IMPROVEMENTS IN THE QUALITY ASSESSMENT OF AUTOMATED SATELLITE-DERIVED CLOUD AND WATER VAPOR MOTION VECTORS

W. Paul Menzel [1], Christopher M. Hayden [1], Steven J. Nieman [2],
Christopher S. Velden [2], and Steve Wanzong [2]

1 - NOAA/NESDIS
2 - Cooperative Institute for Meteorological Satellite Studies
1225 West Dayton Street
Madison, Wisconsin 53706

ABSTRACT

Automated procedures for deriving cloud-motion vectors from a series of geostationary infrared-window images have been developed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and first became operational in NOAA in 1993 (Merrill et al., 1991). Assessment of the quality of these wind vectors has continued to evolve. The quality flags in the automated winds procedure (Hayden, 1993, 2nd International Winds Workshop) have been found to be well correlated to agreement with rawinsonde observations. The quality flag predicts the performance of good winds from 5.0 to 6.5 m/s rms vector difference in 0.5 m/s increments. Past satellite wind verification statistics have relied upon collocations with rawinsondes within 1 or 2 degrees. Recent work suggests that comparison with analyses of the rawinsonde observations lead to more representative estimates of satellite wind accuracy. These results have implications for the CGMS approach to wind verification statistics.

1. IMPROVEMENTS IN AUTOMATED QUALITY CONTROL

Since 1994, NESDIS has been producing GOES-8 cloud motion vectors (CMV) without manual intervention. Suitable tracers are automatically selected within the first of a sequence of images and heights are assigned using the H2O intercept method (Nieman et al., 1993). The tracking of features through the subsequent imagery is automated using a covariance minimization technique (Merrill et al., 1991) and an automated quality-control algorithm (Hayden, 1993; Hayden and Nieman, 1996) is applied. The improved data quality from GOES-8/9 (Menzel and Purdom, 1994) and the improved procedures outlined above have produced automated GOES-8/9 cloud-drift winds that are superior to any previous NESDIS CMV product. Editing the CMVs through analyses with respect to a first guess wind and temperature profile field involves speed adjustment, height adjustment, and quality assessment (Figure 1). This procedure, with some modifications, is also used to infer water vapor motion vectors (WVMV); tracer selection is based on gradients within the target area and vector heights are inferred from the water vapor brightness temperatures. The following paragraphs can be generalized to WVMV also (Velden, 1996a).

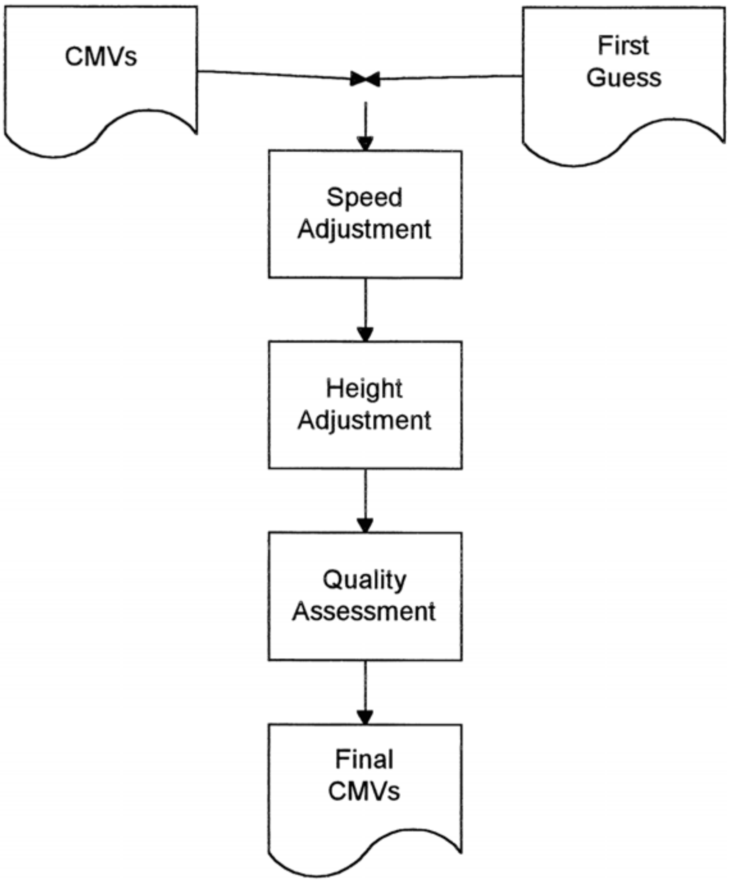

Figure 1. Procedure for editing cloud motion vectors.

