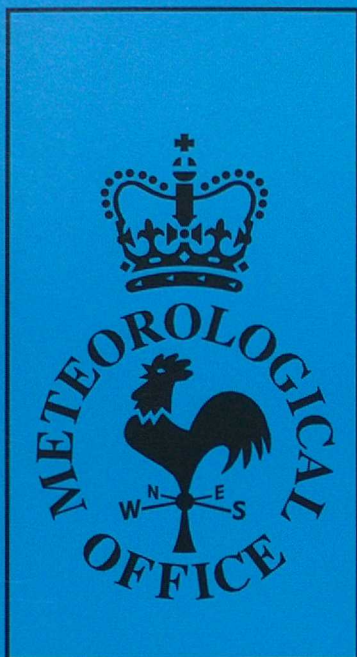


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# Forecasting Research

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Technical Report No. 209

## INVESTIGATION INTO SATELLITE WINDS- I. PRODUCTION

by

P Butterworth

February 1997

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# INVESTIGATION INTO SATELLITE WINDS —

## I. PRODUCTION

P. Butterworth, NWP Division, UKMO, Bracknell

### Abstract

Observations for input into the UKMO NWP model arrive continuously via the GTS. One particular type of observation is the satellite wind, calculated from a sequence of images produced by a geostationary satellite. This observation type has more commonly been thought of as a cloud-motion wind, given that the parameter it attempts to measure is that of wind speed at a particular height level calculated from the movement of clouds. The advent of satellite winds derived from water vapour, as well as infrared and visible channels, now means that clouds are no longer the only tracers able to be followed, and that the concept of a wind at a single level becomes even more blurred than previously. This report is the first of a set of three and was written in an attempt to become up to date with the techniques used by each of the current geostationary satellite wind producers, although methods are changing continuously. Part I — Production — outlines in detail the methods used by EUMETSAT in production of satellite winds from the different channels, with briefer descriptions of those used by the USA, Japan and India. Subsections on other remotely sensed wind derivations and current research in satellite-wind derivation are also included.

Part II looks at the current treatment of satellite winds at UKMO, including observation preprocessing, quality control, assimilation and quality monitoring. Part III assesses the current status and quality of satellite winds and includes recommendations for the improvement of their use within UKMO.



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# 1 Introduction

In order to specify the current state of the atmosphere and predict its future state, knowledge of the flow field, as well as the mass field is essential. The advent of geostationary satellites, with their ability to monitor a constant region of the earth, provided the opportunity to observe the motions of atmospheric features over constant time intervals and thus derive a representative atmospheric motion vector for that location and level. Initially, the features tracked were clouds, but recent advances have enabled the tracking of features in other channels, e.g. regions of high contrast in water vapour absorption channels. However, it must be borne in mind that any tracers used in this derivation are not necessarily passive tracers and are not always



representative of the mean atmospheric flow, for example, tracers in the tropics are predominantly convectively driven and stationary cloud is tied to surface features. For the purposes of this report, we shall refer to the derived vectors as satellite winds. Many assumptions and errors are inherent in application of this technique and so satellite winds must be used with care and their quality monitored to ensure that assimilation of these winds into numerical weather prediction (NWP) models results in a positive impact. Even so, satellite winds are indispensable at low latitudes, where winds cannot be inferred from the mass field, and are a crucial source of observational data in the southern hemisphere, where satellite winds are often the only source of wind data over wide regions. Despite the good coverage of other observation types in the northern hemisphere midlatitudes, positive impact from the use of satellite winds is also seen in these, as well as more data sparse regions (e.g. Graham and Anderson, 1995; Bader and Graham, 1996, and references therein; Ottenbacher *et al.*, 1996; Tomassini, 1997).

This section of this report outlines the methods used to infer satellite winds from the infrared (IR), visible (VIS) and water vapour (WV) channels of geostationary satellites. A detailed description is given of the techniques used to infer satellite winds from the Meteosat satellite operated by EUMETSAT, followed by broader outlines and differences in the techniques used by the other, currently operational, satellite wind producers: GOES (USA), GMS (Japan) and INSAT (India). Derivations of satellite winds based on information other than satellite imagery data are briefly outlined in section 6.

## 1.1 Basic extraction scheme

Most wind extraction schemes follow a similar procedure, with slight variations in the techniques used in each of the steps. Figure 1 shows a schematic of the procedure, which is outlined as follows:

- *Tracer selection*: where the dominant scenes (consisting of a certain number of pixels) in an image segment are selected (manually or, more likely, automatically). Note that, for example, in the case of WV imagery, some use can be made of the whole image, rather than selecting a particular scene.
- *Image filtering*: the scene selected is then enhanced (or filtered) in some way in order to make the matching of the scene with an earlier or later image segment easier.
- *Feature tracking*: the feature within the filtered image has then to be tracked (usually within three successive images) in order to determine a displacement vector for that feature.
- *Height assignment*: the height at which the feature in the observed scene is situated must be determined in order to place the derived displacement vector at the correct horizontal level. This step may take place before the derivation of the displacement vector.



- *Quality control*: generally takes place continually throughout the above process, culminating in final automatic and/or manual quality checks.
- *Monitoring statistics*: are produced after the distribution of satellite winds and are used as indicators of the quality of the vectors derived from geostationary satellites when compared with each other, other forms of observations (e.g. radiosonde, aircraft) or NWP model fields.

## 2 Meteosat Retrieval Scheme

### 2.1 Introduction

Meteosat, positioned at 0° longitude, is operated by EUMETSAT. The spin scan radiometer onboard Meteosat observes the earth in three channels: 0.4–1.1  $\mu\text{m}$  (VIS), 10.5–12.5  $\mu\text{m}$  (IR window region) and 5.7–7.1  $\mu\text{m}$  (WV absorption band). Images are produced every half-hour, and the spatial sampling at the sub-satellite point is  $2.5 \times 2.5$  km for VIS, and  $5 \times 5$  km for the IR and WV channels. Segments of  $32 \times 32$  pixels are used to extract the satellite winds, which then sets the discretisation for the areal coverage. The region of computation now reaches 60° N,S (extended from 55° from 6 January 1997). Most satellite winds are currently reported on the GTS in satob format, which gives speed and direction for the observation. The direction is given in increments of 10°. Satellite winds are derived four times per day, at 0500, 1100, 1700 and 2300 UTC from three successive half-hourly images, with the production time being the middle image of the three. In conjunction with the images retrieved, forecast data are needed as ancillary fields for the purpose of radiative forward calculations and quality control. ECMWF forecast data are used.

Details of the physics involved in the operational procedure of deriving satellite winds from Meteosat images are given in Schmetz *et al.* (1993), and summarized in the following. The changeover in operations from ESOC to EUMETSAT (November 1995) also involved an update of the extraction procedure; details are given in Buhler and Holmlund (1993) with more up-to-date information in EUMETSAT (1996a).

The method used is fully automatic apart from a final manual quality check for certain satellite winds before the winds are disseminated on the GTS.

The concept of the new EUMETSAT modular technique for incorporation into the MTP/MPEF (Meteosat Transition Programme/Meteorological Products Extraction Facility) is that images are received, rectified and segmented, and forecast observations and data accepted outside the satellite wind scheme; these data being made available to product-processing schemes other than that for satellite winds (see Fig. 2). This includes the multi-channel cluster extraction and the correction of the semi-transparency effect (see later). Then, within the satellite wind derivation scheme, cluster processing, tracer selection, height assignment and wind component extraction takes place for all three channels simultaneously, followed by combination of components from the different images to the raw satellite wind products for one time slot, and then automatic QC. These intermediate satellite wind products could consist of potentially contains three winds per geographical location. Finally, the best



wind per geographical location is selected. Outside the MPEF processes, manual QC takes place, which has available the entire image information of all the products, enabling cross-checks to be made for verification. This is then followed by product encoding and distribution.

The satellite wind scheme itself is an evolution of the previous operational method, but the increased modularity allows for several improved processing solutions and future implementation possibilities. A slot-by-slot concept for real-time wind extraction is in use. This allows the most computationally intensive process — the correlation — to be spread over the imaging slot duration time.

