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by

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THE ACCURACY OF SATOB CLOUD MOTION VECTORS.

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ABSTRACT

The available statistics on the quality of operational cloud motion vectors are reviewed, and a methodology is proposed for computation of the accuracy of the vectors. Estimates of SATOB accuracy based on collocations with radio-sonde winds are given, together with comments on the accuracy of radio-sonde wind data and of wind reports from aircraft.

1. WHAT IS A SATOB?

A SATOB is an observation derived from satellite data and reported in a standard WMO code format. This paper specifically discusses the cloud motion vectors (CMV), or cloud winds, generated by three satellite operators (the USA, Japan and ESA) and transmitted in SATOB code over the WMO Global Telecommunications System (GTS).

The same basic principle is used for generation of CMV by all three satellite operators; consecutive images from a geostationary satellite are aligned and the displacement of selected clouds is measured, yielding a vector. The temperature of the cloud top is used to determine the level of the cloud, and this information contributes to the height assignment of the resulting CMV. A human quality control stage follows; this helps to ensure that only clouds which appear to be moving with the wind are used. Mountain wave clouds, for example, are rejected during this stage. Details of the technique vary between the three operators, and are described in the literature. An account of the system used by ESA for Meteosat CMV is given by Bowen et al, 1979. Cloud tracking is by cross correlation methods and height assignment is to the level of the cloud top, using temperatures obtained from the infrared "window" radiances at 11 um corrected for cloud transparency by the so-called "water-vapour" channel at 6 um. The present system differs in detail, and has been extensively tuned, but there has been no major change since that date.

Bristor, 1975, describes the system used to derive operational CMV from the USA satellites (SMS at first, now GOES). The system included cross correlation as an image matching technique to measure displacement for low clouds and a movie loop system for high clouds. Winds identified as being at a low level are assigned to 900 mb, on the evidence of experimental data suggesting that this is marginally the statistical level of best fit. Radiances from high level winds can be examined by an operator and modified if their emissivity is considered to depart significantly from unity. The author understands that since July 1983 the USA have used an automatic cross correlation system for both high and low level winds, and that the movie loop system has now been discontinued, but has found no reference to this.

The system used in Japan to derive CMV from GMS (also known as Himawari) is described in the GMS user guide, 1980. A communication in the CGMS report, 1983, indicates that the present system has been modified to improve height attribution and is now similar to the original USA system, with cross correlation for low level clouds and movie loops for high level clouds. Height assignment of low level winds is to fixed pressure levels which vary according to season.

Both ESA and Japan limit the height of the high level clouds to that of the climatological tropopause in order to eliminate any excessively wild values obtained from the observed radiances.

Examination of the various systems used operationally shows that the CMV must be regarded as a mean wind over a substantial horizontal distance, over an hour or more, and representing a significant depth of the atmosphere. The cross correlation method selects a target area in one image, and searches for the best correlation match in a larger window in another image. The target is typically a square area of side 150 km. Sequences of two or three images are using in correlation methods, with up to five images for the movie loop measurements. Image repetition rates of as little as three minutes are used for some studies and in particular cases, but in general the interval used for the SATOB data is 30 minutes, so that these data represent mean flow over periods ranging from 30 minutes up to two hours. Problems in the assignment of CMV to a particular level also imply that they should be regarded as representative of the mean flow through a layer of the atmosphere, again reminding us that the CMV are not point measurements.

It is the intention of this paper to review the quality of the CMV products from the user point of view, therefore the causes of error are not extensively discussed. The reason for this approach is that in practice the user has to live with the available product and should use the observed diagnostic characteristics both to determine how best to use the data and to comment of their utility. This is entirely consistent with the attitude most users have to other sources of data, such as radio-sonde wind estimates. Use is made of their known error characteristics, but few users concern themselves with details of the techniques.

2. AVAILABLE STATISTICS.

The usual method of obtaining estimates of data quality is to compare the data with some other measure of the same quantity. If we wish to determine the quality of, say, a thermometer we simply compare it with a standard thermometer. For thermometers this is fairly straight forward, since the process can be carried out under controlled laboratory conditions. Notice that one does not discard the test thermometer if it is different from the standard, but simply notes the quality and uses the instrument accordingly. Notice also that the standard thermometer need not measure temperature without error, but simply needs to have error characteristics consistent with its purpose.

The same approach is needed for other quantities, although it becomes more complicated once one has to leave the laboratory. The quality of CMV is bound to vary under different atmospheric conditions because of the variability of the cloud tracers. Therefore it is necessary to adopt a statistical approach and compare the CMV with other estimates of the truth over a fairly long period. Case studies are useful to establish the precise error budgets in individual situations, and are therefore useful for studies into possible ways of improving the product, but do not tell us much about the statistical properties of the CMV over long periods and wide areas.

An alternative method for determination of data quality is to examine the error budget of the entire processing chain, in the way that Olsen, 1978, has quantified some of the error sources for Omega-derived winds. The satellite operators have conducted similar error audits of their system processing chains, but these analyses are necessarily incomplete as they do not consider the possibly large contribution of the cloud tracer itself, and of its relationship to the true wind under all possible circumstances.

Therefore a statistical approach seems essential, and there is no shortage of statistical analyses of satellite winds. The Coordination group for

Geostationary Meteorological Satellites arranges twice yearly inter- comparisons of satellite data (CGMS, 1980), which includes the comparison of CMV with CMV in the areas of mutual overlap (Type I reports) as well as comparisons of satellite winds with collocated radio-sonde winds (Type II reports).

The Meteosat Operations Advisory Group (MOAG, 1979), considered the quality of Meteosat winds through a variety of techniques, including comparison of the winds with subjective and objective analyses, comparison with Meteosat clouds winds derived by optical techniques, comparison with cloud winds from other satellite operators, comparison with collocated radio-sondes and case studies of examples of extreme differences. A review of available comparisons and statistics for CMV generated by all three satellite operators is given in a later report (MOAG, 1983).

Unfortunately, most of the data described above simply tabulate differences between the CMV and some other estimation of the wind made at a nearby location. The actual shear of the wind between the two locations makes a substantial contribution to the observed differences, which are therefore difficult to intepret and do not provide any direct estimate of the actual quality of the CMV.

3. ANALYSIS OF STATISTICS

Several workers have analysed statistical comparisons of CMV with other estimates of the "true" wind. Whitney, 1982, reviews available CGMS statistics, and correlates discontinuities in these with changes (improvements) in the methods used by the three operational data producers. He discusses some of the probable sources of difference but does not quantify the contribution from particular sources and does not indicate any precise error characteristics.

