DEPARTMENT OF METEOROLOGY
University of Helsinki
Report No. 51

GENERATION AND UTILISATION OF QUALITY INDICATORS FOR SATELLITE-DERIVED ATMOSPHERIC MOTION VECTORS

by

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ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in Porthania IV, Yliopistonkatu 3, on 1 June 2001 at 12 o'clock a.m.

Helsinki 2001

Helsingin yliopisto
Meteorologian laitos

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ISBN 951-45-9976-4 (printed version)
ISBN 951-45-9977-2 (pdf-version)
ISSN 0356-6897

Abstract

The extraction of Atmospheric Motion Vectors (AMVs) from motions of cloud and moisture features from successive geostationary satellite images is an established and important part of the global observing system. AMVs are produced almost continuously in near-real time with a horizontal density of a few tenths of kilometres generally using techniques based on targets that cover large areas up to 200 x 200 km^2. The derived displacement vectors are generally used as single point measurements. This poses the main problem in the utilisation of this data that really is a large area average measured over a long time period (up to 2 hours depending on the image frequency). Also the height assigned to the vectors often represents a layer mean and not a single level observation causing further problems and finally some of the features followed are not passive tracers of the atmospheric flow, hence the derived displacement vectors are not representative of the local flow.

In the early AMV derivation schemes the derived vector fields were quality controlled by experienced meteorologists and poor or non-representative vectors were removed. Furthermore suspect vectors showing any kind of deviations in time and space larger than certain thresholds were rejected and hence only about 17% of all possible vectors were disseminated. Today the high production frequency and the increased resolution make manual quality control unfeasible. Furthermore the new assimilation schemes utilised in Numerical Weather Prediction (NWP) require higher density wind fields and qualitative information on the errors of the individual AMVs.

This Thesis describes an Automatic Quality Control (AQC) scheme that is based on the statistical properties of the derived AMVs. The properties of the AMVs, i.e. their consistency in time and space, are interpreted with a number of tests. The outcome of each test is normalised such that they can be combined to a Quality Indicator (QI) that gives an estimation of the expected error of every individual vector. This is shown by statistics against radiosondes and verified by the positive impact in NWP impact studies. The QIs are currently derived and disseminated together with the derived AMVs by several operational AMV derivation centres. The current scheme removes a significantly smaller number of vectors from dissemination than the old quality control procedures (20% or less), leaving the decision on the data selection to the users. The QIs are used operationally at various NWP centres and have alleviated some of the problems related to the assimilation of this data in NWP.

The derived QIs can also be used in other application in order to provide a better determination of the atmospheric flow. This Thesis presents one possibility to use the QIs in a Barnes interpolation scheme, providing better interpolated wind fields. These wind fields can further be utilised to derive divergence fields and to advect cloud and rain information, hence facilitating a more efficient use of the AMVs e.g. for climate studies and nowcasting applications.

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1. Introduction

During the past century meteorology and climate research have become important disciplines that are mandatory for understanding the impact of human activities on the environment. The importance of meteorology and climate research will increase in the future with the global growth in population limiting living space and pushing food production to its limits. Climate change has an unprecedented impact on the human race. It is also one of the suggested causes for the increase in severe weather phenomena that we have experienced in the past years, emphasising the importance of meteorology.

In order to improve our understanding of the important atmospheric processes driving both short- and long-term evolution of the weather patterns, the observation system must be improved. More and higher quality observations are required as input to high-resolution Numerical Weather Prediction (NWP) and General Circulation Models (GCMs). The *in situ* observations of the atmosphere spanning more than a century, are today complemented by a multitude of space based observation systems. In general two kinds of satellites, geostationary and polar, equipped with passive and active instruments, provide us with large quantities of remotely sensed data. Currently, only a fraction of this data is used operationally or in climate research and one of the challenges of the future will be to make better use of these data. This will only become more complex with the advent of new instruments, multiplying the already large data volumes. In order to use all this information efficiently, thereby improving our understanding of the atmosphere, it is imperative to work on methodologies enabling a more efficient use of satellite data.