## **2.2 Infrared channel imagery**

### **2.2.1 Tracer selection**

The first obvious, but crucial step, is the correction and rectification of the raw data; the images must be accurately aligned with each other, otherwise movement can be assigned to a tracer where none exists. A multispectral image analysis (Tomassini, 1981) then extracts the dominant scenes in a segment consisting of  $32 \times 32$  IR pixels (the new modular EUMETSAT method has the potential to alter the sizes of the target and search areas); this provides a statistical description of the elementary scenes. The scenes can be sea, land or cloud at different heights, but no more than four different scenes plus one surface scene in any segment can be selected, the number being reduced by merging close scenes. About 1900–2300 out of a possible 3500 segments per full disc image are generally selected with cloud tracers from IR imagery and thus used for automatic tracking. The coldest cloud cluster in the segment is selected as the tracer.

### **2.2.2 Image filtering/enhancement**

The general technique of image enhancement is: (1) take a segment of the original IR image; (2) plot an IR histogram of the pixels in the segment (frequency vs radiance) and identify any discernible peak; (3) produce a spatial coherence plot of the IR counts (local standard deviation, SD, vs local mean of  $3 \times 3$  pixels).

The upper cloud layer is generally the tracer of interest, and so radiance filtering is required to enhance the upper-level cloud. This consists of the transformation of the IR scene through different filter functions before performing a cross-correlation operation between successive images. The objective is to reduce, or mask, the contribution of the surface and of clouds other than at the highest level. For one or two layers of clouds present, the masking of pixels combined with histogram modification is used. Considering the IR count histogram of a particular segment, some pixels are classed as "too cold" and are masked; these are considered to come from an even higher cloud layer than that being assigned as tracer, in the first instance. If the highest cloud layer has already been analysed, and interest is now focussed upon the second layer, they obviously belong to the previously analysed layer. Pixels that are "too warm" are smoothed and set to a constant value, as they have no information to provide



about the cloud tracers. Between these extremes, processing differs depending upon the number of layers detected during the image analysis. In all the filter functions, the IR count diagram is divided into different domains, whose boundaries are retrieved from the image analysis results (e.g. mean count, upper and lower boundary cluster counts).

One of the filter functions uses the spatial coherence method (SCM), introduced by Coakley and Bretherton (1982) and further described with application to Meteosat satellite winds by Hoffman (1990). The local SD of every IR pixel count of an image is plotted against its local mean, and analysis is carried out for the bidimensional diagram that is produced. A particular scene, for example, may consist of an arch-shaped scatter that links two groups of low SD clusters, with warm and cold "feet". This would be a typical signal for a high-cloud layer over the desert, where the two low SD clusters correspond to the most homogeneous pixels viewed, i.e. mainly over the cloud (cold) or mainly over the desert (warm). The intermediate values can be considered to be pixels viewed over mixed scenes that give higher SDs. Since representative counts can be assigned to the cold and warm areas, an equation can be derived that assigns a particular cloud cover amount for every pixel.

A scene will be rejected and not assigned if (1) four or more scenes exist in a target area and each scene comprises more than 150 pixels or (2) the two highest clouds both undergo altitude correction in the form of the semitransparency correction (see later). On average, 6–8 % of medium- or high-level tracers are rejected. The filtered image (uncontaminated scene) is then used for tracking.

### 2.2.3 Height assignment

This is usually based on the IR cloud brightness temperature of the cloud tracer, where the designation is usually a high cloud for pressures less than 400 hPa, and low cloud for pressures greater than 700 hPa. Using ECMWF forecast temperature profiles, the pressure level of a satellite wind is placed at the level where the brightness temperature fits the forecast temperature; thus a vector is assigned to the cloud-top altitude (IR window technique). The height assignment of low-level clouds is now based on the cloud-base technique (Le Marshall *et al.* 1994), whereby determination of the cloud temperatures associated with various levels within the cloud is achieved by fitting Hermite polynomials to smooth raw histograms of brightness temperature. This allows estimation of cloud-base altitude from cloud-base temperature, by assuming that the temperature difference between cloud top and cloud base is twice the difference between cloud top and modal cloud brightness temperatures. Thus cloud top temperature and altitude can also be retrieved by this method.

The assumption in the IR brightness technique is that the clouds move with the wind at the cloud top, which is obviously not always the case. Low-level cumulus travel with the wind at the cloud base and modification of the method has taken this into account. The new MPEF scheme corrects the height for atmospheric absorption (which the old procedure did not), making a significant difference for low-level clouds. Even if a perfect retrieval of brightness temperature to height could be achieved, the radiation perceived is more representative of a layer of atmosphere, rather than one



particular level (particularly for an optically thin cloud). Therefore the brightness temperature is actually related to a layer, rather than a defined height corresponding to the cloud top.

It is readily apparent that the assignment of satellite wind height is an inexact procedure and a significant source of error in the automatic procedure for determining satellite winds. A large error can result from the effects of semitransparent or sub-pixel clouds, since the IR radiance contains contributions from below the clouds, and so a satellite wind would be assigned to too low a level. Many solutions have been put forward to try to solve this dilemma, notably multichannel observations, and CO<sub>2</sub> slicing (Smith and Platt, 1979), where radiances from different layers of atmosphere are ratioed to infer the correct height.

In the EUMETSAT procedure, simultaneous IR and WV images are used in a method called 'semitransparency correction' (Bowen and Saunders, 1984). It is conceptually correct for subpixel opaque clouds and broken clouds but not for horizontally extended clouds of varying optical depth. The method requires radiance pairs in the two channels for clear and cloudy sky, and is based on the fact that the radiances for the two spectral bands vary linearly with cloud amount. The relationship between IR and WV radiances for opaque clouds at different levels is computed with radiative forward calculations using ECMWF temperature and humidity forecasts; this is conducted in real time for both channels. Measured and calculated radiances should agree for clear and fully opaque cloud conditions. The cloud-top height for semi-opaque clouds is inferred from the linear extrapolation of measured radiances onto the opaque cloud calculations. Subsequently, however, the combined use of radiance calculations and observations requires an accurate calibration for linking the two measurements, since the observed radiances are measured in counts and not physical units. Therefore, the process is highly dependent upon the calibration.

Studies have been conducted into the relative quality of different height-assignment techniques. Eyre and Menzel (1989) used simulated data in assessing the performance of a cloud-top height assignment method (the 'minimum residual' method) using different combinations of spectral channels, including one to simulate the Meteosat method, and the CO<sub>2</sub> slicing technique. All algorithms performed well for high cloud, but the Meteosat method degraded faster as cloud amount decreased. The Meteosat method was the worst of the four methods at determining medium-level cloud-top height, with the authors' method the best, although none performed as well as for high clouds. All methods gave poor results for low cloud, but the authors' method and the CO<sub>2</sub> slicing technique performed best at large cloud amounts, with the latter giving better results at small cloud amounts.

In their study, Nieman *et al.* (1993) used real data from GOES-7, since IR, WV and CO<sub>2</sub> channels were all available. The IR brightness temperature technique was found to be adequate for opaque cloud levels, and the H<sub>2</sub>O technique to be a viable alternative to the CO<sub>2</sub> slicing technique for instruments where no CO<sub>2</sub> channel exists. On a given day, the two latter approaches compare to within 60–110 hPa rms, with the H<sub>2</sub>O method generally retrieving greater heights. The caveat was that the H<sub>2</sub>O technique did not work very well in dry atmospheres, so that CO<sub>2</sub> slicing was to be preferred for cases where a CO<sub>2</sub> channel was available.



A different method of height assignment, but one that is in only limited use, is to determine the height of tracers stereographically, using the common region simultaneously seen by two satellites. Despite the current coverage limitations, Shenk (1991) considers it to be the most accurate method (especially during daytime using the VIS channel). Since the different cloud layers can be easily separated, the high resolution of VIS means that small clouds can be followed and the stereogeometric measurement avoids temperature ambiguities. Purdom and Dills (1993) also recommend the use of stereographic techniques and describe ways in which time-adjusted stereo could be used to infer heights. However, there is no consensus on this method since the error in height assignment is dependent on the horizontal resolution of the satellites in question, and thus may not give better results than the brightness temperature technique.