Mosher and Sidar, 1977, analysed the SMS cloud tracked winds produced by NESS and at SSEC, University of Wisconsin, on the McIdas system. The latter showed a "reproducibility" of 1.3 m/s for low level clouds, and 2 m/s for high level clouds. Comparison with ship radio-sonde data showed 1 m/s RMS error for low level winds at 950 mb, and 2-3 m/s RMS error for high level clouds - but the paper does not say how these values were established and these results have not been reproduced by other workers.

Mosher, 1981, used data generated during the FGGE to compare the CMV from the different satellite producers in the areas of overlap of adjacent satellites, using the SSEC winds as a comparison baseline, and showed similar differences for all the pairs of data producers. Differences in the accuracy of cloud height attribution could be detected, with the Meteosat operational data being best in this respect, and GMS worse (but this was in 1979). Biases between satellites were less than 2 m/s generally, but the GOES high level winds sometimes had alignment errors, attributed to the manual system then in use, giving a bias of slightly more than 3 m/s.

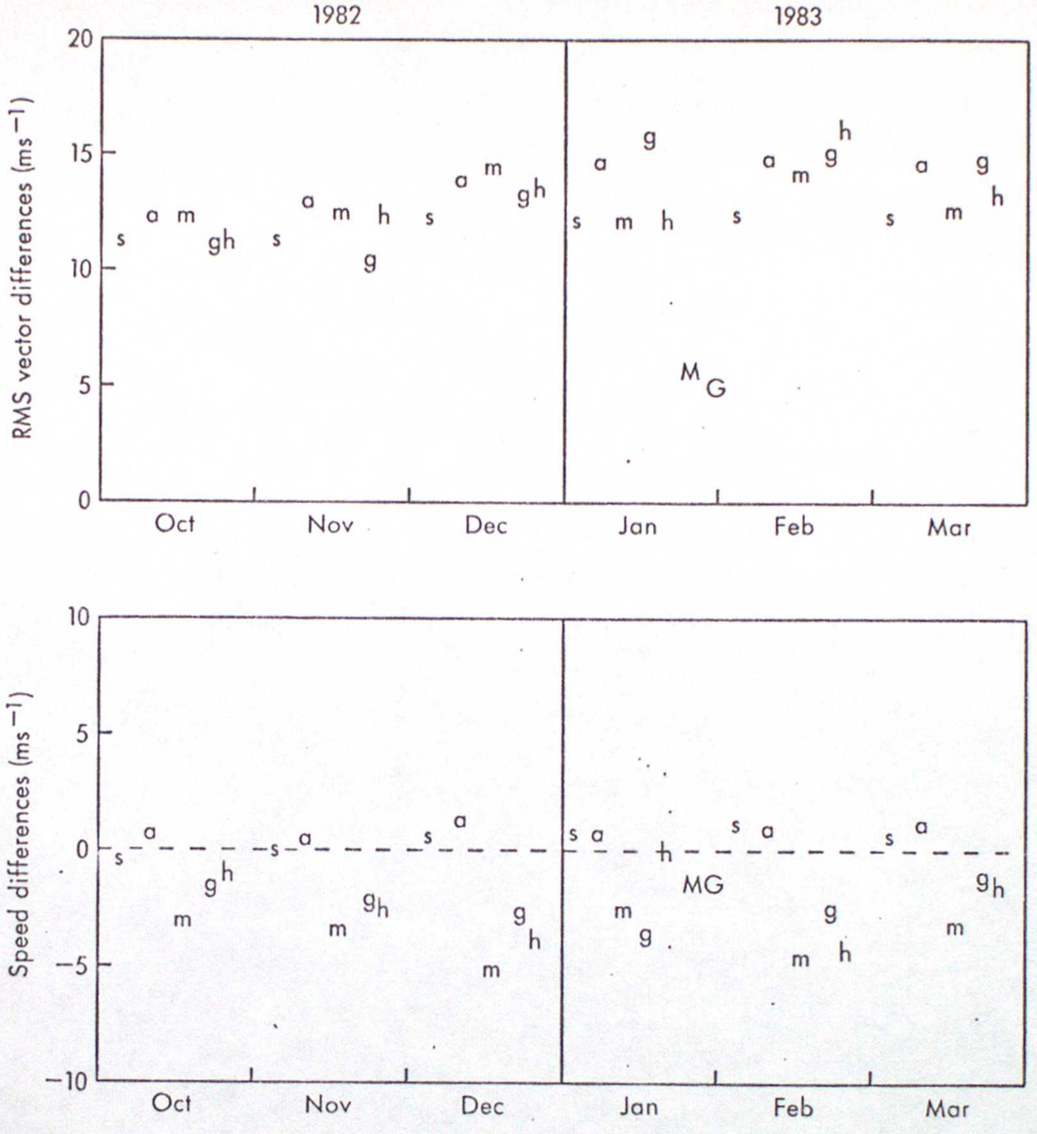
Several studies have indicated that satellite high level winds tend to underestimate the true speed of the wind, and Pailleux et al, 1983, confirm the tendency of Meteosat in particular to underestimate winds at high levels. They note the almost complete inability of the satellite winds to observe a wind greater than 100 kt. As far as can be determined this is not due to limitations of the processing schemes, and may indicate that cloud tracers do not follow the wind at these high speeds. Furthermore the same study shows that the satellite observations also appear to have fewer reports of low wind speed than do sondes, i.e. the distribution is not only biased low, it is also too narrow.

One of the problems in examining statistics such as those generated by the CGMS is that one is confronted with dozens of tables and bottom line numbers without any clear idea as to their implication. Is a Root Mean Square difference of 16.4 m/s good or bad? If a statistic changes from 17.2 to 13.5 m/s in consecutive months has the extraction scheme really improved? What is the contribution of the errors in the observations with which the CMV are being compared? What is the contribution of the shear in the real atmosphere between the measurements (the collocation error)?