One of the most important systems for observing the atmosphere is the geostationary satellite system. The passive radiometers of the geostationary satellites provide near global imagery on a half hourly basis, with even higher frequency locally. The images provided are used at different meteorological product extraction facilities to derive information on sea surface temperature, cloud coverage, cloud temperature, clear sky radiance, atmospheric moisture and atmospheric motion, among other applications. The main products used operationally are the clear sky radiances and the Atmospheric Motion Vectors (AMVs) that are derived from sequences of satellite images.

The derivation of Atmospheric Motion Vectors (AMVs) has been performed operationally for approximately two decades (see e.g. Smith, 1985). The early derivation schemes were completely manual where an experienced meteorologist selected suitable targets in an image and located their movement in subsequent images by eye, however by 1975 the McIdas system, developed at the University of Wisconsin (Suomi, 1975), incorporated cross-correlation techniques for the derivation of the displacements. The advantage of a manual approach is that only the targets most likely to produce reliable displacement vectors are selected. The drawback is the subjectivity and slowness of the method. The development work has therefore concentrated on automated procedures. In Europe a fully automatic AMV derivation scheme has been operational since the launch of the first European geostationary satellite Meteosat-1 (Bowen et. al., 1979). The method that was used operationally at the European Space Operations Centre (ESOC) required manual intervention only in the quality control procedure, therefore enabling the production of hundreds of vectors within the Meteosat field of view. During the first decade of operations in the 80’s the quality of the derived vector fields increased significantly as the derivation scheme was improved not only in Europe, but also at other satellite centres producing AMVs operationally (e.g. EUMETSAT, 1991). Simultaneously the disseminated winds established themselves as an integral part of the global observation system providing valuable information about the atmospheric flow (e.g. Kelly and Pailleux, 1989) even though the positive impact mainly manifested itself in the Southern Hemisphere.

In the last decade the extraction of AMVs from geostationary satellite imagery data rapidly evolved as the production frequency, vector density and spectral bands used increased continuously (e.g. EUMETSAT, 2000). As manual intervention became impossible due to the large data volumes, and the improved NWP (Numerical Weather Prediction) assimilation schemes required more detailed information on the characteristics of the derived vectors, the demand for fully Automatic Quality Control (AQC) procedures able to estimate the errors of the individual vectors increased.

The early AQC schemes performed simple checks on the temporal and spatial consistency of the derived vectors. Any vector with large deviations was deleted from the final product. Generally the vectors were also compared against a background field, normally a NWP wind field and again any vector showing a large discrepancy was rejected. The comparison against the NWP field is especially critical as potentially valuable vectors that may be removed due to a poor background field. Therefore one of the desired features of any improved quality control scheme was to lessen the dependence on NWP data.

The purpose of this thesis is to present the Automatic Quality Control (AQC) scheme that was developed as a response to the requirement of a better characterisation of the errors of the individual AMVs. Furthermore the positive impact of the improved AQC approach on various applications is shown. The new AQC scheme provides each derived AMV with a Quality Indicator that is based on statistical tests that evaluates the stability of the derived vector components and the height associated to the AMVs. It combines the results of the individual tests in order to estimate the error of the individual AMVs thereby enabling a better utilisation of the derived vector fields in NWP as well as in other applications.

The following papers are included in this thesis:

I. Kenneth Holmlund, 2000: The Atmospheric Motion Vector Retrieval Scheme for Meteosat Second Generation. The Fifth International Wind Workshop, Lorne, Australia, 28 February – 3 March 2000, 201 - 208.

II. Kenneth Holmlund, Andreas Ottenbacher and Johannes Schmetz, 1993: Current System for Extracting Cloud Motion Vectors from Meteosat Multi-Channel Image Data. Second International Winds Workshop, Tokyo, Japan, 13 - 15 December 1993, 45 - 53.