#### 2.2.4 Cloud tracking

Automatic cloud tracking uses a cross-correlation technique, whereby three successive images are used to determine a displacement vector. An initial  $32 \times 32$  pixel segment is chosen as the target area, and the cross-correlation is performed at times  $t - 30$  min and  $t + 30$  min in search areas that contain  $3 \times 3$  segments. This leads to a possible  $65 \times 65$  displacements. Tracking now involves a multiple-correlation-peak search where a set of relevant peaks are selected. The search used to start at a location suggested by a wind forecast, but recent modifications to the method have removed this model dependency. The new method also has the potential to alter the sizes of the target and search areas.

Within a particular segment, there may be a number of peaks selected to indicate tracers, and two wind speed components are generated for each. The final tracer is selected based on the best match between the speed components, with quality marks for the components carried over to give a quality mark for the combination of the final wind speed. In the case where a cluster is tracked in more than one channel, this process will identify these multiple winds and keep the best-suited one, using the height information and the extraction quality marks.

The computations are performed only at alternate displacements (i.e. at half resolution), with a complete computation being performed around the maximum found by the first coarse correlation surface. A second vector is produced using the second and third images, although in this case the search area is only a quarter of the search area in the first step. Thus two vectors can be deduced from the movement of the clouds between the successive images, however these must agree within certain limits in order to be accepted (symmetry check). Satellite winds  $< 5$  m/s are suppressed at low levels, which eliminates directionally inconsistent wind fields due to any image registration error. It also has the effect of removing stationary clouds produced by topographic forcing, which would not give an indication of the local wind field.

The final displacement speed is calculated as the mean speed of the vector pair produced; the final direction is computed from the vector sum.



### 2.2.5 Quality control

Automatic QC (AQC) has been heavily revised since the changeover from ESOC to EUMETSAT; each of the processes that participate in producing the final product also generate one or more quality marks, which are a measure of the confidence in the resultant wind. The AQC process gathers together the individual marks and combines them to produce a global processing mark. A battery of consistency checks are then performed, each in turn generating a mark. The AQC process then assigns a final quality indicator to the product together with the decision flag (passed/rejected), but all products are made available for the manual QC.

Quality marks are generated at several stages of the retrieval procedure:

- image filtering
- pattern matching
- speed  $< 5$  m/s
- symmetry check
- final automatic quality control (QC)
- final manual QC (also allows for possible reinstatement)

The above stages can be separated thus:

Processing quality marks are assigned for every relevant peak (up to three) that have been identified in the correlation surface:

- tracer entropy and normalized tracer size in target area
- correlation coefficient value of the peak
- number of non-masked pixels used at the correlation peak
- means of the target and search areas at the correlation peak
- standard deviation, min and max gradients of the correlation surface in the peak area

The above marks apply to each wind component. When the components are combined, marks equivalent to the above are generated by combining the marks for the components. A new set of quality marks is also generated, based on the comparison of the two (or more) components:

- wind components' direction consistency



- wind components' speed consistency
- wind components' correlation consistency
- wind components' height consistency

Consistency quality marks are given for comparison with, typically, forecast information at the same spatial and temporal location; satellite wind products extracted in neighbouring segments at the same time and pressure; and the previous satellite wind product for the same segment at the same pressure level. The consistency marks generated are:

- forecast consistency mark
- spatial consistency mark
- temporal consistency mark
- product height consistency mark (removed 29 April 1996 since investigations showed that this test did not contribute significantly to the overall AQC mark)

The AQC finally computes a weighted sum of this information and generates the satellite wind product quality indicator, with a final threshold applied for pass/reject. The above satellite wind method for MPEF was presented in 1993, and was implemented in November 1995, however ongoing changes to the method are being made continually in order to achieve the best product possible. Research is ongoing in the fields of quality control and height assignment.

The marks for the AQC tests are combined with different weights to form a normalised quality mark. The overall threshold is around 0.7, but has been revised both upwards and downwards in order to optimise the quality/coverage of the winds supplied. The quality penalty for high-level WV winds was removed in May 1996; this significantly increased the total number of high-level winds in the disseminated product without degrading the quality. This increase in total number was accounted for by a substantial increase in high-level WV winds, and a decrease in high-level IR winds.

At the final stage, the satellite winds are examined by an experienced meteorologist, who can delete or reinstate any satellite wind. Reinstatement generally occurs in the tropics, particularly as a result of incorrect forecast fields (the use of forecast fields, especially in the tropics, should be treated with care). After QC about 8 % of the winds remain for dissemination (Leighton, 1996), and are produced approximately 2 h after the last image scan.

#### **2.2.6 Quality monitoring**

One way of judging the quality of the satellite winds is by comparing the results with colocated radiosonde measurements (e.g. EUMETSAT, 1996b) on a daily basis,



and computing monthly mean statistics. The thresholds for colocation are 1.5 h, 25 hPa, 150 km. The average speed difference is calculated and produces a mean velocity bias inherent in the satellite winds (provided one assumes the radiosonde produces an unbiased measure of velocity). The root mean square vector difference between the satellite wind and the radiosonde measurement is calculated which gives a relative measure of satellite wind error, since errors also exist in the radiosonde measurement. It also contains the differences due to separation in time and space between the two measurements; this may sometimes be the dominant error but can be estimated. The satellite wind error still contains the vertical separation error between the satellite wind and the radiosonde, since this is considered to be a consequence of the height-assignment technique used.

A common feature of all the satellite winds produced is that there exists a slow bias for high-speed high-level winds, most noticeable at jet stream locations. This bias was seen to be a linear function of wind speed, and a reduction in this bias generally taken as a sign of improvement in the wind derivation. However, Holmlund *et al.* (1993) note that as the quality of the satellite winds increases, this linear dependence is not as pronounced as before, which they consider to be some indication of the differences in scales and nature between the radiosonde winds and satellite winds.

A particular problem with using radiosondes to judge the quality of satellite winds is that radiosondes are point measurements, whereas satellite winds are more indicative of a spatial and temporal average. An alternative way of quality monitoring is to compare the satellite winds with a model first-guess field ( $T + 6$ ). This method is particularly useful for global monitoring due to the scattered nature of radiosonde measurements, and also model fields are more representative of an "average" state. However, there is a drawback in that the model field itself was produced with the benefit of satellite wind data, and so a doubt arises as to whether the judgement is sufficiently independent. Strauss (1991) gives details of ECMWF monitoring results, and quarterly reports are produced. UKMO monitoring procedure is outlined in Part II and representation of current quality in comparison with a Unified Model background field given in Part III.

### 2.3 Water vapour channel imagery

The WV channel is already used in satellite wind retrieval, in the semi-transparency correction applied to optically thin or subpixel clouds. However, recent years have seen the testing and operational use of satellite winds derived from WV images. We will denote these as WV winds. Holmlund *et al.* (1994) provide an overview of the different methods of wind vector extraction using the different channels. WV winds can be used as complementary data for the IR satellite winds in regions where clouds are present or as an isolated dataset where there are no clouds and thus no IR satellite winds. The former are now output operationally on the GTS, with the latter destined to be disseminated from January 1997 on the GTS in BUFR code. The winds are disseminated four times a day at the main synoptic hours.

UKMO started to assimilate cloudy WV winds in January 1996; EUMETSAT consider the cloudy WV winds to have achieved comparable quality with the IR satellite



winds (Holmlund *et al.*, 1994), while having a greater spatial coverage. Laurent (1993) outlines the advantages of tracking using WV targets: (1) tenuous cirrus clouds are easier to detect in the WV channel, (2) cloudy areas apparent in the IR are extended by slightly cloudy or very moist areas, providing a large number of WV vectors and (3) the use of an absorption channel masks the background radiance and thus implicitly provides radiance sliced image data. It should be mentioned here that high-level WV winds are always cloudy WV winds.