To mitigate the well known slow bias of the CMV, each vector is incremented by 7 percent of the speed of the forecast, interpolated to the assigned level.

The height adjustment is accomplished through preliminary analyses of the satellite data CMV at their initially assigned pressure height and pseudo data from the National Center for Environmental Prediction (NCEP) 12-hour aviation forecast (or the 6-hour forecast from the Global Data Assimilation System). The analysis is a 3-dimensional objective analysis (Hayden and Purser, 1995) of the wind field using background information from the numerical forecast. The pressure altitudes of the CMVs are adjusted by minimizing a penalty function which is given by

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

V = velocity, T = temperature, P = pressure, dd = direction, s = speed

Subscript *m* refers to a measurement; *i* and *j* are horizontal dimensions in the analysis, and *k* is the vertical level. The *F* are weighting factors given to velocity, temperature, pressure, direction, and speed; default values are 2 ms^{-1}, 10 °C, 100 hPa, 1000 degrees, and 1000 ms^{-1} respectively.

The pressure levels for height adjustment in hPa are 925, 850, 775, 700, 600, 500, 400, 350, 300, 250, 200, 150, and 100. The pressure or height reassignment is constrained to 100 hPa. A tropopause test looks for lapse rates of less than 0.5 K per 25 hPa above 300 hPa and prohibits re-assignment to some stratospheric heights. As selected, neither speed or direction enter into the computation of the penalty. Increasing a value of F downweights that component. Note that these default selections give equal “worth” to a 2 ms^{-1} discrepancy, a 10 degree temperature discrepancy, or a 100 hPa discrepancy.

A quality assessment for each vector is accomplished by a second analysis using the CMVs at the reassigned pressure altitudes and by inspecting the local quality of the analysis and the fit of the observation to that analysis. Thresholds are given for rejecting the data. Accepted data and the associated quality estimate, denoted by RFF for Recursive Filter Flag, are passed to the user (Hayden and Purser, 1995).

Several options are available for regulating both the analysis, the penalty function, and the final quality estimates. These have been empirically optimized, over several years of application, for the operational GOES CMVs. However the optimization may be situation dependent; what works best with GOES CMVs may not be optimal for water vapor motion vectors (WVMV), or winds generated at higher density, or winds generated with an improved background forecast, etc. Research on optimal tuning of this system in its various applications continues (Velden, 1996b).

2. VERIFICATION

Verification of CMVs is accomplished by comparison with rawinsonde data. The rawinsonde data can be quality controlled with the same approach used for the CMVs, omitting the height reassignment. The rawinsonde data from the surface to 100 hPa are interpolated to pressure levels which are no more than 20 hPa apart. Interpolation is linear in log p for temperature and linear in p for wind components. The satellite CMV is compared with each level of the interpolated profile and the penalty function is calculated for each level; the minimum is chosen as the level of best fit (LBF). The objectively selected level may be further modified to an average with the adjacent levels above (below) the original choice if the averaged P, T ,V yield an improved minimum penalty. For the verification pass, the averaging of levels above and below the drift wind’s assigned pressure may also be averaged. A final check is made to insure adequate representation in the rawinsonde profile. It is required that an actual measured wind be given within 25 hPa of the selected level. If not, the match is rejected.

The vector difference $(VD)_i$ between an individual CMV report (i) and the collocated rawinsonde (r) report used for verification is given by,

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

The speed bias is given by

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

The mean vector difference (MVD) traditionally reported is,

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

And the standard deviation (SD) about the mean vector difference traditionally reported is,