III. Johannes Schmetz, Kenneth Holmlund, Joël Hoffman, Bernard Strauss, Brian Mason, Volker Gaertner, Arno Koch, and Leo Van De Berg, 1993: Operational Cloud Motion Winds from Meteosat Infrared Images. Journal of Applied Meteorology, 32, 1206 - 1224.

IV. Kenneth Holmlund, 1993: Operational Water Vapour Wind Vectors from Meteosat Imagery Data. Second International Winds Workshop, Tokyo, Japan, 13 - 15 December 1993, 77 - 84.

V. Andreas Ottenbacher, Maria Tomassini, Kenneth Holmlund and Johannes Schmetz, 1997: Low Level Cloud Motion Vectors From Meteosat High Resolution Visible Imagery. Weather and Forecasting, 12, 175 - 184.

VI. Kenneth Holmlund, 1998: The Utilization of Statistical Properties of Satellite-Derived Atmospheric Motion Vectors to Derive Quality Indicators. Weather and Forecasting, 13, 1093 - 1104.

VII. Kenneth Holmlund, 1997: Quality Indicators for Atmospheric Motion Vectors: Reliability and Impact On the Eumetsat Product Generation. The 1997 Meteorological Satellite Data Users' Conference, Brussels, 29-9 – 3-10, 1997, 355 - 362.

VIII. Kenneth Holmlund, 1995: Half Hourly Wind Data From Satellite Derived Water Vapour Measurements. Adv. Space Res., 6, 10(59) - 10(68).

IX. Kenneth Holmlund, 1995: Present Status of Water Vapour Wind Extraction at ESOC. CGMS XXIII plenary meeting, Darmstadt, Germany, 15 - 19 May, 1995, A.138 – A.141.

X. Kenneth Holmlund, Christopher S. Velden and Michael Rohn, 2001: Enhanced Automated Quality Control Applied to High-Density Satellite-Derived Winds. Monthly Weather Review, 129, 517 - 529.

XI. Kenneth Holmlund, 1999: The Use of Observation Errors as an Extension to Barnes Interpolation Scheme to Derive Smooth Instantaneous Vector Fields from Satellite-Derived Atmospheric Motion Vectors. The 1999 EUMETSAT Meteorological Data Users' Conference, Copenhagen, Denmark, 6 - 10 September 1999, 633 - 637.

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XIII. Johannes Schmetz, Kenneth Holmlund, Hans-Peter Roesli and Vincenzo Levizzani, 2000: On the Use of Rapid Scans. The Fifth International Wind Workshop, Lorne, Australia, 28 February – 3 March 2000, 227 - 234.

XIV. Johannes Schmetz, C. Geijo, W. P. Menzel, K. Strabala, L. Van De Berg, Kenneth Holmlund, and S. Tjemkes, 1995: Satellite Observations of Upper Tropospheric Relative Humidity, Clouds and Wind Field Divergence. Beiträge zur Physik der Atmosphäre, November 1995, 345 - 357.

XV. Johannes Schmetz, W. Paul Menzel, Christopher Velden, Xiangqian Wu, Leo Van De Berg, Steve Nieman, Christopher Hayden, Kenneth Holmlund, and Carlos Geijo, 1995: Monthly Mean Large-Scale Analyses of Upper-Tropospheric Humidity and Wind Field Divergence Derived from Three Geostationary Satellites. Bulletin of the American meteorological Society, 76, 9, 1578 - 1584.

Chapter 1 of this thesis is this introduction. Chapter 2 describes the current state of the art of the existing AMV extraction schemes (papers I – V). The development of the current methodologies has been performed in close co-operation with all satellite centres producing AMVs operationally. The main forum for the exchange of new ideas which forms the basis for international co-operation is the International Winds Workshop held approximately every two years (e.g. EUMETSAT, 2000). The contribution of the author of this thesis in papers I – V are the continuous improvements of the AMV extraction schemes demonstrated in these papers including the implementation and the validation of new methodologies, especially all aspects related to automatic quality control. The new AMV scheme described in paper I has been completely designed by the author of this thesis.

