STUDY OF CIRRUS CLOUD WINDS : ANALYSIS OF I.C.E. DATA

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ABSTRACT

High level satellite cloud motion winds (SCMWs) winds are not as accurate as low level ones, and it is believed that the major source of error is the height assignment, in particular the semi-transparency correction applied to the radiances from cirrus clouds. During the International Cirrus Experiment (I.C.E.) in 1989, measurements of wind, temperature, humidity and a number of microphysical and radiative parameters were made by up to 5 aircraft flying simultaneously in cirrus cloud.

In assessing the extent to which cloud motions were representative of the true wind field, comparisons were performed at the Empirical Level of Best Fit (ELBF), that is, the level at which the SCMW agrees best with the aircraft wind data. A template size of 16 * 32 pixels (16 pixels in the north-south direction, 32 in the east-west) gave the best results. However it is considered that a template size of 16 * 16 pixels would be the most informative for users.

It was found that the semi-transparency correction was very sensitive both to the incoming radiance data and to the water-vapour channel calibration coefficient. Therefore a vicarious calibration of the water-vapour channel was performed, using the ELBFs. The calibration coefficient arising from this was 10 to 20 %. lower than the operational value. However it should be stressed that different interpretations should be placed on this vicarious value and the operational value, and consistency should not be expected a priori. Furthermore it was shown that, because of the sensitivity the semi-transparency correction to the incoming data, and because the correction is not performed if the water vapour channel radiance, converted to physical units, is too high, the best results are to be obtained using the operational value.

1 Introduction

SCMWs are produced operationally by all the operators of geostationary meteorological satellites. The low level SCMWs produced operationally by ESA from METEOSAT data (Schmetz et al, 1992) are extremely accurate: when verified against numerical analyses the accuracy is very close to that of radiosonde winds (Thoss, 1992). However, high level winds are not so accurate, when compared with radiosonde winds. Sources of error in SCMWs can be split into the following areas

- Image navigation - the fact that there is an error in the earth-referenced position of a point in the image.
- Image contamination - ideally images should comprise a selection of well defined tracers against a completely uniform background, but in practice, particularly for high level clouds, this is rarely the case.
- Tracking error - a tracer will be tracked without error only if pixels in all the requisite images comprise either entirely tracer or entirely background, and the tracer moves without changing its shape in any way.
- The combined effects of height attribution error and the tendency for cloud motion not to be representative of wind at cloud top.
- The use of an inappropriate form of ground truth. Operational SCMWs from ESA in mid-latitudes are representative of spatial scales of approximately 160 * 300 km and time scales of one hour. They are often compared with other sources of wind information which are representative of smaller space and time scales.

Lunnon and Lowe (1990) showed that there was significant correlation between the error in SCMWs and the vertical wind shear. This, together with the acknowledged accuracy of low-level SCMWs, leads us to believe that the major source of error is the height assignment, in particular the semi-transparency correction applied to the radiances from cirrus clouds. A further complication is that cirrus clouds may not move with the wind at the cloud top. Thus complete understanding of the problem involves dynamics, microphysics and radiative transfer theory. During the International Cirrus Experiment (I.C.E.) in 1989, measurements of wind, temperature, humidity and a number of microphysical and radiative parameters were made by up to 5 aircraft flying simultaneously in cirrus cloud, of which three were considered the most critical for processing. Thus the data obtained provided the best opportunity to study the problem of the semi-transparency correction using contemporaneous observations of all the relevant variables.

The complete report of this work is Lunnon et al (1992b). However, some of that material, particularly a more complete account of the method than is given here and graphical illustration of some of the results, are given in Lunnon et al (1992a). There is very little overlap between Lunnon et al (1992a) and the present paper.

Section 2 of this paper gives more details of the I.C.E. experiment, with details pertaining to the particular missions chosen for study in this project. Section 3 compares cirrus motion vectors (obtained from the satellite data) with the true wind (from the aircraft data) on a variety of scales. Section 4 describes the application of the operational (as used by ESOC) semi-transparency correction to data from the I.C.E. experiment.