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

The root-mean-square error (RMSE) 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,

$$(RMSE) = \sqrt{(MVD)^2 + (SD)^2}$$

Table 1 gives an example of statistics which can be generated from the rawinsonde match file. Water vapor motion vectors have been chosen for the comparison because they have more uniform spatial coverage enhancing the number of rawinsonde collocations. Table la corresponds to the statistics of all rawinsonde and WVMV collocated within a distance of 2 degrees latitude/longitude. These are the statistics which have been routinely generated at NESDIS/CIMSS since November 1992. For this sample of 1059 matches, the forecast root mean square error (RMSE) is 7.39 m/s and the WVMV RMSE is 8.05 m/s; such numbers are fairly typical. The results are segmented by latitude zones (mid-latitude and tropics) as well as heights (high above 400 hPa and mid between 400 and 700 hPa). The bottom entries in the table indicate the categorization of wind vector quality by RFF; as hoped for, the quality of the wind increases as the value of RFF increases. As the RFF increases, the errors are generally lower, the WVMV RMSE improves relative to the forecast RMSE, and the error correlation increases. Table 1b corresponds to the statistics of all rawinsonde and WVMV collocated within a distance of 1 degree latitude/longitude. The sample size is reduced to 312 and the forecast RMSE is 5.87 m/s and the WVMV RMSE is 6.63 m/s; both RMSEs are reduced by roughly 1.5 m/s just by demanding better collocation of rawinsonde and WVMV.

Table la: Verification statistics for water vapor motion vectors for February 1996 collocated within 2 degrees of a rawinsonde. FMVD is the mean vector difference of the forecast wind with respect to the rawinsondes, FSD is the standard deviation about the mean vector difference, and FRMSE is the root mean square error. SMVD, SSD, and SRMSE are the same for the satellite WVMVs. CC is the correlation in the error for the forecast and the satellite.

	NUM	FMVD	SMVD	FSD	SSD	FRMSE	SRMSE	CC
TOTAL	1059	6.14	6.74	4.11	4.41	7.39	8.05	.73
HIGH	865	6.07	6.64	4.13	4.31	7.34	7.92	.73
MID	194	6.45	7.21	4.06	4.79	7.62	8.65	.72
MIDLAT (20-60 N)	877	6.32	6.94	4.20	4.49	7.59	8.27	.73
HIGH	691	6.25	6.84	4.23	4.39	7.55	8.13	.74
MID	186	6.58	7.31	4.08	4.85	7.75	8.77	.72
TROPICS (20N-20S)	183	5.28	5.82	3.57	3.85	6.38	6.97	.66
HIGH	175	5.37	5.86	3.63	3.92	6.48	7.05	.66
MID	8	3.30	4.80	.97	1.64	3.44	5.08	.01
RFF 50-60	143	6.73	8.74	4.43	4.79	8.06	9.96	.35
RFF 60-70	212	6.11	6.70	3.91	4.15	7.25	7.88	.59
RFF 70-80	349	5.82	6.33	3.40	3.74	6.74	7.35	.73
RFF 80-90	350	6.26	6.37	4.69	4.80	7.83	7.97	.93

Table lb. Same as Table la except the collocation has been reduced to one degree.

	NUM	FMVD	SMVD	FSD	SSD	FRMSE	SRMSE	CC
TOTAL	312	5.04	5.64	3.00	3.48	5.87	6.63	.53
HIGH	251	4.89	5.48	2.86	3.38	5.67	6.43	.48
MID	61	5.65	6.31	3.47	3.85	6.63	7.40	.65
MID-LAT (20-60N)	255	5.13	5.79	3.06	3.54	5.98	6.79	.56
HIGH	197	4.94	5.62	2.91	3.41	5.73	6.57	.52
MID	58	5.79	6.37	3.50	3.94	6.77	7.49	.66
TROPICS (20N-20S)	57	4.63	4.97	2.70	3.14	5.36	5.88	.32
HIGH	54	4.73	4.95	2.73	3.22	5.46	5.90	.33
MID	3	2.85	5.31	1.13	1.29	3.06	5.47	na
RFF 50-60	47	5.79	7.35	3.48	3.76	6.76	8.26	.08
RFF 60-70	66	5.07	5.68	2.96	3.56	5.87	6.70	.34
RFF 70-80	91	4.81	5.36	2.74	3.35	5.54	6.32	.60
RFF 80-90	107	4.86	5.03	2.97	3.19	5.70	5.96	.83

Table 1c. Same as Table la except the rawinsondes have been quality checked.