Chapter 3 of this thesis concentrates on the main topic of this thesis namely the generation of Quality Indicators for Atmospheric Motion Vectors (papers VI – IX). The fully automatic quality control scheme described has been developed in response to the increased requirements to estimate reliability factors for each derived wind vector. It utilises temporal and spatial statistical properties of the derived vector fields in order to assign a normalised Quality Indicator (QI) to each vector. The basic research that led to the current design is described together with the new scheme. The new scheme is further evaluated against other existing approaches, demonstrating the benefits and drawbacks of the different schemes. The author of this thesis bore the sole responsibility for all aspects related to the development of the new AQC scheme that provides every derived wind vector with a quality indicator. All work presented in this Chapter (papers VI – IX) was completely performed by the author of this thesis.

The success of the new AQC scheme and the derived QIs is demonstrated in Chapter 4 where several different applications are presented (papers X – XV). Currently the most important application is within the NWP assimilation system where the introduction of the QIs has enabled a better data usage. Another potential application is the derivation of smooth interpolated wind fields with improved quality. These improved fields are further utilised to extrapolate precipitation data and to compute upper tropospheric divergence fields. The upper tropospheric divergence fields are then used to study the relationship between upper tropospheric dynamics, cloud evolution and upper tropospheric humidity. The potential of the QIs to provide better estimates of the upper tropospheric divergence and the importance of the divergence fields in these studies is demonstrated. The author of this thesis devised and bore the main responsibility for the experiments and results reported in paper X. The utilisation of the derived quality indicators in new applications (papers XI – XIII) and the adaptation of the new AMV extraction scheme (paper I) to new data (radar reflectivity data, rapid scan) data was performed solely by the author of this thesis. The contribution of the author of this thesis to papers XIV and XV is the extraction and interpretation of divergence fields from AMVs.

Finally, Chapter 5 contains the conclusions.

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2. Derivation of Atmospheric Motion Vectors

2.1 Introduction

The derivation of wind information has since the launch of the first geostationary satellites been a fundamental task for the scientist working in the area of the utilisation of satellite imagery. Some of the concepts behind the Atmospheric Motion Vector (AMV) derivation schemes, can therefore be traced back to the pioneering era of satellite product derivation. One of the earliest description of methods for derivation of winds from cloud motion was given by Suomi (1969). These early efforts have led to fully automated derivation schemes (e.g., Rattenborg and Holmlund 1996, Tokuno 2000, Daniels et. al. 2000, Le Marshall et. al. 2000, Xu at. al. 2000) now applied to data from geostationary satellites at all operational satellite centres.

The current derivation schemes are generally based on two primary assumptions: the derived AMVs are utilised as point measurements; tracers, (e.g. cloud or humidity features) are assumed to be passive tracers of the atmospheric flow. These two assumptions place both limitations and strict requirements on the processing schemes. The derivation schemes should be able to identify tracers that are in principle passive tracers of the flow. Furthermore they should represent flow at various scales depending on the requirements of the users and should be able to provide reliable estimates of the height of the flow that has been detected. The largest user community is the NWP (Numerical Weather Prediction). Therefore the AMV schemes are often tailored towards the resolution of NWP assimilation systems. The requirements on quality and coverage are in general difficult to achieve as the atmosphere poses some real challenges to the wind derivation community. Multi-layered clouds, convective clouds and semi-transparent clouds are only some of the difficulties that have to be addressed.

This Chapter will present the current status of wind derivation from geostationary satellite data at Eumetsat (European Organisation for the Exploitation of Meteorological Satellite data). In general the AMV derivation schemes are based on the following five steps: target extraction; image enhancement; derivation of target displacement (tracking); height assignment; and quality control. In the past years much effort has been placed on the target extraction and image enhancement methodologies. Also, quality control and height assignment have advanced significantly during the past decade, but operational target tracking is still based on traditional template matching procedures. In the future new matching procedures (e.g. optical flow methods, Memin and Perez, 1998), which have already demonstrated their potential, might evolve sufficiently for operational applications.