2 The use of data from the International Cirrus Experiment (I.C.E.)

2.1 Rationale

The major field campaign was carried out between 18th September and 20th October 1989 in the southern part of the North Sea. Intensive observations were made by ground-based and airborne systems, and extensive use has subsequently been made of satellite data. The study made use only of the aircraft data (in conjunction with satellite data and archived operational numerical forecast data).

The factors considered when selecting missions were the availability of satellite and aircraft data, whether all three of the aircraft (the Falcon operated by DLR, the Merlin operated by Centre d'Aviation Meteorologique, and the C130 Hercules operated by Meteorological Research Flight) were flying colocated patterns, the synoptic situation and the likelyhood of being able to generate SCMWs, which was determined by examining the histograms of infra-red radiances. In a typical mission, the Merlin would be flying at about flight level 220, the C130 at about flight level 260 and the Falcon at about flight level 300. The following were the chosen missions, together with the MIEC calibration coefficients taken from METEOSAT calibration reports (ESOC, 1989 & 1990). The Julian day is shown in this table for convenience in cross-refering to the calibration reports.

Mission	*Date*	*Julian Day*	*Infra – red Calibration Coefficient*	*WaterVapour Calibration Coefficient*
ICE - 201	18*th September* 1989	261	0.06760	0.0082
ICE - 202	20*th September* 1989	263	0.06723	0.0081
ICE - 207	28*th September* 1989	271	0.06794	0.0082
ICE - 208	10*th October* 1989	283	0.07022	0.0085

2.2 The basic processing

The analysis of the aircraft wind, temperature and humidity data was performed on a grid of 40*km* in the horizontal and standard pressure levels in the vertical, and separate analyses were performed at half-hourly intervals, at the times for which the correlation surfaces were produced (see section 3).

3 Comparison of cirrus motion with the actual wind on various scales

3.1 The method used to generate "correlation surfaces"

In general, the production of SCMWs by automated means relies on the calculation of the correlation between a pair of images at successive times, for a range of possible displacements of one image relative to the other. This two-dimensional array of correlations is generally referred to as a correlation surface. Although operationally at ESOC the true correlation coefficients are calculated, in the present study the Sequential Similarity Detection Algorithm (SSDA) was used. SSDA is simply the sum of the magnitudes of the differences between the images at the specified displacements. Thus whereas one seeks maxima in true correlation surfaces as indications of the true wind, in SSDA surfaces one seeks minima.

One advantage of SSDA surfaces is that if one has already calculated them for two templates, say, two neighbouring 8 * 8 arrays, then in order to generate the one for the 16 * 8 template comprising the two original 8 * 8 templates, one simply adds the two existing surfaces. This property was exploited in the present work: altogether template sizes of 8*8, 8*16, 16*16, 16*32 and 32*32 pixels were all processed. (An 8*16 template has 8 pixels in the north-south direction and 16 pixels in the east-west: at the latitude of the North Sea this is roughly square on the earth's surface. The operational production of SCMWs uses a template size of 32 * 32 infrared pixels, but Lunnon and Lowe (1992) showed that the use of a smaller template size produces better results for low level SCMWs. Because the term correlation surface is used throughout the SCMW literature, it will be used in this report but the algorithm actually used was SSDA.

Before comparing the analysed aircraft wind data with the correlation surfaces, the former were averaged onto the spatial scale of the latter, which is of course a function of the template size. Having produced the correlation surface, the next stage is to produce an empirical level of best fit (ELBF) - this is the level at which the SCMW agrees best with the aircraft data. The definition of ELBF used in its derivation is that it is the level corresponding to the point on the wind profile having maximum correlation. Lunnon et al (1992a) provides the justification for this. Of course an ELBF will be produced for each correlation surface at each scale.

3.2 Summary statistics of agreement between SCMWs and aircraft data on various scales

In order to assess quantitatively, but without reference to any height attribution process, the extent to which cloud motions are representative of the true wind field, statistics were generated as to the accuracy of winds at the ELBF. However, it was recognised that for the smallest scale winds, the ELBF might be misleading in the sense that noise in the SCMWs could be accomodated by using a slightly erroneous height attribution. Therefore, not only was the ELBF at the scale in question used, but in addition the winds were verified using the ELBF from the 32 * 32 scale. Verification was performed by comparing the wind using the prescribed height assignment with the wind derived from the aircraft wind at that level, and the root mean square vector difference was calculated. The results are given in the following table (RMS vector differences in pixels per half hour). The results are for all the missions and times specified in table 5.1.