### 2.3.1 Tracer selection and tracking

Tracer selection is again based on a multispectral image analysis. Tracking for WV winds on the GTS in SATOB code is performed, at present, only in segments where medium- or high-level clouds are present, but only WVV's derived at levels above 400 hPa are currently considered for dissemination (January 1997). The coldest cloud cluster is selected as the tracer. No image enhancement is employed, because the nature of the WV weighting function provides a natural filtering of low-level clouds. Tracking is performed in the same manner as for IR satellite winds: three successive images are used, with cross-correlation performed to match the tracer between images. Full resolution image data are used. Overall, the tracking of moist/cloudy features in the WV channel provides a much better spatial coverage of high-level vectors than the IR channel due to its higher sensitivity to high altitude cloud and moisture.

### 2.3.2 Height assignment

The WVV height-assignment scheme was changed upon the move to MPEF. It used to be based upon the IR cloud brightness temperature, which worked well in regions where high clouds were present. For other scenes, the height was corrected by an approximation of the moisture content above the highest identified scene. WVV heights are now based upon the WV brightness temperature for the coldest scene. The semi-transparency correction is also used. This method provides similar heights in high-cloud areas to the old scheme, but a more stable height in areas where no high clouds are present.

Buche *et al.* (1994) investigated the height assignment of WV vectors, discussing ways based on either the effective brightness temperature taken from the measured radiance or on the contribution function calculated from atmospheric profiles (with the height taken at the level of the maximum). The latter method makes an appropriate definition of the effective site of a tracked structure, and runs a forward radiative transfer model which calculates the transmittances, the contribution functions and radiances for that scene. Inversion of the radiances produces effective brightness temperatures, and heights can be assigned based upon the atmospheric profiles, the maximum of the contribution function and a formula based upon the sum of the contributions below the maximum. Note that this method does not make use of radiances measured that coincide with the WV imagery. Buche *et al.* concluded that no single method appeared to give a better result than the others. Since WV winds are implicitly derived from a layer of atmosphere, then attempts to fix a single-level height to a WV wind must invariably be flawed. Thus regardless of the method used



to do this, there cannot be a correct answer to this problem.

### 2.3.3 Quality control

Quality control is now uniform for all three channels. The QC tests are now continuous functions rather than definite filters, and they all return a reliability assessment between 0 and 1. The final quality is a weighted mean of the individual qualities, and is used to determine which vectors are of acceptable quality for dissemination.

### 2.3.4 WVWs in cloud-free areas

EUMETSAT are planning to disseminate WVWs in cloud-free areas in January 1997 in BUFR format. In cloud-free areas, wind vector information can be derived from the structure of the WV images. However if the feature tracked is just water vapour, then the vertical depth is determined solely by the  $6.3\ \mu\text{m}$  water vapour weighting function. This means that the winds produced represent the displacement of a layer as deep as 300–400 hPa. More vectors can be produced by tracking features in WV images in regions where there are no cloud tracers, and the quality is expected to be comparable to the operational cloudy WV winds (Elliott and Holmlund, 1996).

Buche *et al.* (1990) evaluated the wind vectors produced by cross-correlation not only of the images but also the matrices generated from analysis of the first and second-order derivatives of the main curvatures. They found that the resultant vector field matched radiosonde values at the 500-hPa level, although a larger segment size ( $48 \times 48$  pixel) was used due to the shallower structure of WV images. More vectors can be produced using this method, however a slight loss of quality results.

Lunnon *et al.* (1994) described a method of WV wind production in clear air at higher resolution target image ( $16 \times 16$  pixel), compared with a  $80 \times 80$  search image, over northern Europe. In the western part of the domain, winds were produced on a regular grid, whereas in the east they were produced to coincide with radiosonde locations. An ellipse was produced with each wind, which specified the confidence one could have in the different components. They also described the derivation of a wind weighting function, which would give information on the contribution of winds at different levels to the derived wind vector. It was dependent on the horizontal gradient of the radiance weighting function, and could be derived from a two-dimensional distribution of temperature and humidity (Lunnon and Gairey, 1993). They found that winds derived for segments that exhibited two peaks in the statistical distribution of radiances were particularly reliable, when compared with radiosonde data, since this corresponded to a sharp feature in the WV radiances, making tracking more reliable.



## 2.4 Visible channel imagery

### 2.4.1 Half-resolution VIS winds

Visible winds are currently produced by EUMETSAT and are derived from a triplet of VIS data at half the resolution of the VIS channel (corresponds to the resolution of the IR and WV channels) and placed on the GTS in SATOB format (Holmlund *et al.*, 1994).

#### *Tracer selection and tracking*

Tracer selection is the same as for IR satellite winds, however VIS winds are used only to extract low-level winds, and so these winds are only tracked in regions where there are no high- or medium-level clouds. Image enhancement is not required since the tracking is only performed for low-level clouds over sea, which results in selection of marine stratus and stratocumulus. There is a scarcity of good tracers over the continents, possibly due to short-lived tracers and lack of contrast over land.

#### *Height assignment and quality control*

Height assignment is performed using the IR radiance of the low-level cluster with the highest entropy (Rattenborg and Holmlund, 1997). Quality control is as described for IR channel winds.

### 2.4.2 Full-resolution VIS winds

Full-resolution VIS winds went operational in November 1996, but only in BUFR format. The resolution of these winds is about  $80 \times 80$  km at sub-satellite point. Yield is increased through the better spatial resolution of the VIS images and a better contrast between cloud and ocean surface, which effectively leads to an increase in wind vectors by a factor of six over corresponding IR winds (Ottenbacher *et al.*, 1996). These winds are disseminated five times per day at 6, 9, 12, 15 and 18 UTC. A full description of these winds is given in Schmetz *et al.* (1997).

#### *Tracer selection and tracking*

A multispectral image analysis (Tomassini, 1981; Schmetz *et al.* 1993) extracts the dominant features in an image segment only if the segment is over the sea and low clouds at altitudes below 700 hPa have been identified. Tracking is very similar to that in IR imagery: a fully automated cross-correlation technique is applied. As for IR tracking, a target area of  $32 \times 32$  VIS pixels is moved in a search area of  $96 \times 96$  VIS pixels in order to find the best match between images.

#### *Height assignment and quality control*

Height assignment is the same as for half-resolution VIS winds. The observed brightness temperature is also corrected for the WV absorption above cloud top. This can give an increase in temperature of up to 1–2 K in the tropics, i.e. a lowering of height of up to 40 hPa.

High-resolution VIS winds are subject to symmetry and internal consistency checks and a final rough check against a short-term forecast. The quality control is fully automatic; VIS winds undergo no final manual quality check.



Assimilation of high-resolution VIS winds at ECMWF showed the mean vector RMS difference versus verifying analysis at 850 hPa to be 1–2 m/s over the whole area, with the largest local difference over the South Atlantic; a difference that corresponded to up to 15 % of the mean wind speed (Ottenbacher *et al.*, 1996). The impact on the 24-h forecast was less pronounced, but the assimilation of high-resolution VIS winds gave a small positive impact. It was suggested that the VIS winds would have larger impact at times when forecast model performance was poor.

## 2.5 Quality of the derived wind fields

A number of papers exist which monitor the steady improvement in quality of satellite winds over recent years with regard to the modifications made to the retrieval scheme (e.g. Woick, 1991, 1994; Schmetz *et al.*, 1993). These are written by both wind producers and users. Thoss (1991) also showed the impact upon numerical weather forecasts at the ECMWF. She found that the quality of satellite winds was satisfactory for all height levels in the tropics and for low-level data in all regions; and that the slow bias in high-level satellite winds differed with satellite.

Holmlund *et al.* (1994) produced some statistics for the WV winds (high level) and VIS winds (low level) in comparison with the IR satellite winds derived at equivalent heights. In their study, WV winds show a smaller bias than high-level IR satellite winds, but greater rms error and rms vector difference. The overall WV wind statistics appear slightly worse than the satellite wind. However, the statistics turn out to be equivalent if comparison is made in the same geographical regions. The two sets have significantly different areal coverage in the tropics, where more than three times as many WV winds are produced as IR winds. Elsewhere, there are only slightly more WV winds than IR winds produced. The apparent difference in quality could be due to the fact that cloud displacements in convective regions are generally not representative of the local wind flow, and so the WV winds suffer unduly in the statistics due to their greater representation in the tropics. Another possible reason is that a lack of manual QC for WVWs produces lower quality winds.