To help answer these question Morgan and Chapman, 1983, introducted the idea of "perspective statistics", and compared sondes with sondes, and aircraft reports with sondes, under the same collocation conditions as the CGMS Type II comparisons of CMV against sondes. The CGMS collocation box was divided into five nested zones (Figure 4) to help determine the mean distance separating pairs of observations. Not surprisingly the sonde - sonde distances are larger than the CMV - sonde distances. Possible bias caused by this can be minimised by only examing results for the two outer zones, in which all data have approximately the same average horizontal separation. The results for these outer zones, for the period October 1982 to March 1983, are shown in Figures 1,2 and 3 for high, medium and low level winds respectively. The Figures do not give a quantitative answer to the quality question, but reveal a number of important features of the CMV. For example the statistics of the sonde-sonde comparisons and the airep-sonde comparisons are almost as noisy as the CMV-sonde differences, indicating the large contribution made by real atmospheric variability. There is a tendency for the high level CMV to be biased low in speed compared with sonde data. The low level winds are not biased. The RMS vector differences increase with height in much the same way as one believes the real atmospheric wind shear increases with height, again indicative of the contribution of atmospheric shear. A particularly revealing feature of these figures are the values for satellite - satellite comparisons, obtained from the CGMS Type I reports, which are invariably smaller than any other comparisons in the Figures. Any analysis of the statistics must explain this feature.

The zoned data were also used to determine how the differences vary as a function of separation distance. Results for high level winds in Figures 4 and 5 indicate that the sonde - sonde comparisons are more strongly affected by separation distance than the CMV - sonde differences; indicative of the fact that the CMV are averaged over a larger area than the sondes.

High level winds



Key

s = sonde	- sonde	h = himawari	- sonde
a = airep	- sonde	G = GOES-E	- GOES–W
m = meteosat	- sonde	M = Meteosat	- GOES–E
g = goes e/w	- sonde		

Fig. 1 RMS vector and speed differences for high level winds within collocation zones 4 and 5. The average separation between observation pairs is about 200 km.
The satellite – satellite differences are obtained from CGMS statistics and are averages over all collocation zones.

Medium level winds

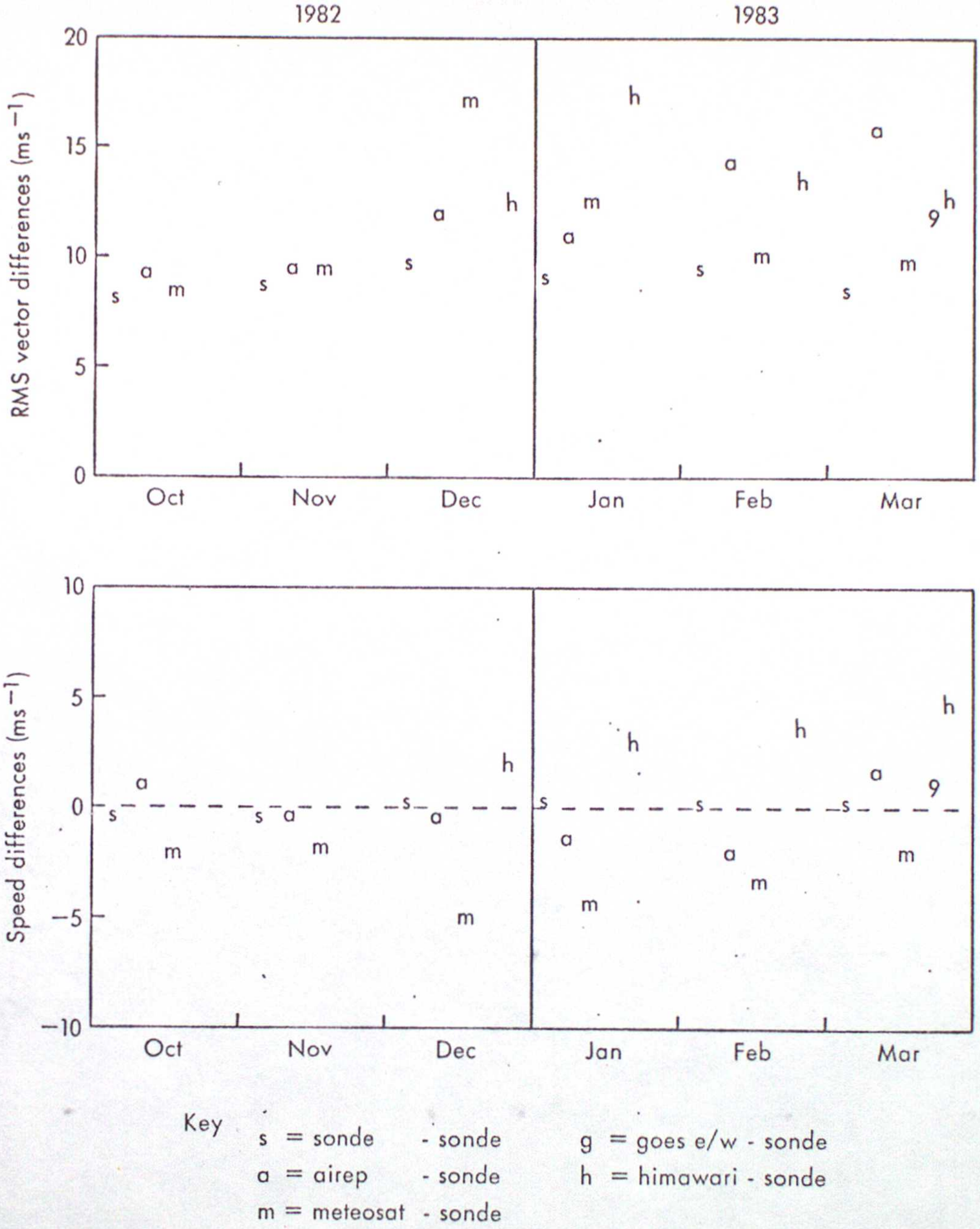


Fig. 2 As for Fig. 1 but for medium level winds (700 to 400 mb).