Scale of wind	8 * 8	8 * 16	16 * 16	16 * 32	32 * 32	8 * 8	8 * 16	16 * 16	16 * 32
Scale of ELBF	32 * 32	32 * 32	32 * 32	32 * 32	32 * 32	8 * 8	8 * 16	16 * 16	16 * 32
RMS Vector error	2.67	2.40	1.94	1.56	1.55	1.88	1.56	1.81	1.48
No of cases	125	75	45	24	16	125	75	45	24

It had been hoped that there would be a single minimum in the statistics as a function of scale, with values increasing as a function of difference of scale from the optimum. Therefore it is difficult to explain the relatively high value for the 16 * 16 scale, using the ELBF at that scale for height assignment, which is considered to be anomalous. There is clear evidence that 16 * 32 is to be preferred to 32 * 32.

4 Application of the operational semi-transparency correction to I.C.E. data

4.1 Experience using the MIEC water vapour calibration

The calculation of the semi-transparency correction is performed exactly as it is done operationally at ESOC, as described by Bowen and Saunders (1984). However, the generation and selection of the model atmospheres for which the radiative transfer calculations are performed is different, and this is described in Lunnon et al (1992a). Note that the model selection is performed using the aircraft data averaged onto the appropriate scale.

Briefly, the method consists of finding the intersection between two lines plotted in IR/WV radiance space. One line, referred to henceforth as the straight line, is a straight line connecting the cluster means for the background and cloud clusters. It has to be extrapolated to intersect the other line. This latter line is known as the opaque cloud curve, and it is generated using radiative transfer theory and a specified temperature and humidity distribution. It specifies what radiances would be observed at spacecraft level if an opaque cloud were placed at a variety of levels in the atmosphere.

The application of the semi-transparency correction is very sensitive to the registration of the WV and IR channels. Registration information is available with the archived image information obtained from ESOC, but using this alogorithm (admittedly, with the registration only applied to the nearest pixel) gave rise to occasions when the mean WV channel radiance for the background cluster was colder than the mean WV channel radiance for the cloud cluster. Therefore an empirical reregistration was applied whereby a total of 9 possible registrations were used (a 3*3 array centred on the ESOC registration) were examined, and the one that gave the minimum number of occurences of the background cluster being colder than the cloud cluster was used. This procedure was applied to arrays of 8*8 pixels, but a consistent registration was applied across the full segment of 32 * 32 pixels.

It was found that no semi-transparency correction correction was applied on a large number of occasions, because, given the infra-red radiance, the water vapour channel radiance is greater than the corresponding value on the opaque cloud line. There are a number of possible explanations of this, which will be considered in detail later in this section.

4.2 Vicarious calibration of WV channel

Because of the good measures of the ELBF obtained as described in the previous section, it was decided to use them to perform a vicarious calibration of the water-vapour channel, using the following steps:

1. Convert ELBF from pressure to temperature, using aircraft temperature data.
2. Convert temperature to infra-red black-body radiance in physical units
3. Convert I-R radiance to counts using published MIEC calibration coefficient
4. Use straight line of semi-transparency correction to give W-V radiance in counts (this process does not make use of any model atmosphere).
5. Use model atmosphere, specified in physical units, to give W-V radiance (in physical units) corresponding to I-R radiance (in physical units) from step 2.
6. Use two forms of W-V channel radiance, from steps 4 and 5, to give calibration coefficient.