Woick (1994) outlines changes to the IR and WV wind schemes, and assesses the impact of these changes on both methods of retrieval. He chooses to base his comparisons for both against radiosonde data, so that a direct comparison of the two methods can also be achieved. The WV wind speed bias against radiosonde winds was reported as being close to zero, with the rms vector difference about 0.8 m/s greater than for IR satellite winds.

Low-level satellite winds appear not to have improved so much over the years (Holmlund *et al.*, 1994), since most modifications have been geared towards improving high-level winds. However, the most recent modification at EUMETSAT (September 1996) was designed to increase coverage and quality of low-level winds. Comparison of IR winds with VIS winds showed that VIS winds have a similar bias, but greater rms error and rms vector difference. Laurent (1991) found that use of the VIS channel at low resolution improved the tracking of low-level clouds, and sometimes provided



wind observations over land. He found the main area for improvement being in the identification of the tracked structures. However, full-resolution images produced a greater number of tracers over the ocean at low levels, allowing for better tracking of smaller structures, and hence a better resolution of the low-level circulation.

Fujita (1991) estimated using GOES data that the tracking accuracy of satellite winds was 1 m/s or better, with the reported higher errors being due to inaccurate height assignment and particular tracer types being studied. Fujita (1991) also suggested that stereoscopic height assignment was the most accurate method, if available, and recommended the use of rapid-scan imagery (5–10-minute intervals) to achieve errors of 1–2 m/s in the derived satellite winds. Purdom (1996) also demonstrated the increased yield of satellite winds from GOES when time intervals between consecutive scans were reduced to 30 seconds.

Overall, the changeover in wind extraction procedure from ESOC to EUMETSAT resulted in far fewer winds being distributed on the GTS, partly as a result of the 'best wind' policy, and there was a corresponding fall in quality. Since November 1995, EUMETSAT have been continually adjusting their method in order to achieve better quality winds with more vectors distributed.

### 3 GOES Retrieval Scheme

NOAA/NESDIS currently operate two geostationary satellites: GOES-8 (or GOES-E) at 75° W and GOES-9 (or GOES-W) at 135° W. GOES satellites do not scan the full disk in one sweep; they monitor the area in fixed regions, and do not even scan the entire disk, so that more frequent images can be taken of the USA. Winds that are eventually disseminated on the GTS are on a lat/lon grid, extending as far out to 60° N and 50° S. Winds are reported as speed and direction, with the direction being given in increments of 5°. Winds are currently produced four times daily, but plans are in hand to produce winds every 3 h. The three-axis stabilised GOES satellites makes manual registration corrections of the images necessary, however an automated system is under testing to deal with this (Nieman *et al.*, 1997). These investigations show that the registration error, if uncorrected, could lead to a wind speed error of 2 m/s. Even though automatic correction is shown to be successful, problems will still arise in the GOES-9 southern hemisphere sector due to the lack of cloud-free land to fix navigation.

#### 3.1 Infrared channel imagery

In 1992, an automated system was introduced to extract satellite winds from GOES images. The previous technique had been highly interactive. Suitable tracers were automatically selected based on a local gradient of brightness around high values, with targets being selected where a gradient was large enough and not too close to another target. This led to a coarse grid. Heights were assigned using several methods, the CO<sub>2</sub>-slicing method being used for semitransparent features. (As one moves through successive channels to become closer to the centre of the 15  $\mu$ m CO<sub>2</sub> absorption band,



the lowest clouds disappear in successive images, allowing for more accurate height assignment.) Tracking was automated using the auto-correlation technique (Merrill *et al.*, 1991), and an automatic QC procedure was established. The final step involved manual editing (insertion and/or deletion of winds).

In 1994 further changes to this system became necessary due to the lack of a CO<sub>2</sub> channel on the current series of GOES satellites (-8, -9; Nieman *et al.*, 1996); the semi-transparency correction procedure is now a variation on that used at EUMETSAT — H<sub>2</sub>O-intercept height assignment.

At the same time, tracer selection was enhanced using an initial brightness check to filter clouds at certain levels and then followed by spatial coherence analysis (Coakley and Bretherton, 1982), with only two coherent signals allowed: multi-deck scenes are discarded, as are scenes that are too coherent. Tracking is automated using a covariance minimization technique.

The new system is fully automatic using an auto editor to perform two distinct functions (Hayden *et al.*, 1993) — first it considers the possibility of altitude re-assignment of the satellite wind and then it provides a quality flag. In the height reassignment, each satellite wind is 'best-fit' to the initial analysis (background) by vertical movement and minimizing a function dependent on cloud temperature, pressure and vector. In this formulation, a velocity discrepancy of 2 m/s is equated (and constrained) to a pressure reassignment of 100 hPa or a temperature change of 2 K. The auto editor also involves a tropopause check to avoid reassigning heights to stratospheric values. The new procedure contains a correction for the slow bias of satellite winds, by incrementing each vector with 7 % of the speed of the forecast, interpolated to its reassigned level, provided that the forecast wind speed is greater than 10 m/s. Nieman *et al.* (1996) consider this correction to be "no different from the bias corrections routinely applied to radiance measurements to achieve agreement with forward calculations".

Quality control is now fully automated, the basic tool of the auto editor being 3D recursive filter objective analysis. A recursive filter flag (RFF) is obtained by using a threshold value to determine which data are not passed to the user. This also has been improved and is appended to each datum following analysis.

### **3.2 Water vapour channel imagery**

Water vapour winds are produced similarly, and have been so on a daily basis for GOES-8 since 1994. However, the new tracer selection procedure is not used since clear air targets in areas of relatively weak water vapour gradients are desired (Nieman *et al.*, 1996). This means that most WV winds are produced in clear air in order to supplement the winds produced in cloudy areas. Unlike current EUMETSAT processing, NESDIS does not distinguish between cloudy and cloud-free areas in the disseminated winds. A water vapour brightness temperature comparison scheme is used for height assignment, although these are susceptible to reassignment by the auto editor (Hayden *et al.*, 1993). Again, the method is fully automated.



### 3.3 Quality monitoring

Monitoring has shown (Nieman *et al.*, 1996) that this latest version of automated satellite wind has yielded significant improvement for GOES-8 winds in comparison to GOES-7. WV winds produce a bias comparable to IR winds while the vector rms error is greater by 0.5–1 m/s. The WV winds have been operational since May 1996, and typically produce over twice as many vectors as IR winds for the same level.

Hayden *et al.* (1993) conducted a comparison experiment in the overlap region between the Meteosat and GOES satellite and concluded that GOES-7 IR winds were the best product, with Meteosat WV winds the worst, however they consider the results to be masked slightly since the accuracy of the winds mirrors closely the accuracy of the forecast used in derivation of the winds. However, the superior GOES-7 results they attribute to the height assignment method for GOES at that time (CO<sub>2</sub> slicing vs H<sub>2</sub>O height assignment).

High-resolution IR and WV winds are currently under development; these are produced by taking smaller search areas for wind production. They are expected to become operational when extra computer hardware is installed. It is planned that these will incorporate the automatic registration error correction software. CIMSS have also produced 'multi-spectral winds', by making use of GOES sounding channels. These winds can be derived over a particular area of interest, and are seen to be especially useful for the tracking of hurricanes due to the fact that 300 hPa winds are needed, and satellite winds provide almost the only source (Velden, 1997).

## 4 GMS Retrieval Scheme

GMS-5 went operational in June 1995 and is situated at 140° E. Satellite winds are produced by the Meteorological Satellite Center of the Japan Meteorological Agency and are disseminated on the GTS, with WV winds beginning transmission on March 1996. Wind vectors are produced on a latitude/longitude grid, and extend out to 50° N,S. They are reported as speed and direction, with direction being given in increments of 5° and are distributed in total four times per day. However, low-level IR and VIS winds alternate their time slots.

GMS-4 winds suffered from poor height assignment in semi-transparent cloud regions since it had no water vapour channel (i.e. only one IR channel) and had to rely on preconstructed tables. Although the sophistication of the tables increased throughout the years, this still provided a constraint on the quality of the winds, with GMS winds being far more scattered than GOES or Meteosat winds, which have the benefit of multi-channel height assignment techniques. However, GMS-5 has a water vapour channel.