	NUM	FMVD	SMVD	FSD	SSD	FRMSE	SRMSE	CC
TOTAL	858	5.31	5.99	3.11	3.60	6.16	6.99	.58
HIGH	702	5.25	5.85	3.09	3.49	6.09	6.81	.57
MID	156	5.60	6.62	3.17	3.99	6.43	7.73	.60
MID-LAT (20-60N)	692	5.40	6.10	3.09	3.62	6.23	7.10	.58
HIGH	544	5.32	5.94	3.06	3.47	6.14	6.88	.57
MID	148	5.72	6.72	3.20	4.05	6.56	7.85	.59
TROPICS (20N-20S)	166	4.93	5.50	3.15	3.49	5.85	6.51	.56
HIGH	158	5.01	5.54	3.20	3.56	5.95	6.58	.56
MID	8	3.30	4.80	.97	1.64	3.44	5.08	.01
RFF 50-60	107	5.79	8.42	3.31	4.22	6.67	9.42	.20
RFF 60-70	179	5.55	6.13	3.43	3.80	6.52	7.21	.51
RFF 70-80	294	5.43	5.98	3.12	3.54	6.27	6.95	.68
RFF 80-90	274	4.84	4.92	2.73	2.70	5.56	5.61	.76

Table 1d. Same as Table la except the collocation has been reduced to one degree and the rawinsondes have been quality checked.

	NUM	FMVD	SMVD	FSD	SSD	FRMSE	SRMSE	CC
TOTAL	261	4.53	5.21	2.53	3.12	5.19	6.07	.39
HIGH	215	4.52	5.11	2.56	3.13	5.19	5.99	.40
MID	44	4.61	5.70	2.39	3.04	5.19	6.46	.34
MID-LAT (20-60N)	209	4.54	5.28	2.48	3.09	5.17	6.12	.41
HIGH	166	4.49	5.17	2.50	3.08	5.14	6.02	.43
MID	43	4.73	5.72	2.41	3.13	5.31	6.52	.35
TROPICS (20N-20S)	52	4.49	4.94	2.73	3.23	5.26	5.90	.30
HIGH	49	4.59	4.92	2.78	3.31	5.37	5.93	.32
MID	3	2.85	5.31	1.13	1.29	3.06	5.47	na
RFF 50-60	37	5.24	7.55	3.08	3.41	6.07	8.28	-.06
RFF 60-70	58	4.56	5.29	2.32	3.08	5.11	6.12	.08
RFF 70-80	78	4.58	4.97	2.68	3.19	5.31	5.91	.55
RFF 80-90	87	4.13	4.29	2.13	2.34	4.65	4.89	.67

Table 1e. Same as Table la except the rawinsondes have been quality checked and rawinsonde collocation with the satellite WVMV has been screened to that they are within 1 m/s in the verification analysis.

	NUM	FMVD	SMVD	FSD	SSD	FRMSE	SRMSE	CC
TOTAL	436	3.98	4.61	2.26	2.50	4.58	5.24	.21
HIGH	358	4.00	4.50	2.33	2.47	4.63	5.14	.23
MID	78	3.89	5.08	1.94	2.60	4.34	5.71	.10
MID-LAT (20-60N)	338	3.98	4.58	2.21	2.41	4.55	5.18	.18
HIGH	264	3.98	4.43	2.27	2.33	4.59	5.00	.21
MID	74	3.96	5.13	1.96	2.62	4.42	5.76	.10
TROPICS (20N-20S)	98	4.00	4.68	2.47	2.81	4.70	5.46	.29
HIGH	94	4.06	4.70	2.50	2.84	4.76	5.49	.30
MID	4	2.58	4.14	.48	2.13	2.63	4.66	-.80
RFF 50-60	55	4.38	7.67	2.29	2.90	4.94	8.20	-.14
RFF 60-70	102	4.32	4.89	2.28	2.34	4.88	5.42	-.11
RFF 70-80	150	4.12	4.30	2.39	1.91	4.77	4.71	.37
RFF 80-90	128	3.39	3.39	1.99	1.83	3.93	3.85	.43

Table 1c presents a third set of statistics where quality control has been exercised on the rawinsonde data. Only those rawinsondes with a quality (RFF) of 80 or better are included. The sample size is reduced to 858 and the forecast RMSE is 6.16 m/s and the WVMV RMSE is 6.99 m/s; both RMSEs are reduced by a little more than 1.0 m/s by controlling the quality of the rawinsonde using the recursive filter as a screening mechanism. More importantly, however, for the high quality WVMVs (RFF > 80) the apparent error is reduced by 2.4 m/s and the error correlation is reduced. Table 1d presents statistics where both collocation of one degree and rawinsonde quality checking has been invoked. Under these very stringent criteria, the sample size is reduced to 261 and the forecast RMSE is 5.19 m/s and the WVMV RMSE is 6.07 m/s; both RMSEs are reduced by about 2.0 m/s.