Low level winds

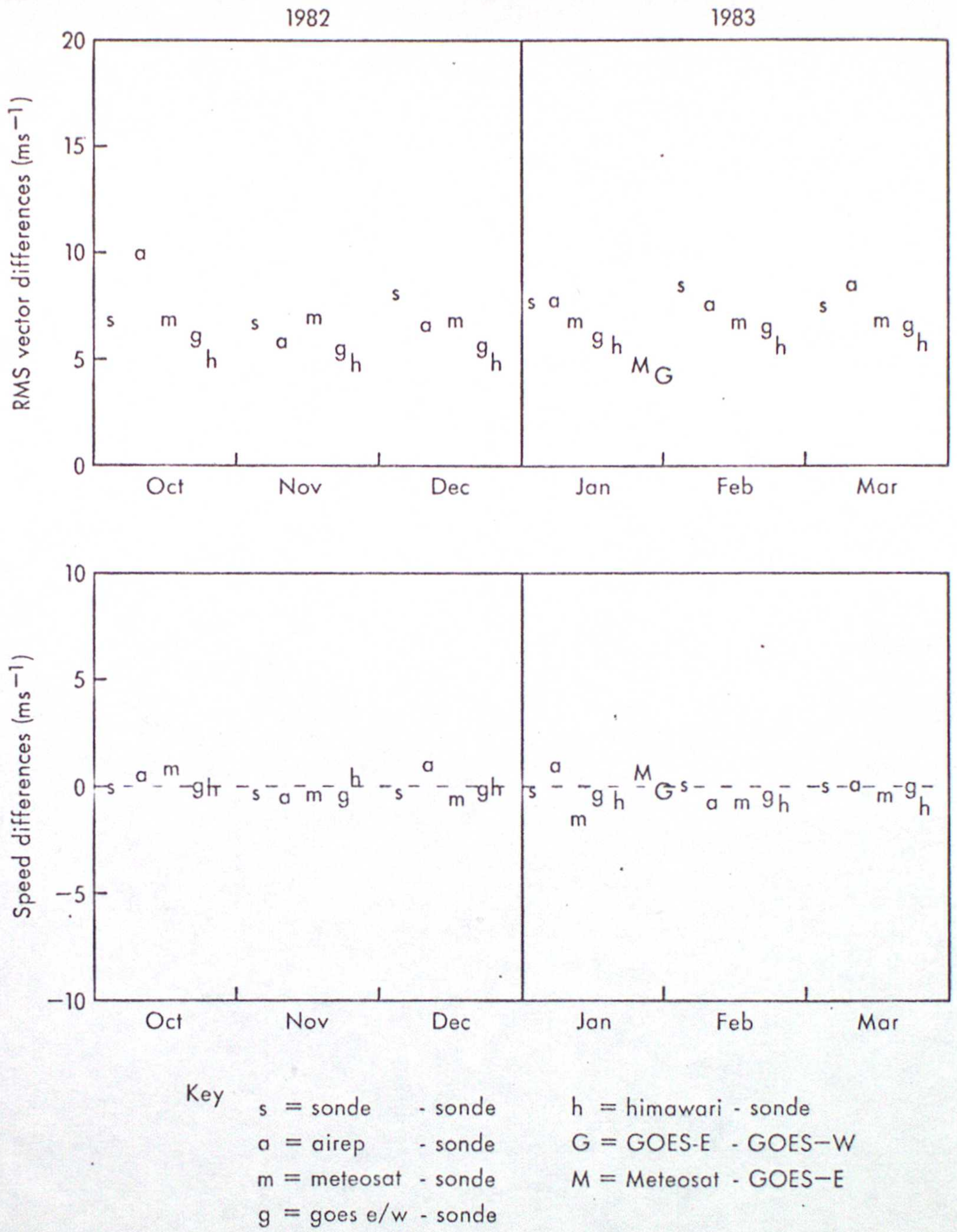


Fig. 3 As for Fig. 1 but for low level winds.

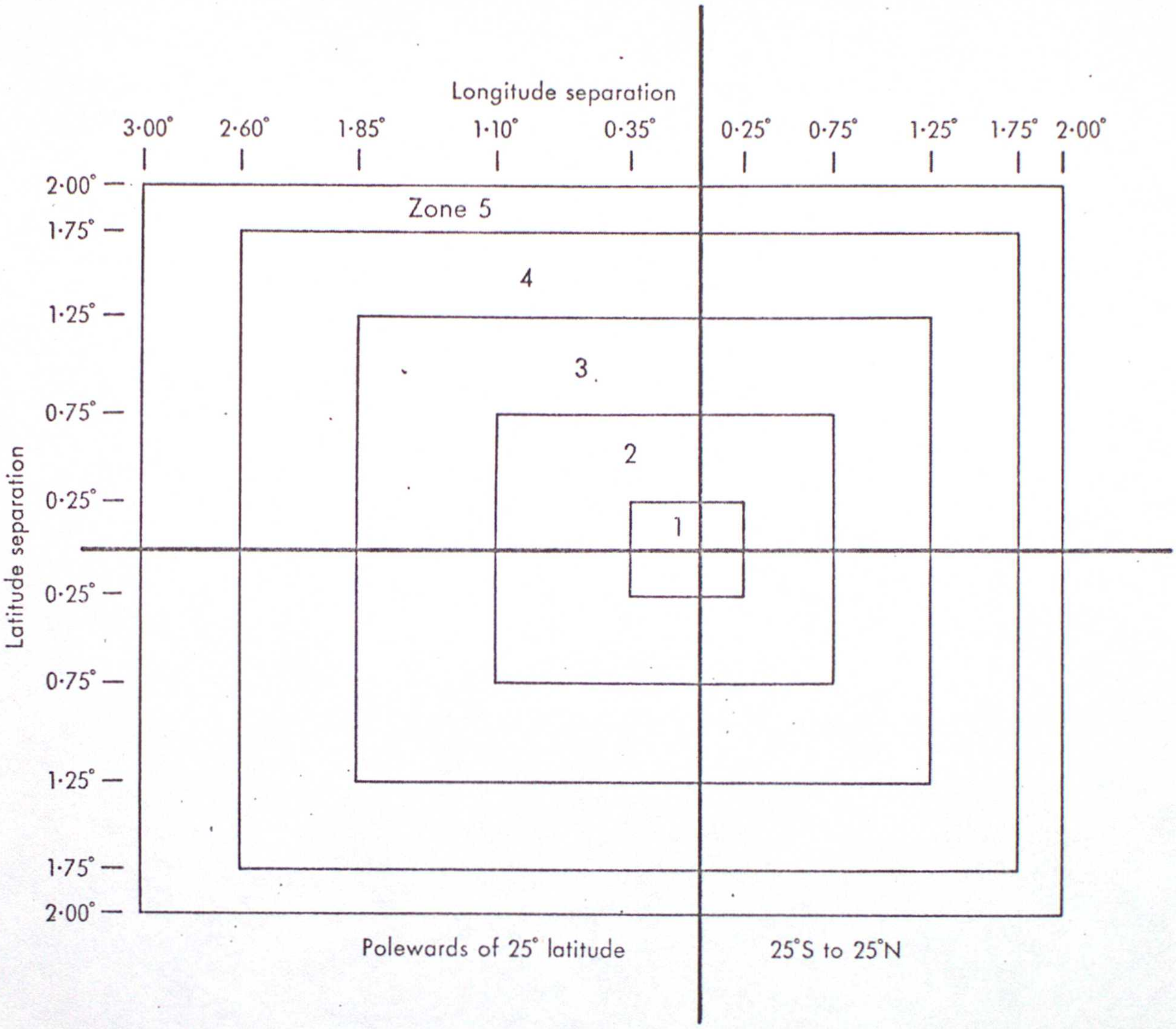


Fig. 4 Sketch of collocation zones 1 to 5. The full collocation box is as used for the CGMS comparisons.