### 4.1 Infrared and visible channel imagery

Low-level satellite winds are produced using the IR and the VIS channels alternately, from three consecutive images at 30-minute intervals (Takata, 1996; Tokuno, 1997).



Both manual and automatic tracer selection and tracking are used. In the automatic process, the IR brightness temperature is used for selecting the tracer. Tracking is conducted by a pattern matching technique. In the manual process, an operator selects and tracks suitable targets using display animation. Low-level satellite winds are produced automatically, while high-level satellite winds are derived through a combination of automatic and human-machine interactive processes.

For automatic cloud selection, grid points are prepared at intervals of one-degree latitude and longitude. The target area is a small area centred around the grid point, and a corresponding IR brightness temperature is assigned to each pixel in that area. A histogram is produced to obtain parameters concerning the cloud amount, thickness and cloud-top height. The altitude (high or low level) of the cloud is estimated, and whether enough cloud is present to continue with the procedure determined by comparing these parameters with threshold values. Using the difference between IR and WV brightness temperatures, areas containing cumulonimbus are excluded from the process.

The target area in the middle time segment is tracked, both forward and backward in time, using cross-correlation. Two successive displacement vectors are calculated, and if the magnitude of the difference does not exceed a threshold value, the later vector is adopted as the resultant wind.

As a result of statistical investigation, which revealed that the velocity of low-level satellite winds represents the atmospheric wind well at a pressure of 850 hPa, all low-level satellite winds are assigned to that pressure level. The height of semi-transparent cirrus is now estimated using the IR and WV intercept technique following the theory of Bowen and Saunders (1984), which it is hoped will reduce the load on the interactive procedure.

Objective QC includes a horizontal consistency check, a vertical shear check and comparison with NWP wind fields. Unreliable data are flagged and then assessed in interactive QC: the operator examines the resultant satellite winds and compares them with the movement of the target cloud in the animation. The interactive procedure also derives winds in data-sparse areas, and a quality check including reassignment of wind height is performed. Winds considered reliable are distributed on the GTS. Land/sea discrimination is performed, with no low-level tracers being extracted over land. Monitoring at UKMO (see Part III) indicate that there do exist GMS satellite winds over land.

## **4.2 Water vapour channel imagery**

WV winds are produced in essentially the same way as IR winds, but with no manual QC. Winds are derived automatically four times a day, from three 30-minute interval images. Target selection occurs if the lowest WV brightness temperature in the target area (32 lines by 32 pixels) is colder than a threshold value. Winds are produced both in cloudy and in clear-air regions. Due to the smooth nature of the WV fields, quality assessment of the WV data is conducted in the satellite wind extraction. Tracking is the same as for satellite winds, with the later vector being used after the symmetry



check. The height determined from the WV brightness temperature (lowest 10 % of the pixels) is assigned to the WV wind. Automatic QC checks consistency of speed, direction and height, with automatic rejection if considered unreliable. WV wind quality is comparable to IR satellite winds at high levels, but mid-level WV winds are of poorer quality than high-level IR winds.

### 4.3 Australian-produced winds from GMS

Real-time satellite winds every 6 hours using data from GMS are also produced at the Australian Bureau of Meteorology (Le Marshall *et al.*, 1993) for the Australian region, and are used in the local operational NWP system (Le Marshall *et al.*, 1994).

The system is automatic, using a triplet of images received from GMS and using areas of maximum brightness gradient for tracking. Tracking is carried out automatically using a local model first-guess field to initiate searching. A lagged correlation technique which minimizes rms differences in brightness from successive pictures is used to estimate the vector displacement. The height-assignment technique differs from that at JMA in that characteristics of the target area brightness temperature histogram and the forecast temperature profiles are used. Hermite polynomials are fitted to raw histograms of brightness temperature, which enables estimation of cloud-base altitude from cloud-base temperature using the model. Cloud-base and cloud-top temperature are assigned using properties of the smoothed data, with lower and upper-level cloud heights, respectively, being assigned those levels. Height assignments move progressively from the cloud base to the cloud top as one progresses from low to high cloud. The automatic QC, involving a speed symmetry check, correlation threshold, and a consistency check against the FG field, also includes a quality flag attached to the vectors. This error is assigned taking into account zonal and meridional wind speed tolerances, based on previous collocation statistics. The BoM system provides 400–600 operational wind vectors every 6 h. The BoM consider their locally produced winds to be invaluable in that satellite winds are available in time for model runs and have produced improvements in their local and global NWP models.

Additionally, test winds have been generated in real time on an hourly basis from IR and VIS imagery, and have been shown to have a positive impact on the NWP model (Le Marshall *et al.*, 1996, 1997). Full-resolution IR 5-km and for VIS image-based winds, full resolution 1.25 and resampled 5-km IR imagery has been used from hourly and half-hourly images. The test systems have several enhancements, such as correction or elimination of poor height assigned cirrus, and velocity testing which checks the level of best fit (Le Marshall *et al.*, 1997).

The satellite wind data also provide useful information for the bogusing of observations by their experts in MSLP charts (which is needed since NMC data do not reach Australia in time for their model runs). Such bogus surface wind information is input to the GTS, but are not used at the UKMO.



## 5 INSAT Retrieval Scheme

INSAT is situated at 74° E, and is operated by the India Meteorological Department. The IMD produces wind datasets on an irregular basis. Data from INSAT are used to produce satellite winds over the entire Indian Ocean, however at present the quality of the derived winds is not sufficient to allow inclusion into NWP models (e.g. Leighton, 1995). The method of operation and subsequent improvements are given in Gopala Rao (1991), Kelkar *et al.* (1993) and Bhatia *et al.* (1997).

Initially, satellite winds were derived only from VIS channels, with low-resolution (11 km) IR used for height assignment. The launch of INSAT-2 in 1992, with an 8-km resolution IR imager, has allowed the use of IR data for cloud tracking also. The segment area for possible tracer selection is  $14 \times 14$  pixels. IR image triplets are used, centred at 0 and 12 UTC, with tracking performed using the cross-correlation method on both visible and IR imagery. The height of the vector is assigned to one of three fixed heights, depending on whether the tracer is perceived from a temperature histogram to be at high, low or medium levels. Automatic QC is administered with a symmetry check (speed and speed-dependent direction limits), thresholding (speeds must be greater than 8 kts, but less than 50, 70 and 200 kts for low-, medium- or high-level clouds, respectively), and a consistency check with an NCEP forecast field, if available (with climatological values, if not) and then final manual editing. The IMD have found their satellite winds to be of great use in day-to-day synoptic analysis, particularly in relation to the monsoon.

VIS winds, centred at 6 UTC, have recently been produced operationally (late 1996) but on an erratic basis, to take advantage of the higher resolution (2.75 km) of INSAT 1D. They are assigned height on the basis of modal temperature in the central IR band imagery using forecast temperature profiles.

## 6 Russian and Chinese geostationary satellites

The series of geostationary satellites circling the globe is being extended. The Russian GOMS (76° E) meteorological geostationary satellite is currently in orbit, and plans are in hand to produce satellite winds.

A launch date in the first half of 1997 is planned for the Chinese FY-2 meteorological geostationary satellite. The Satellite Meteorological Centre in Beijing have already been testing, with GMS imagery, their extraction method, which differs from those of the major producers with respect to calculation of wind speed and direction, height assignment procedure and cross-correlation calculation in order to reduce computation (Xu and Zhang, 1997). Wind speed and direction are calculated using spherical coordinates. Height assignment is based on an arithmetic derivation of reflectances in both the IR and WV channels under certain conditions, and avoids the use of radiative transfer integration. A quick-search procedure is used to find the maximum correlation coefficient with the minimum of calculation.

It must be borne in mind that the satellite wind derivation techniques of all the



satellite-wind producers are constantly undergoing review and improvement, thus the techniques outlined above may not be exactly those that are in operation at the present moment. Unless the producers always notify the users of changes to the method used then it is always possible that we lag slightly behind in knowledge of the procedures being used. Consequently, we need to monitor the observations carefully to spot any major unnotified changes that may have significant impact on the performance of our model.