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The first Section of this Chapter is this Introduction. The second section will describe a state of the art AMV extraction scheme that has been developed in preparation for Meteosat Second Generation (MSG) (Holmlund, 2000). This derivation scheme has evolved from experience with the operational scheme employed at Eumetsat. The current Eumetsat scheme is almost equivalent to the scheme already used at the European Space Operations Centre (ESOC) in 1993 (Holmlund et. al., 1993) and is described in Section 3. The new scheme aims to use the capabilities of MSG to the full extent. It combines several of the key features of operational derivation schemes in use at the different satellite centres deriving AMVs, and also incorporates results from recent research (e.g. EUMETSAT, 2000). Particularly important in this development has been the close co-operation with the Co-operative Institute for Meteorological Satellite Studies (CIMSS) and the University of Wisconsin, Madison (e.g. Holmlund and Velden, 1998).

Further details on methods for derivation of AMVs, and the early improvements made to the ESOC extraction scheme are given in Schmetz et. al. (1993), Section 4. This scheme used the infrared window channel data from Meteosat to derive four vector fields per day at a synoptic scale (the distance between two vectors was roughly 160 km). It incorporated an early Automatic Quality Control (AQC) scheme that removed any wind with large deviations in any of the components constituting the final wind or that did not agree with the NWP (Numerical Weather Prediction) wind field used as background. Of particular interest is the statistical analysis performed in this Section showing the dependency between vector RMS errors and mean wind speeds as well as the necessity to separate the statistics into periods where no modifications to the extraction scheme has been introduced. The impact of image enhancement demonstrated in Section 4 is important as it has paved the way for derivation of Water Vapour Wind Vectors (WVWVs) (Holmlund, 1993) described in Section 5. The water vapour image data has proven to be extremely successful for the derivation of high level winds (above 400 hPa). The 6.3 μm water vapour channel is mainly sensitive to radiance emitted from the upper troposphere and performs a kind of an image enhancement by suppressing radiance emitted from the lower atmosphere and the surface. As the operational derivation of WVWVs doubled the number of AMV fields produced, it posed a major problem for manual quality control. Therefore the quality control applied to the WVWVs was fully automated. However, this quality control removed 90% of the extracted winds, hence diminishing the impact of the new product and further emphasising the need to improve the AQC-scheme. This Section also shows that it is possible to separate vectors with different quality using different thresholds in the quality control procedure.

Section 6 completes the picture of the current state of the art multi-spectral AMV derivation schemes. It introduces the derivation of AMVs from high-resolution visible imagery (Ottenbacher et. al., 1997), which enables a better description of the low level (below 700 hPa) atmospheric flow.

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3. Generation of Quality Indicators for Atmospheric Motion Vectors

3.1 Introduction

The derived Atmospheric Motion Vectors (AMVs), as presented in Chapter 2, are intended to be representative of single level motion. The utilisation of these vectors is highly dependent on their quality, and on how representative they are of single level motion. The early quality control methods, manual and automatic (e.g. Nuret 1990, Le Marshall et. al. 1994, Bhatia et. al., 1996), removed all vectors that were inconsistent either with respect to surrounding vectors, or a background field, or that had accelerations larger than pre-defined thresholds. Although successful, these methods often removed up to 90% of the derived vectors. Furthermore manual quality control, if employed, was time consuming and therefore not practical in an environment where the production frequency and density is high. Therefore more elaborate systems were developed of which the Recursive Filter Function (RFF) approach developed at the University of Wisconsin (Hayden and Purser, 1995) proved to be quite successful (e.g. Menzel et. al., 1996). This approach first performs simple acceleration checks as used in the schemes mentioned above and then subsequently compares the AMVs against a Numerical Weather Prediction wind (NWP) field. Any wind with large deviations from the background field is re-adjusted in height for a better fit, the maximum re-adjustment being 150 hPa. Finally the fit of each vector against the background is used to give an indication of the relative quality of the vectors, as derived against the background field. The RFF-based quality control is currently used operationally at NOAA/NESDIS, however today it is also complemented by the Automatic Quality Control (AQC) scheme described in this thesis.