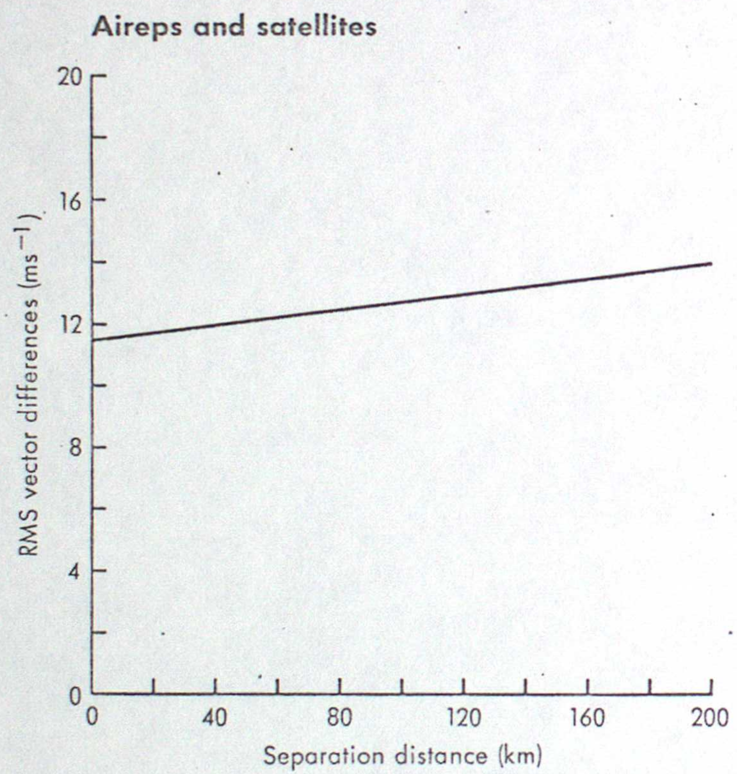


Fig. 5 Linear regression of high level wind RMS vector differences against separation distance, including satellite-sonde differences and airep-sonde differences.

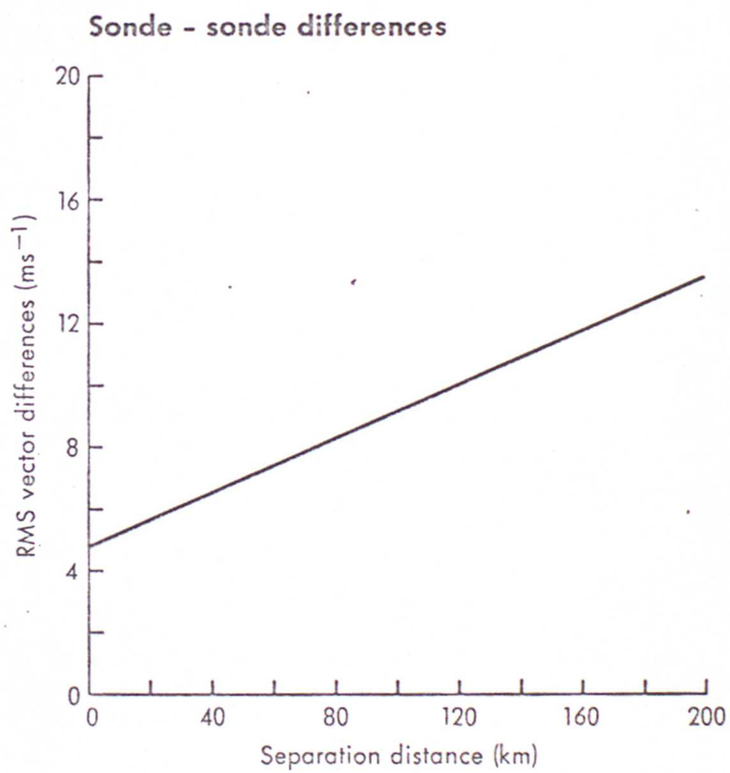


Fig. 6 Linear regression of high level wind sonde-sonde RMS vector differences against separation distance.

4. ANALYSIS OF DIFFERENCES

As the available raw statistics do not measure accuracy directly it is necessary to consider just what these differences represent, in an attempt to derive the required quality values.

Any measurement of an atmospheric quantity is a function of the "truth" at the precise time and place at which the measurement is made, the local gradients in time and space on the occasion of the measurements, the manner in which the measurement system averages over local gradients in (x,y,z,t), and the error or noise of the individual measurements with respect to the ideal for that measurement system. The function is clearly very complex, and varies for each measurement system, but in the interests of simplicity it is assumed that an individual measurement, m_{jk}, made by system j, has components;

- r_k the "true" value at the measurement site,
- b_j the overall mean bias of measurement system j with respect to the truth,
- n_{jk} the random "noise" component of the error of the individual measurement related to the (biased) system characteristics.

The term "bias" is used here to denote the general characteristics of the observing system with respect to some arbitrary "truth". The bias term b_j will itself be a function of local conditions, but is assumed to be constant within a typical series of measurements by one measurement system over a few weeks through a defined and limited depth of the atmosphere. The residuals, that is the real variation in system bias, will appear within the n_{jk} and thus contribute to the over-estimation of the random error component.

Thus a measurement m_{1k} by system 1 can be represented by:

$$m_{1k} = r_k + b_1 + n_{1k} \qquad (1)$$

A second measurement m_{2k} by system 2 would not in general be at precisely the same time or location as m_{1k}, so that:

$$m_{2k} = r_k + t_k + h_k + v_k + b_2 + n_{2k} \qquad (2)$$

where;

t_k is a component difference in the true quantity due to the time difference of the two measurements;

h_k is a component difference due to horizontal gradients in the true quantity between the sites of the two measurements,

v_k is a component difference due to vertical shear of the true quantity between the levels of the two measurements.

