_i) - \log_e (\text{CH}_{i+1})) \\
 \text{CU}_e &= U_{s,i} + (U_{s,i+1} - U_{s,i}) \cdot \text{RATE} \\
 \text{CV}_e &= V_{s,i} + (V_{s,i+1} - V_{s,i}) \cdot \text{RATE} \\
 \text{CVEL}_e &= \text{SQR} (\text{CU}_e \cdot \text{CU}_e + \text{CV}_e \cdot \text{CV}_e) \\
 \text{CRAD}_e &= \arctan (\text{CU}_e / \text{CV}_e) \\
 \text{CRAD}_e &< 0.0 \text{ -----} > \text{CRAD}_e = 2.0 \cdot 3.1415 + \text{CRAD}_e \\
 \text{CDEG}_e &= \text{CRAD}_e / \text{RATE}
 \end{aligned} \tag{2}$$

where, CHT , CH_i are respectively satellite wind height and sonde wind height at i -pressure level. CU_e , CV_e , CVEL_e and CDEG_e are the values interpolated from sonde wind corresponding to satellite wind height.

Statistics for the monthly wind vectors

Vector Difference (VD) between satellite wind and the collocated rawinsonde wind.

$$\text{VD}_e = \sqrt{ (U_e - \text{CU}_e) \cdot (U_e - \text{CU}_e) + (V_e - \text{CV}_e) \cdot (V_e - \text{CV}_e) }$$

The speed bias (BIAS)

$$(\text{BIAS})_e = \sqrt{ (1/N) \sum_{i=1}^N (U_{e,i} \cdot U_{e,i} + V_{e,i} \cdot V_{e,i} - \text{CU}_{e,i} \cdot \text{CV}_{e,i} + V_{e,i} \cdot V_{e,i}) } \tag{3}$$

The root-mean-square error (RMSE)

$$(\text{RMSE})_e = \sqrt{ (1/N) \sum_{i=1}^N (\text{VD}_{e,i} \cdot \text{VD}_{e,i}) }$$

References

- Bowen, R., and R. Saunders, 1984 : The semi transparency correction as applied operationally to METEOSAT infrared data: A remote sensing problem. *ESA Journal*, **8**, 125-131.
- Hamada, T., 1982: Representative heights of GMS satellite winds. Meteorological Satellite Center Technical Note No. **6**, 35-47.
- Ohshima, T., H. Uchida, T. Hamada and S. Osano, 1991: A Comparison of GMS Cloud Motion Winds with Ship-Observed Winds in Typhoon Vicinity. *Geophysical Magazine* **44**, No.1, March, 28-36.
- Takata; S., 1993: Current status of GMS wind and operational low-level wind derivation in a typhoon vicinity from short-time interval images. Proceedings of Workshop on Wind Extraction from Meteorological Satellite data, Tokyo, 17-15 Dec. 1993. Published by EUMETSAT, 6100 Darmstadt, Germany, EUM P14, 29-36.
- Tokuno, M. and K. Tsuchiya, 1994: Classification of cloud types based on data of multiple satellite sensors. *Adv. Space Res.*, **14**. No.3, P(3)199-(3)206.
- Uchida H., T. Ohshima, T. Hamada and S. Osano, 1991: Low-Level Cloud Motion Wind Field Estimated from GMS Short Interval Images in Typhoon Vicinity. *Geoph. Mag.* **44**, No.1, Mar., 37-50.
- Uchida H., 1991: Height Assignment of GMS High-Level Cloud Motion wind. Pro. First International Winds Workshop, Washington, D.C. USA, 17-19 September 1991. 27-32.