Table 1e presents the statistics for the data where the collocation has been made exact by comparing WVMV with the analysis of the quality checked rawinsondes. When the WVMV collocation to the analysis of rawinsondes produces a vector difference (VD) differing by more than 1 m/s from the WVMV VD with respect to the nearest rawinsonde, the data are rejected; this seeks to avoid false gradients due to changes in the rawinsonde data density often encountered near coastlines. The sample size is reduced to 436, and the overall errors are reduced 2.5 m/s from Table la (or 1.5 m/s beyond the reduction achieved from rawinsonde quality control alone). WVMVs with RFF>70 are now found to be more accurate than the forecast, and the error correlation is less than .5. It has been previously reported (Hayden, 1993) that an undesirable high correlation between forecast error and quality control wind error is inevitable with this type of wind processing. However, this example shows that most of the correlation is attributable to non-representativeness of the rawinsonde or large horizontal gradients in the wind. The quality-controlled WVMV (or CMV) is not unduly biased to the forecast.

It is apparent that as the match quality is improved, the errors of the high quality (large RFF) drift winds are reduced much more than those of lower quality. This is not the case with the forecast error which improves quite uniformly. We feel that this result is largely caused by the use of the forecast as a background in quality controlling the rawinsondes and generating the verification analyses. By requiring an RFF>80, the background field is defined as accurate. The WVMV (or CMV) winds have some independence. This same reasoning applies as to why it is so difficult to show that drift winds are as, or more, accurate than the forecast.

One might ask, looking at the statistics in Table 1e for the collocation-checked sample, why we retain drift winds for RFF<60. Their error is 8.2 ms^{-1} as compared to a forecast error of only 4.9 ms^{-1}. The reason is intuitive. We believe that such winds are useful in regions of high curvature and where the forecasts are presumably not so good (i.e. not in the immediate vicinity of a rawinsonde). Qualitative inspection of wind fields in sparse data areas as well as quantitative investigations of model impact on hurricane trajectories (Velden, 1996) seem to confirm this belief. However in regions where the forecast has skill (such as near straight line jets), there is good argument for deleting winds with RFF<60.

It should by now be obvious that the most difficult part of optimizing the quality control procedure is in properly weighting the influence of the forecast. If large weight is given, one will inevitably edit good winds where the forecast is bad. Conversely, if small weight is given, one will retain poor winds where the forecast is good. The dilemma could be solved only by knowing where the forecast is good; which is impossible except in the broadest terms. Velden (1996b) advocates minimizing dependence on the forecast in assessing CMV and WVMV quality by intercomparing high density winds from multispectral sources. The wind field from one spectral band can be used to screen the motion vectors from another; achieving internal consistency of the high density wind field becomes the editing process and the influence of the model forecast background field is downweighted.

3. WINDS PERFORMANCE FOR MARCH – MAY 1996

The performance of the operational GOES-8/9 CMVs and WVMVs has been reported elsewhere (Menzel et al., 1996). Statistics produced in March through May 1996 are shown in Table 2. Collocation within 2 degrees latitude has been required. As the QC flag increases in value, the MVD (and RMSE) decreases accordingly; vectors with 80>RFF>70 are 1.3 to 1.6 m/s better than the vectors with 60>RFF>50. The highest quality vectors have an MVD better than 5.5 m/s (RMSE better than 7 m/s) for both GOES; GOES-9 vectors are a little better than GOES-8 for this sample. However, a subtle speed dependence in the QC flag is also evident.

Table 2. GOES-8/9 operational CMV and WVMV comparison with rawinsondes for March-May 1996. SMVD is the mean vector difference, SRMSE is the root mean square difference, and SPD is rawinsonde mean speed.