Thus the difference, d_k, between the two measurements of the same atmospheric quantity can be represented approximately by:

$$d_k = t_k + h_k + v_k + b_{1,2} + n_1 - n_2 \qquad (3)$$

where $b_{1,2}$ is the bias (assumed constant over limited periods and for defined layers in the atmosphere) between the two observing systems.

Notice that this approximate relationship does not include the true wind at all; this is probably a deficiency in the analysis but convenient. It is a perfectly general relationship, equally applicable to intercomparisons of CMV with sondes or with analyses.

It is not very helpful to look at individual differences, and a more useful quantity is the Root Mean Square (RMS) differences of P pairs of measurements, where P is suitably large. Using the following notation to represent the mean square value;

$$D^2 = \frac{\sum_{k=1}^{P} d^2_k}{P}$$

one can write:

$$D^2 = T^2 + H^2 + V^2 + B^2_{1,2} + N_1^2 + N_2^2 \qquad (4)$$

since all the cross product terms contain at least one random element with zero mean, and therefore vanish.

This description of the components of difference would help define the errors of one of the estimating systems if one only knew the error characteristics of the other, as well as the three components attributable to the natural variability of the atmosphere in space and time. This has been tried by Hubert and Thomasell, 1979, in comparing GOES winds with sondes. They used an equation similar to (4) but with the atmospheric contributions, T,H,V combined into one variable and the inter-system bias B, included within the noise. They estimated atmospheric variability from NMC objective analyses and assumed that the noise in one system is an arbitrary fraction of that in the other. This eliminates the unkowns and produces error estimates for the CMV notwildly different from those proposed in the present paper. But their second assumption is rather awkward as it prejudges the very point at issue. An alternative approach is therefore proposed.

The T,H,V components of equation (4) are the contribution of the real atmosphere to the differences. If the measurements are made at precisely the same time and place then;

$$T = H = V = 0 \quad \text{and} \; ;$$

$$D^2 = B^2_{1,2} + N^2_1 + N^2_2 \qquad (5)$$

The above equation does not mention the "truth", but if it is assumed that observing system 1 is an unbiased estimator of the truth one can write

$$E^2 = B^2_{1,2} + N^2_2 \qquad (6)$$

or,

$$E^2 = D^2 - N^2_1 \qquad (7)$$

where E is the RMS error of observing system 2 relative to the "truth" defined by observing system 1.

If both measurements are made by the same measurement system then, in equation (5), $N_1 = N_2 = N$, and;

$$D^2 = 2N^2 \qquad (8)$$

Thus if one compares CMV with CMV (for example) at zero collocation distance, equation (8) provides an estimation of the purely random errors of these data. The RMS noise is simply the RMS differences divided by the square root of two. For any given system the equation yields the random, noise, component of the error relative to whatever biases that system might have.

Equation (5) illustrates that differences in measurements made by different types of measuring systems also includes the inter-system biases.

Therefore CMV - sonde differences are likely to be higher than either sonde - sonde differences or CMV - CMV differences. Equation (4) reminds us of the obvious fact that raw differences usually contain many components other than the error of any one of the measurement systems.

Obviously, one can also say that the algebriac mean difference of P pairs of measurements is simply the inter-system bias $b_{1,2}$, since all the other terms of equation (3) can be assumed to be random with zero mean.

5. COMPUTATION OF ERROR

When computing quality estimates it is necessary to consider exactly what we mean by the "truth". This may be different for different purposes. Hawson, 1970, discusses desirable error characteristics of observing systems and makes this point very clearly:

'When a measurement is made of any observed quantity the result may be regarded as made up of two parts: the "signal" and the "noise". The "signal" constitutes the quantity which one sets out to determine, and the "noise" that part which is relevant. The "noise" may arise in several ways: from observational error, because the observation is not made at the right time and place, or because short-period or small-scale irregularities occur in the observed quantity which are irrelevant to the use to which the observation is put, and have to be smoothed out ...'

The equations derived in section 4 are intended to help address this particular point; the distinction has been made between the system noise N and the inter-system biases B and these components of error are identified separately in the following sections.

5.1 Satellite - Satellite Comparisons

The only source of comparisons of CMV with CMV readily available to the author is the CGMS Type I comparisons. A few parameters derived from recent comparisons are listed in Table 1. Consider first the GOES E - GOES W data. These satellites are from the same series, and have the same data producer, therefore the inter-system bias B in equation (4) should be zero. This is confirmed by the rather small differences in the mean wind speeds. The data are assumed to be derived at about the same time, so the time component of collocation error T can be assumed to be negligible. Hopefully, the two satellites would be tracking the same cloud layer, so the vertical component of collocation error V is also small. Finally, although the CGMS collocation box permits distances of more than 200 km between "collocated" observations, both of the satellite measurements represent averages over a fairly large area, and these areas are likely to overlap substantially. Therefore the horizontal component of collocation error H will also be small. Hence equation (8) becomes applicable, and the "noise" of the GOES satellites can be estimated by their RMS differences divided by the square root of two. The resulting noise values are shown in the first column of Table 2.

This provides information on the noise component of the other two satellites. Consider equation (4) again, and the Meteosat - GOES E and GMS GOES W differences. The T,V and H components are all likely to be small, so that equation (5) becomes relevant, with the noise components being that of the GOES satellite. The mean speed differences against GOES are higher (Table 1) than the internal GOES differences, so one is reluctant to assume that the inter-system bias is negligible. Therefore equation (7) is used to determine the total error of the satellites with respect to GOES, by subtraction of the GOES noise from the observed differences.

Comparison:	GOES E – GOES W		GMS (HIMAWARI) – GOES W		METEOSAT – GOES E	
Date:	July '83	Jan '84	July '83	Jan '84	July '83	Jan '84
HIGH LEVEL WINDS (<400 mb)						
Number of comparisons	102	40	51	0	59	157
RMS vector differences (m/s)	4.7	5.8	5.7	–	4.7	5.4
Mean speed differences (m/s)	0.2	–0.5	1.2	–	–1.4	–0.9
LOW LEVEL WINDS (>700 mb)						
Number of comparisons	574	433	321	289	1071	321
RMS vector differences (m/s)	4.5	4.7	4.5	4.0	4.5	3.9
Mean speed differences (m/s)	0.3	–0.6	0.6	0.3	1.4	1.6

Table 1: Extract from CGMS Type 1, intersatellite, comparisons for July 83 and January 1984.