## **7 Other Wind Derivations**

Methods other than the monitoring of clouds and water vapour structures in satellite imagery exist for the remote determination of winds in the atmosphere; these are also considered as satellite winds. A brief outline is given here.

### **7.1 Scatterometer winds**

Ocean surface wind speed and direction swathe can be derived from, for example, the Active Microwave Instrument in scatterometer mode onboard the European Remote Sensing polar-orbiting satellites ERS-1 and ERS-2 (ERS-1 is scheduled to be taken out of operation in April 1997). This uses three antennae to generate radar beams looking 45 °forwards, sideways and backwards with respect to the satellite's flight direction. These beams continuously illuminate a 500-km wide swathe and each provides measurements of radar backscatter from the sea surface on a 25-km grid. The result is three independent measurements for each grid point, obtained using the three different viewing directions and separated by a short time delay. As the backscatter depends on the wind speed and direction at the ocean surface, it is possible to calculate the surface wind speed and direction using mathematically from the three measurements (ESA, 1995). Directional accuracy is estimated to be within 20 °, speed within 2 m/s or 10%. Spatial resolution of the resultant wind is 50 km.

The UKMO makes use of scatterometer data from ERS-2, and derives wind vectors from them. Weekly monitoring reports are produced for both ERS-2 UKMO- and ESA-derived winds compared against the appropriate 6-h global model forecast. Current monitoring shows an average of 600,000 observations weekly, with mean wind speeds around 8 m/s. Mean O - B wind speed holds steady at around -0.5 m/s.

### **7.2 Winds from microwave imagers**

The Special Sensor Microwave/Imager (SSM/I) instruments on the US Defense Meteorological Satellite Program satellites provide data on integrated atmospheric water vapour, cloud liquid water and precipitation over the ocean by passively measuring surface/atmospheric brightness temperatures. However, if the emission, absorption and scattering from such atmospheric water is low, near surface wind speed can be retrieved (e.g. Katsaros, 1993). The passive microwave emissivity of the sea surface varies in response to deformations caused by wind stress. The ocean surface becomes



rougher as the wind speed increases and a change in brightness temperature is expected, although the exact nature of the correlation between the two is more difficult to derive. The two operational SSM/Is in polar orbit monitor oceanic wind speed fields with almost complete daily coverage.

### 7.3 Doppler winds

The Upper Atmosphere Research Satellite (UARS) carries instruments (High Resolution Doppler Imager and Wind Imaging Interferometer) that measure the atmospheric winds at upper levels. They view the limb of the atmosphere in passive mode and measure the Doppler shift in emission and absorption lines in the visible and near-IR portion of the spectrum, detecting molecular oxygen, atomic oxygen, and the OH radical. The shift measures the relative velocity between the satellite and the air, and by observing the same location as the satellite approaches and departs the area, an estimate of horizontal wind speed is derived. The instruments scan vertically at the same time, to give a profile with a 4-km resolution. Comparison of stratospheric Doppler winds with radiosondes show a standard deviation of 8–12 m/s (Ortland *et al.*, 1996). Measurements can also be made in the mesosphere and lower thermosphere, up to 120 km (Fleming *et al.*, 1996).

While active Doppler lidar systems are already in use onboard aircraft, there are plans for a European-operated Doppler wind lidar to be flown onboard a polar-orbiting satellite in order to measure line-of-sight wind components (ESA, 1996). It calculates winds by measuring the Doppler shift of radiation backscattered to the instrument by particles (generally aerosols) moving at the same velocity as the ambient wind. This has the potential to provide multi-level global wind data in clear air, i.e. above or in the absence of thick cloud, supplying measurements of tropospheric wind profiles with higher accuracy and better vertical resolution than currently available. Expected tropospheric resolution would be  $50 \times 50 \times 1$  km, with the requirement relaxed in the stratosphere. A laser Doppler instrument would also provide information on cloud top heights, vertical distribution of cloud, aerosol properties, tropospheric height and the height of the atmospheric boundary layer.

The UKMO uses data from the ground-based Doppler wind profiler in Wales, but none from the American stations due to low quality. Flags are supplied with these data, and have only recently been deciphered. The monitoring software now needs to be updated but assimilation of these data will not take place yet. There appear to be no satellite Doppler winds on the GTS.

## 8 Current Research in Satellite-wind Derivation

New objective quality and control parameters for WV winds were recently proposed by Jedlovec and Atkinson (1996). They put forward a tracking technique that involves a "template matching number" (TPM; the sum of the absolute value differences between every pixel in the template/segment and the corresponding search area) being computed for every pixel in the search area, thereby avoiding the search area



being dictated by a first-guess field (a technique that wind producers are moving away from anyway). This Marshall Automated Wind algorithm is differentiated from other tracking algorithms in the way it determines the best position of segment from one image to the next. Their QC technique is based on the use of statistical structure functions, which independently quantify the random error associated with the wind vectors — the ultimate goal being to reduce the random error. The magnitude of mean non-direction gradients (structure) in data fields are estimated, and the slope of the structure curves at small separation intervals used in error estimation. This method sidesteps the problems associated with using radiosondes and first-guess fields for monitoring the quality of derived winds. Thus the extracted winds are less constrained by model-derived wind fields.

Inoue and Smith (1994) demonstrate the feasibility of extracting low-level wind by tracking moisture patterns from the GOES-7 split window (11 and 12  $\mu\text{m}$  channels), where the weighting functions peak below 800 hPa. The technique is based on brightness temperature difference between the two channels and is valid over cloud-free ocean areas. The level of best fit for the extracted wind is 825 hPa, with a vector rms error of about 5.2 m/s, comparable with wind estimates based on low-level cumulus cloud drift measured in the IR, but are useful for application in areas where no cloud tracers exist.

Methods also exist of producing satellite winds for high-latitudes from polar-orbiting satellites (Warren and Turner, 1988). The rms error is found to be 6 m/s when compared with radiosondes, with the lower quality being due to greater times between images, however positive impact on NWP models at high latitudes can be large, especially where no other data exist (Herman, 1991). Purdom and Dills (1993) also investigated the retrieval of satellite winds from polar-orbiting satellites, using adjusted stereo and shadows for cloud heights and velocities. They also looked at the prospect of using relative animation images, which would aid in the unambiguous selection of targets.

Wu (1993) has developed a correlation-relaxation algorithm for tracking of satellite winds. This method considers many possible positions associated with high correlations, not just the position of maximum cross-correlation, in a search image. It then selects an estimate from all candidates using a relaxation labelling technique, which iteratively updates the estimates for best correlation using knowledge of the problems inherent in tracking particular tracers. Results of this method appear promising, with a denser vector field being produced, since better tracking leads to fewer vectors that are discarded in subsequent quality checks.

A different method of feature tracking is outlined in Cote and Tatnall (1995): the use of neural networks in identifying the features being tracked on sequential (and manually rotated) Meteosat images is found to be more accurate and faster than the maximum cross-correlation method. Neural networks are also shown to be more able to identify rotational movement in a tracer, and be better suited to tracking deformed features.

It would appear that significant effort is being put into improved tracking for satellite winds. However it could be argued that the tracking is already a reasonably accurate



process, and that the errors that arise with regard to satellite winds are mainly due to the methods of height assignment. The above modifications and improvements are matters for the producers of satellite winds but interaction and feedback need to be maintained with the producers and the users.

## 9 General Recommendations for Satellite Wind Producers

In each of the three wind workshop proceedings (EUMETSAT, 1991, 1993, 1997), recommendations have been given for satellite wind datasets to become more standard between producers, and improvements made. The following summarises some of those recommendations.