As the production frequency was expected to grow over the years and the NWP requirements for estimated absolute errors attributed to each vector during assimilation was increasing, the focus of research turned towards the development of reliable Quality Indicators (QIs). The work presented in this chapter shows the current status and early work related to the derivation of the QIs.

The main approach for derivation of QIs for AMVs is presented in Section 2 (Holmlund, 1998). The AQC scheme presented places its emphasis on the sensitivity of different quality tests to the error of the AMVs, assuming that these represent single level point measurements. It uses temporal and spatial statistical properties of the derived vector fields in order to assign a normalised Quality Indicator (QI) to each derived wind vector. The success of the QIs is demonstrated using visual examples together with statistics derived against collocated radiosondes and NWP (Numerical Weather Prediction) data. This section also introduces the concept of Normalised RMS (NRMS) error, which is a good indicator of a speed independent quality measure.

Previous research and and early validation is presented in the following Section (Holmlund, 1997). This Section incorporates further examples and validation results highlighting an example of manual quality control. This example clearly demonstrates the difficulty to perform manual quality control for a large number of AMV fields in near-real time. In Section 2.4 it is also demonstrated that for many different kinds of tests there is no single threshold above or below which a wind is good (or bad). The research has therefore concentrated on the development of continuous tests that only increased or decreased the quality of any derived wind vector.

Section 4 shows the results of an early method using continuous quality functions. This method was implemented in a near-real time water vapour wind extraction scheme and incorporated a fully automated quality control scheme that paved the way for the current operational design (Holmlund, 1995a). The quality control scheme presented in this Section shows the impact of a multitude of quality control tests that led to the final design of the operational quality control scheme now applied at Eumetsat. It also demonstrates the importance of combining the results of several different tests to obtain reliable estimates of the final quality assigned to each vector.

Finally, section five (Holmlund, 1995b) presents validation results from a two week validation campaign based on the near real-time system introduced in the previous section. During this period the performance of the new AQC scheme was evaluated against ECWMF (European Centre for Medium range Weather Forecasting), demonstrating the success of the new scheme.

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4. Utilisation of Quality Indicators

4.1 Introduction

Chapter 3 described the development and early validation of methodologies to generate Quality Indicators (QIs) for Atmospheric Motion Vectors (AMVs). The scheme, as described in Section 3.2, has formed the baseline of the Automatic Quality Control (AQC) scheme that is already implemented, or will be implemented, at all major satellite centres that derive AMVs operationally. The capability of the QI-scheme currently implemented at Eumetsat (European Organisation for the Exploitation of Meteorological Satellite Data) to assign reliability estimates to each individual vector has already been demonstrated in Chapter 3. The final test of the success of the QI-scheme is the improved use of the AMVs in different applications. This Chapter will describe the current utilisation of these quality indicators in NWP (Numerical Weather Prediction) and their potential in other meteorological disciplines.

In Section 2 the impact of the QIs derived with the Automatic Quality Control Scheme applied to high-density wind fields derived during the 1998 North Pacific Experiment at CIMSS (Co-operative Institute for Meteorological Satellite Studies) in Wisconsin is shown (Holmlund et. al. 2001). The performance of the derived QIs is compared to the operational automatic quality control applied at CIMSS, based on a Recursive Filter Function (RFF) (Hayden and Purser, 1995). The results show that during this particular two-week period the RFF-scheme performs better than the QI-scheme, however combining the two schemes has the largest positive impact on the short range forecast. It should be noted that although both schemes rely to some extent on background fields, normally wind fields from NWP, the dependency on the background field is smaller and more clearly defined in the QI-scheme than in the RFF-scheme. The main conclusion of Section 2 is that a combined approach, where the QI is used to select the best winds in an assimilation grid box, is the preferred approach. Currently QIs are disseminated operationally with AMVs derived from Meteosat and GOES (Geostationary Operational Environmental Satellite) and are used operationally at ECMWF (European Centre for Medium range Weather Forecasting).