The results are given in the table 4.1, which requires a little explanation. In addition to the mission number and time, the table gives the infra-red cut-off, used to discriminate between cloud pixels and background pixels, the mean, uncorrected radiances from the background and cloud clusters, the pressure of the ELBF and the radiance in counts corresponding to it, the vicarious calibration coefficient in $W\,M^{-2}\,St^{-1}\,Ct^{-1}$, the model atmosphere used (see appendix for the explanation of this number), the second derivative of correlation with respect to pressure, and the average visible channel variance for pixel pairs comprising infra-red pixels. (Note that from the archive, only every alternate line of visible data is available). A convention was adopted whereby if the radiance in counts corresponding to the ELBF is higher than the uncorrected radiance, the water vapour channel calibration coefficient was set to be negative. There is a perfectly reasonable explanation for this: it would occur if the cloud were opaque and moved with a wind at a level below cloud top. It is noteworthy that all the occurences of the ELBF being below (in the atmosphere) the level corresponding to the uncorrected IR radiance have rather low values of d^2c/dp^2, that is, there is considerable uncertainty about the ELBF.

Table 4.1

Mission /Time	*IR cut -off*	*IR B/G*	*IR cloud*	*IR ELBF*	*Press ELBF*	*WV Cal Coef*	*WV B/G*	*WV cloud*	*Model*	$\frac{d^2c}{dp^2}$	*VIS dif*
2011105	90	123	82	64	318	.0049	92	89	18	0.2	2.7
2011135	92	135	83	68	334	.0051	94	88	17	0.5	2.3
2011205	92	134	84	49	250	.0046	94	87	1	0.1	2.3
2021035	92	122	76	60	300	.0059	81	75	43	0.0	4.4
2021105	90	123	77	85	400	–.0049	80	76	43	0.0	4.7
2021135	94	124	82	60	300	.0057	81	71	43	0.0	4.6
2021205	96	128	87	90	430	–.0054	81	82	43	0.2	4.2
2071235	88	108	77	53	315	.0059	84	75	64	1.5	2.7
2071305	92	110	82	65	375	.0061	85	78	64	1.0	3.0
2071335	96	113	86	62	359	.0057	85	81	43	0.8	3.5
2071405	82	110	71	60	347	.0061	85	74	43	0.5	2.6
2081235	62	90	54	68	400	–.0070	71	61	64	0.0	0.8
2081305	72	90	59	68	400	–.0069	71	64	64	0.2	1.1
2081335	70	81	61	64	382	–.0069	68	65	64	0.1	1.2
2081405	72	80	65	68	400	–.0068	70	66	64	0.1	1.4
2081435	76	84	68	68	400	–.0068	72	67	64	0.1	1.6

Although the inconsistency between values of WV calibration coefficient is dissapointing, (and this variability will be discussed later) it is considered that a value of about 0.006 $W\ M^{-2}\ St^{-1}\ Ct^{-1}$, is more appropriate than the value of about 0.008 $W\ M^{-2}\ St^{-1}\ Ct^{-1}$, published by MIEC. The MIEC calibration coefficient was obtained as described by Schmetz (1989). The method is based on applying the radiative transfer equation to temperature and humidity data from radiosondes and then comparing the computed radiances (in physical units) with the observed radiances (in counts). It is noted with considerable interest that a calibration coefficient some 17% below the MIEC value was obtained by Gärtner (1990) by comparing the counts obtained for very high, thick clouds in the IR and WV channels. This approach is much closer in philosophy to that of the vicarious method and it is very revealing that such similar results are obtained. Therefore a thorough consideration of possible reasons for the discrepancy is given below. It is considered easier to explain the relatively small difference between Gärtner’s calibration and our own (which is probably within the combined experimental error of the two methods) than it is to explain the relatively large difference between Gärtner’s calibration and the MIEC value.

4.3 Possible causes of the discrepancy between the MIEC water vapour channel calibration coefficient and the vicarious value

- Inconsistent emissivities at infra-red and water-vapour channel wavelengths.
- Anomalous radiometer performance at the time of the I.C.E. experiment.
- Possible bias in radiosonde data.
- Inconsistency between radiative transfer models used at ESOC and the UK Met Office.
- The presence of aerosols.
- Large amounts of anthropogenic water vapour in the low stratosphere.
- Uncertainty in the spectral response of the WV channel.

These causes are discussed further in Lunnon et al (1992b).