Satellite:	GOES	GMS (HIMAWARI)	METEOSAT
HIGH LEVEL WINDS (400 mb)			
July 1983	3.3	4.0	3.3
Jan. 1984	4.1	-	3.8
LOW LEVEL WINDS (700 mb)			
July 1983	3.2	3.2	3.2
Jan. 1984	3.3	2.8	2.8

Table 2. Estimates of satellite cloud motion vector system noise, N.

The results are shown in the second and third columns of Table 2, for GMS and Meteosat respectively. Even though these two columns contain inter-system biases the values are similar to those for the GOES noise values shown in column one.

In fact the differences between months are larger than the differences between satellites, so it is concluded that the latter are not real differences, the inter-satellite bias is close to zero, and the noise component of the error can be reasonably estimated by the means of all these values, that is 3.7 m/s for high level CMV and 3.1 m/s for low level winds.

These are bound to be over estimates of the noise because of all the approximations made, for example the H component of the atmospheric shear is not exactly zero. Furthermore, these values are obtained at the outer edge of the extraction area, in the small sector where the fields of view of adjacent satellites overlap and where the noise is likely to be greatest. It would seem not unreasonable therefore to round these values down to

3.5 m/s and 3.0 m/s respectively.

The GOES system produces few medium level winds, so there is no inter-satellite data at this level. It would appear that it is at least as difficult to assign correct heights to medium level winds as to high level winds, so that an estimate of medium level noise should be similar to that for high level CMV. With all these assumptions, estimates for the noise component of CMV for all satellites are shown in Table 3.

	Noise estimates, all satellites
High level winds	3.5 m/s
Medium level winds	3.5 m/s
Low level winds	3.0 m/s

Table 3. Noise estimates for GOES, GMS and METEOSAT cloud motion vectors.

These noise figures represent the quality of the CMV if one assumes that the CMV are an unbiased estimator of the "truth". For example certain users call for observations which are averages over a hundred or more km, over an hour and through a finite depth of the atmosphere. This is exactly what a satellite CMV is, and with that definition of the "truth", the CMV are close to the often stated accuracy requirements of 3 m/s. However, there are alternative definitions of the truth, and this results in a different definition of the quality of the CMV.

5.2 Comparisons of sondes with sondes.

The Meteorological Office Synoptic Data Bank (SDB) was searched for all radiosonde ascents within 60 degrees of the equator, for the period October 1982 to March 1983 and for January 1984 and July 1984. The sonde - sonde differences were computed according to CGMS rules for Type II comparisons of CMV with sonde data, except that the results were binned into the collocation zones defined in Figure 4. The results, for outermost two zones, are shown in Table 4, together with similar "perspective statistics" for Airep - Sonde comparisons. The differences are variable between months due to the atmospheric contribution and, in an attempt to reduce this, the data were adjusted through linear regression against collocation distance to estimate the vector difference at zero collocation distance. The results are shown in Table 6, together with corresponding

Comparison:	SONDE – SONDE			SONDE – AIREPS		
Date:	82/83 *	Jan 84	Jul 84	82/83 *	Jan 84	July 84
HIGH LEVEL WINDS						
Number of comparisons	32395	6915	6626	21233	2276	1184
RMS vector differences (m/s)	12.2	13.3	10.9	14.5	16.5	11.5
Mean speed differences (m/s)	0.5	1.1	–0.6	1.1	2.2	0.1
Mean direction difference (deg.)	–0.4	–0.4	0.8	–0.5	–1.4	4.6
MEDIUM LEVEL WINDS						
Number of comparisons	34507	7224	6906	923	102	11
RMS vector differences (m/s)	9.2	9.8	8.0	13.0	9.5	–
Mean speed differences (m/s)	0.1	0.3	–0.4	0.1	–1.1	–
Mean direction difference (deg.)	–0.7	–1.0	–1.1	1.2	0.5	–
LOW LEVEL WINDS						
Number of comparisons	30427	6252	6006	124	69	0
RMS vector differences (m/s)	7.5	7.8	8.0	7.6	6.3	–
Mean speed differences (m/s)	–0.1	0.0	0.0	–0.8	–0.9	–
Mean direction difference (deg.)	–0.2	–0.5	0.1	8.3	–0.1	–

Table 4: Differences of sondes & aireps, compared with sonde winds, in collocation zones 4 and 5 (ie an average separation of about 200 km). * Period was Oct 82 until March 83

Comparison:	GOES - SONDE			GMS - SONDE			METEOSAT - SONDE		
Date:	82/83*	Jan 84	July 84	82/83*	Jan 84	July 84	82/83*	Jan 84	July 84
HIGH LEVEL WINDS									
Number of comparisons	826	128	220	4842	48	0	2975	475	432
RMS vector differences (m/s)	13.3	13.0	9.6	12.8	16.6		13.5	13.3	12.0
Mean speed differences (m/s)	-2.0	-3.5	0.2	-1.8	-0.6		-3.3	-3.3	-3.7
Mean direction difference (deg.)	-3.4	-1.4	-8.6	-3.6	0.6		-0.7	-4.7	1.5
MEDIUM LEVEL WINDS									
Number of comparisons	(6)	0	0	2065	118	0	1498	155	252
RMS vector differences (m/s)				14.4	14.6		11.5	12.8	9.1
Mean speed differences (m/s)				3.8	-2.4		-2.7	-3.9	-2.5
Mean direction difference (deg.)				-4.8	-3.3		2.2	3.5	-1.1
LOW LEVEL WINDS									
Number of comparisons	2073	230	411	1596	249	0	1826	253	259
RMS vector differences (m/s)	6.2	6.0	6.0	5.6	5.7		7.2	6.1	6.5
Mean speed differences (m/s)	-0.1	-0.3	0.3	-0.2	-0.5		-0.2	1.3	0.4
Mean direction difference (deg.)	0.7	0.9	-1.5	-3.1	-2.9		3.0	-1.7	0.9

Table 5: Differences between satellites and sondes, in collocation zones 4 and 5 (ie an average separation of about 200 km). * Period was Oct '82 until March '83