- increasing the production frequency of the winds produced; this would mean more reliance on automatic QC, with strictly limited manual intervention
- using shorter time intervals between images for calculation of winds
- each vector to be flagged with a "quality mark", which could be used as a weight in data assimilation, for example. Work is currently under way into a feasible way of doing this fully automatically, with EUMETSAT committed to this approach
- development into a method of combining multi-spectral wind data to produce an overall "best" wind field, presumably for real-time forecasting purposes
- height assignment methods to be improved as far as possible, e.g. the use of cloud base for low-level clouds has been recently adopted by EUMETSAT, but improvements in other areas and for the different channels (especially WVWs where no high clouds are present) would always be welcome
- possibly improving the accuracy of the semi-transparent correction where no background is present
- more information is required about the quality and nature of the target. Variational analysis methods can make good use of information concerning the nature of the measurement, e.g. if it is a deep layer water vapour wind or a shallow layer cloud wind
- a move towards standardisation from the major wind producers
- EUMETSAT are planning to send high-resolution VIS winds in BUFR form from autumn 1996; these should include a quality flag for the winds. The flag will be produced from results for the six different QC tests, weighted, from which one number would be produced. Users are in favour of being passed the six different results and then using the data as they think best



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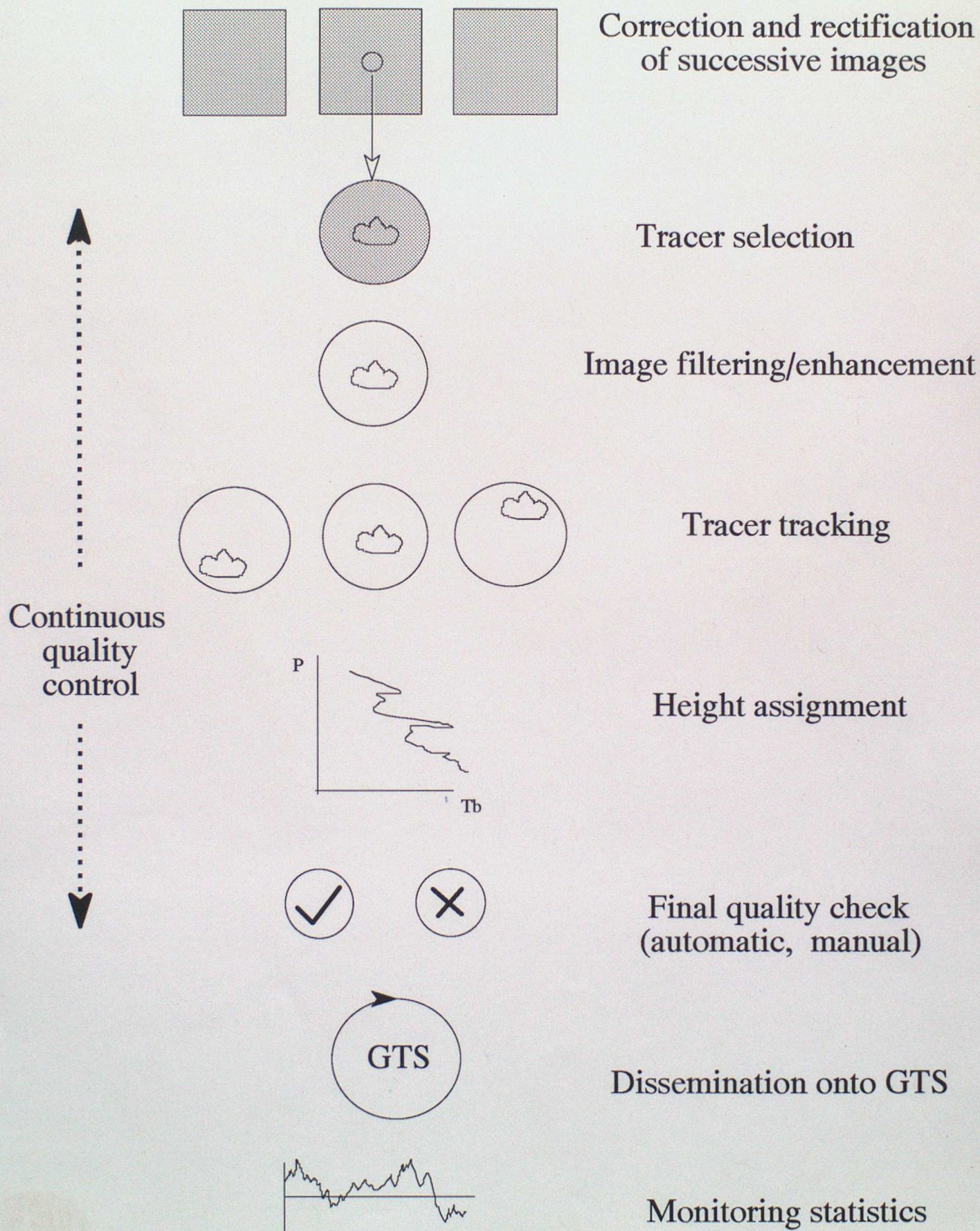
## FIGURE CAPTIONS

**Fig. 1.** Flow chart for wind extraction procedure.

**Fig. 2.** Schematic of new MPEF scheme (EUMETSAT, 1996a).



Fig. 1. Flow chart for wind extraction procedure.





# CLOUD MOTION WIND (CMW) PROCESS

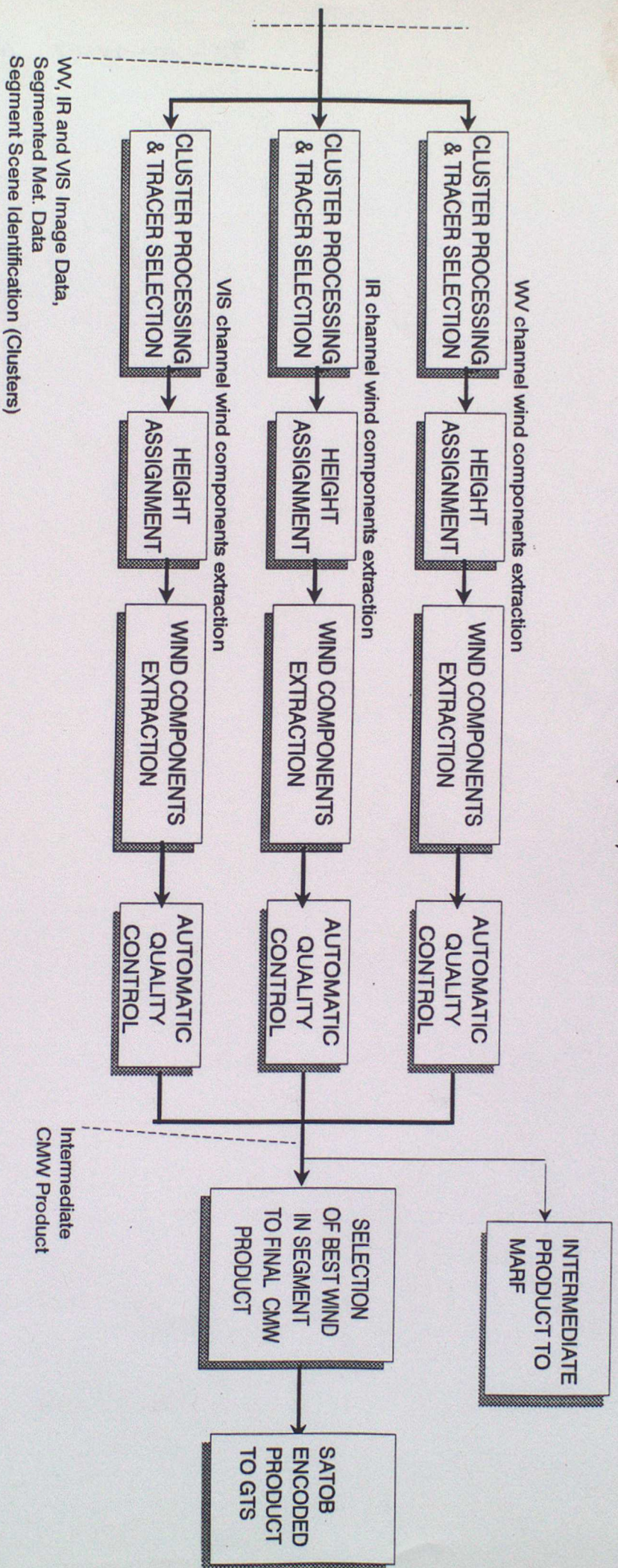


Fig. 2. Schematic of new MPEF scheme (EUMETSAT, 1996a).