4.4 Inherent uncertainties in the semi-transparency correction

Because of the uncertainty in the specification of the straight line, it is argued that the use of an artificially high value of the WV channel calibration coefficient can produce better height assignment than the use of a value which might be obtained from a vicarious procedure, such as outlined above. The reasoning is as follows. If an artificially high value of the calibration coefficient is used this leads to the semitransparency correction not being applied on a large number of occasions, because, given the IR radiance (in counts), the WV channel radiance (in counts) is greater than the corresponding number on the opaque cloud line. In these circumstances, the uncertainty in the slope of the straight line does not have any deleterious effects. As described by Schmetz et al (1992) and confirmed by Woick (1992) the quality of ESOC’s winds improved in September 1987 after the introduction of the new WV channel calibration scheme, as a result of which higher calibration coefficients were used. It is considered that this can be explained by the above argument.

4.5 Results of tests with different WV channel calibration coefficients

Because it was hypothesised that the semitransparency correction can, potentially, function more effectively if the value of the WV channel calibration coefficient is higher than vicarious calibration would suggest, it was decided to perform the height assignment of the SCMWs generated for the I.C.E. experiment using a range of possible coefficients. The range chosen was from 0.0050 $W\ M^{-2}\ St^{-1}\ Ct^{-1}$ to 0.0085 $W\ M^{-2}\ St^{-1}\ Ct^{-1}$, in steps of 0.0005 $W\ M^{-2}\ St^{-1}\ Ct^{-1}$. Winds were verified for all five template sizes under consideration, and in addition, for the four smaller template sizes, the semi-transparency correction was applied both using radiances on the scale in question and using the radiances for the 32 * 32 segment. Verification was performed by comparing the wind using the prescribed height assignment with the wind derived from the aircraft wind at that level, and the root mean square vector difference was calculated. The results are given in the following table (RMS vector differences in pixels per half hour). The results are for all the missions and times specified in the earlier table.

Table 5.2 : *RMS vector differences for various scales and calibrations*

Scale of Wind	*Scale of Semi – transparency Correction*	*WV channel calibration coefficient* $W M^{-2} St^{-1} Ct^{-1}$ .0050	.0055	.0060	.0065	.0070	.0075	.0080	.0085
8 * 8	32 * 32	3.67	3.67	3.67	3.67	3.66	3.66	3.66	3.66
8 * 16	32 * 32	3.55	3.56	3.55	3.55	3.54	3.54	3.54	3.54
16 * 16	32 * 32	3.45	3.45	3.42	3.39	3.37	3.36	3.36	3.36
16 * 32	32 * 32	3.17	3.21	3.15	3.11	3.07	3.06	3.06	3.06
32 * 32	32 * 32	2.22	2.15	2.06	2.06	1.87	1.84	1.86	1.92
8 * 8	8 * 8	2.43	2.30	2.21	2.21	2.19	2.17	2.18	2.18
8 * 16	8 * 16	2.16	2.10	2.02	1.96	1.93	1.93	1.96	1.97
16 * 16	16 * 16	2.45	2.20	2.11	2.12	2.08	2.04	2.04	2.03
16 * 32	16 * 32	2.20	1.97	1.88	1.92	1.87	1.83	1.79	1.77

From the above table it can be concluded that the use of a high WV channel calibration coefficient produces better results than a low coefficient, with little to chose between .0080 and .0085. As far as scale is concerned, the best results in terms of RMS vector error were produced using a 16 * 32 array both to track the cloud system, and to perform the semi-transparency correction. However, the fact that using a 16 * 16 array produces worse results than either of the two neighbouring scales is difficult to explain, and is thought to stem from the relatively small sample used. It should be born in mind that even though a relatively small scale may produce worse statistics than a larger one, there may be useful information implicit in the enhanced resolution. Therefore the conclusion from this part of the study is that *probably* the best scale to use is 16 * 16. Of course if it proves feasible to produce winds with a 16 * 16 array of visible channel data, this will have the effective resolution of an 8 * 8 array of IR data. It should be borne in mind that, even if the semi-transparency correction and tracking are performed with a 16 * 16 array, significant processing will still be carried out on a 32 * 32 array, specifically the histogram interpretation and the selection of the peak in the correlation surface used to guide selection at smaller scales.

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