Date:	Oct 82 – March 83	Jan 84	July 84	Mean
HIGH				
Sonde – sonde	4.9	6.5	4.6	5.3
Airep – sonde	8.0	7.2	5.6	6.9
GOES – sonde	9.3	9.2	6.0	8.2
GMS – sonde	8.8	(5.5*)	–	8.8
METEOSAT – sonde	8.1	6.1	8.1	7.4
MEDIUM				
Sonde – sonde	4.3	5.5	3.6	4.5
Airep – sonde	6.6	10.2	3.4	6.7
GOES – sonde	–	–	–	–
GMS – sonde	10.6	12.2	–	11.4
METEOSAT – sonde	7.5	7.5	6.8	7.3
LOW				
Sonde – sonde	4.8	5.1	4.1	4.7
Airep – sonde	5.4	7.1	–	6.3
GOES – sonde	4.9	4.8	5.1	4.9
GMS – sonde	3.4	3.5	–	3.5
METEOSAT – sonde	4.4	4.2	4.1	4.2

* Standard error of estimate 3.9 m/s; this value ignored

Table 6. Table of differences regressed to zero collocation distance. The standard error of the estimate is approximately 0.5 m/s for all sondes, for high level aireps, and all low level winds. For other comparisons it is about 1.5 m/s.

results for CMV - Sonde and Airep - Sonde differences.

For the sonde differences, in equation (4), the horizontal atmospheric shear term, H, has been eliminated (approximately) by regression. All the winds are at the same level, so that we can neglect V, and within the collocation time window of 3 hours one can expect most of the soundings to have been made within a short time of each other, so that T should be small. The inter-system bias B should also be small, at least much smaller than Sonde - CMV differences. Therefore equation (8) can be adopted, and the noise of the sonde winds can be estimated as the mean differences in the last column of Table 6 divided by $\sqrt{2}$, that is 3.8 m/s for the high level winds, 3.2 m/s for the medium level winds and 3.3 m/s for the low level winds.

These values are higher than some estimates of sonde data quality, but they have been derived in the real operational environment rather than in a carefully controlled experiment using perfectly maintained and well calibrated equipment. Furthermore the values include components due to the fact that the balloon is not exactly at the assumed station location, and the small scale (<50 km) variability has probably not been eliminated through the regression technique. However, the derivation has been subject to approximations which all lead to an over-estimation, and therefore these estimates are also rounded down for the purposes of this paper to 3.5 m/s, 3.0 m/s, 3.0 respectively.

5.3 Comparisons of CMV with sondes.

The CMV in the SDB were extracted and compared with collocated sondes in accordance with the CGMS rules, and binned into the five collocation zones of Figure 4. The raw data for the same periods as the sonde - sonde comparisons are listed in Table 5, and in Table 6 with the vector differences regressed to zero collocation distance.

Considering equation (4) again, component H is assumed negligible for the data in Table 6, the V component is small at the defined levels because the sonde data have been interpolated to the reported level of the CMV, and the time component T will also be fairly small because the CMV are generated close to the appropriate synoptic time. The inter-system bias B cannot be disregarded, therefore the equation reduces to equation (7); that is if the sondes are assumed to be an unbiased estimator of the "truth" then the total errors of the CMV are the differences in Table 6 less the sonde noise. The results of this operation are shown in Table 7.

This Table unfortunately casts doubt on the arguments developed so far, because in two cases the total of the bias and noise is less than that of the noise alone as given in Table 3. For the METEOSAT low level CMV the difference of 0.1 m/s is less than the uncertainty in the assumptions, and does not pose particular problems if the inter-system bias is assumed to be zero at this level. The GMS low level result is surprisingly low but there are several possible explanations. The value used for the noise of the sondes may be too high and should be checked from other sources. The GMS User's Guide, 1980, describes an interactive quality control system in which CMV are compared with sonde winds in real-time before distribution. If this is done systematically and wild values rejected by the satellite operators it would clearly distort the statistics presented in this paper. In the absence of any other estimate it is proposed that the error figures for both GMS and METEOSAT low level winds should be the same as the noise figure, 3.0 m/s, derived from satellite - satellite intercomparisons. This assumes zero biases, which is consistent with the observed small differences in the arithmetic means. For consistency the GOES data should be reduced to the same value.

	Level of winds		
	High	Medium	Low
	(<400 mb)	(400–700 mb)	(>700 mb)
GOES	7.4	–	3.9
GMS	8.1	11.0	1.8*
METEOSAT	6.5	6.7	2.9*
AIREP	5.9	6.0	5.5

Table 7. Estimates, derived from Table 6, of the system errors (bias plus noise) relative to sonde data.

Note * These values are lower than the independent estimates of satellite noise in Table 3. See text for discussion and explantions.

5.3 Airep - Sonde comparisons.

Available aircraft report (Aireps) in the SDB were also processed in the same way as the CMV, and the results are included without discussion in Table 4, 6 and 7. They do not add anything to the analysis of SATOB quality except to provide an additional perspective.

5.4 Other estimates of CMV quality.

Hubert and Thomasell, 1979, compared GOES winds with collocated sonde winds and evaluated the system noise as 2.5 to 3 m/s for low level winds and about 4 m/s for high level winds. Their estimate of total error, including what they describe as meteorological influences (which do not include the collocation errors), was 4.7 m/s for the low level winds and 8.5 m/s for high level winds. Their results are reasonably close to those presented in the present paper, even though different approaches have been used to eliminate the collocation error in particular. They also point out that truth itself is "fraught with uncertainties", and on this we can also agree.

6. SUMMARY OF RESULTS.

The preceding arguments have yielded two estimates of the quality of SATOB data. The first, given in Table 3, assumes that the SATOBs are unbiased estimators of some absolute "truth" which in some way represents a mean flow in the atmosphere. The second estimate assumes that sonde data are unbiased estimators of a different "truth", and this yields the higher estimates given in Table 8. The arguments depend critically on estimates of the noisiness of sonde data, and alternative estimates of this quantity should be examined before accepting the values given in Table 8.

	Level of winds		
	High	Medium	Low
	(<400 mb)	(400–700 mb)	(>700 mb)
	Error estimates in m/s		
SONDES	3.5	3.0	3.0
AIREPS	5.9	6.0	5.5
GOES	7.4	–	3.0
GMS	8.1	11.0	3.0
METEOSAT	6.5	6.7	3.0

Table 8: Estimates of RMS error of the observing systems examined in the paper, assuming that the Sonde data are unbiased estimates of the "truth".

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