PRODUCT	QC FLAG (RFF)	NUM	SMVD	SRMSE	SPD
GOES-8 CMV	50-60	1368	6.36	7.61	19.86
	60-70	1684	5.35	6.60	17.85
	70-80	1167	4.89	6.15	17.03
GOES-9 CMV	50-60	725	6.44	7.66	19.73
	60-70	950	5.17	6.31	17.72
	70-80	626	4.96	5.99	17.32
GOES-8 WVMV	50-60	4894	7.03	8.38	21.96
	60-70	5816	6.01	7.40	21.37
	70-80	3436	5.57	7.07	20.48
GOES-9 WVMV	50-60	2455	6.75	7.99	21.95
	60-70	2985	5.89	7.02	20.98
	70-80	1763	5.43	6.68	19.93

4. SUMMARY

The GOES-8 automated cloud motion vectors are significantly improved. Operational automated cloud motion vectors are now equal or superior in quality to those which had the benefit of manual quality control a few years ago. The single most important factor in this improvement has been the upgraded auto-editor. Improved tracer selection procedures eliminate targets in difficult regions and allow a higher target density and therefore enhanced coverage in areas of interest. The incorporation of the H2O-intercept height assignment method allows an adequate representation of the heights of semi-transparent clouds in the absence of a CO2-absorption channel. GOES-8 water-vapor motion winds resulting from the automated system are superior to any done previously by NESDIS and should now be considered as an operational product.

The quality assessment of the GOES-8/9 CMV and WVMV winds has been investigated with respect to rawinsondes using different collocation criteria and quality checking the rawinsondes. The usual statistics produced from two degree collocation criteria can be improved by as much as 2.0 m/s when one degree collocation and rawinsonde quality screening are required. When attempting exact collocation with an analysis of the rawinsonde data and screening out false gradients due to changes in the rawinsonde density (such as those encountered near coastlines), the comparison of WVMV (or CMV) are improved another 0.5 m/s. It can be inferred the quality of the satellite derived winds as inferred by the RMSE is probably about 2.5 m/s better than the usual statistics indicate. The remaining differences of 5 to 6 m/s can be attributed to both rawinsonde and satellite measurement errors.

Finally, a quality flag (RFF) has been introduced that is derived by evaluating how well the derived wind measurement fits with an analysis of all the available wind data (model, rawinsonde, and GOES CMV and WVMV). The results presented in this paper confirm that, with quality controlled and well collocated data, the WVMV and CMV comparison with rawinsondes improves as RFF increases. In areas where other observations of wind fields are plentiful, the RFF could be used as a screening tool. However, in data sparse areas, RFF is an attempt to be as an indicator of the wind quality, but it should be used with caution when weighting winds and it should not be used to reject winds. Qualitative inspection of wind fields in data sparse regions supports the notion that these wind vectors are providing useful information; research is being directed towards this issue.

5. REFERENCES

Hayden, C. M., 1993: Recent research in the automated quality control of cloud motion vectors at CIMSS/NESDIS. *Proceedings of the Second International Winds Workshop, Tokyo, Japan.* December 13-16. 219-226.

Hayden, C. M. and R. J. Purser, 1995: Recursive filter objective analysis of meteorological fields - applications to NESDIS operational processing. *J. Appl. Meteor.*, **34,** 3-15.

Hayden, C. M. and S. Nieman, 1996: A primer for tuning the automated quality control system and for verifying satellite-measured drift winds. Submitted for publication as a NESDIS Technical Memorandum.

Menzel, W. P. and J. F. W. Purdom, 1994: Introducing GOES-I: The first of a new generation of Geostationary Operational environmental Satellites. *Bull. Amer. Meteor. Soc.*, **75**, 757-781.

Menzel W. P., S. Nieman, D. Gray, and C. Hayden, 1996: Recent Performance of the NOAA/NESDIS Automated Cloud-Motion Vector System. Report on the CGMS XXIV, Lauenen, Switzerland, 22-26 April 1996.

Merrill, R. T., W. P. Menzel, W. Baker, J. Lynch, and E. Legg, 1991: A report on the recent demonstration of NOAA's upgraded capability to derive cloud motion satellite winds. *Bull. Amer. Meteor. Soc.*, **72**, 372-376.

Nieman, S., J. Schmetz and W. P. Menzel, 1993: A comparison of several techniques to assign heights to cloud tracers. *J. Appl. Meteor.*, **32**, 1559-1568.

Velden, C. S., 1996a: Winds derived from geostationary satellite moisture channel observations: Applications and impact on NWP. Meteor. and Atmos. Physics, 219, 1-10.

Velden, C. S. 1996b: Positive impact of satellite derived winds during the 1995 hurricane season: Example of optimizing data application and processing strategy. Proceedings of the Third International Winds Conference, Ascona, Switzerland, 10-12 June 1996.