A further use of the QIs, where the QI is introduced as a separate weight in a Barnes interpolation scheme, is demonstrated in Section 3 (Holmlund, 1999). This approach provides improved and more reliable interpolated wind fields, demonstrated by reduced RMS differences as compared to originally derived high quality AMVs. These interpolated wind fields are in general not suitable for use in NWP. Instead they can be used to advect cloud information as described in Section 4 or to study the interaction between upper tropospheric circulation and humidity as described in Section 5.

In Section 4 the current Atmospheric Motion Vector derivation scheme, developed for MSG and presented in Section 2.2, has been modified to work with Doppler radar image data showing the versatility of the new scheme (Hohti et. al. 2000). It also incorporates the Automatic Quality Control scheme described in Section 3.2 providing Quality Indicator values for vectors derived from the movement of the radar echoes. The data used in this specific study is composite radar imagery data over Finland derived every 5 minutes. The Barnes interpolated vector fields are utilised to advect the rain intensities of the composite imagery and has shown to give useful information up to three hours in advance. The advected precipitation fields are now produced and disseminated semi-operationally.

In Section 5 the Barnes interpolated vector fields are used to compute upper tropospheric divergence fields. Upper tropospheric divergence fields derived from geostationary satellite imagery data can be used, in conjunction with rapid scan data, to look at convective development (Section 4.5.1, Schmetz et. al., 2000). They can also be used to investigate the interaction between upper tropospheric divergence and humidity (Sections 4.5.2 and 4.5.3, Schmetz et. al. 1995a and 1995b). The work in 4.5.1 shows that the use of the Barnes interpolated mean wind fields provide realistic instantaneous divergence fields. Another important result is that the divergence fields produced are 15% higher when they are used with rapid scan data (7.5 min. imagery) than the fields derived with the nominal scan interval (30 min. imagery).

Sections 4.5.2 and 4.5.3 demonstrate the close relationship between upper tropospheric divergence and humidity as observed with satellite imagery data. A shortcoming of these studies has been the integration time required to derive reliable divergence fields, i.e. the studies have concentrated on monthly mean fields. The new approach to derive divergence fields using the QI-based Barnes interpolation scheme is capable of providing realistic divergence fields from single wind fields and will enable more accurate investigation on smaller time scales in the future.

This Chapter shows several potential applications of the Quality Indicators (QIs) and their importance in providing a better description of the state of the atmosphere. In the future, as NWP (Numerical Weather Prediction) assimilation schemes improve, the impact of the QIs will also increase. One of the possible future applications of the QIs is to use them to modify errors assigned to the derived Atmospheric Motion Vectors during assimilation. In doing so, by reducing the errors assigned to winds with higher QI, their impact will be increased.

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5. Conclusions

Weather prediction, climate research and nowcasting are continuously increasing their requirement for more high quality observations. With the current expectation that the global radiosonde network will be reduced, the importance of geostationary satellite data will increase and is the only feasible way to retrieve information about the state of the atmosphere at the required temporal and spatial resolution. The data from geostationary instruments does however have limitations. Therefore data from polar orbiting satellites incorporating passive and active instruments measuring in various spectral bands currently not available on geostationary satellites (e.g. microwave, ultraviolet), and at a higher resolution that is possible from geostationary orbit, is mandatory for a better understanding of the atmosphere. In the future new and better instruments will complement the current observing system increasing our capability to observe and predict small and large-scale variations of the atmosphere.

One of the key quantities to be observed is the atmospheric flow. In addition to in-situ measurements, (e.g. from radiosondes) Atmospheric Motion Vectors (AMVs) derived from sequences of multi-spectral images retrieved with geostationary satellites are currently used. These observations are complemented by clear sky radiances, i.e. radiances derived in cloud-free areas. The direct assimilation of radiance data will become increasingly important in the future when radiances in cloudy areas may be assimilated. The need to derive AMVs will remain as long as the quality and representative scale of the derived vectors is sufficiently high. Furthermore information on the quality of the derived vectors is required in order to maximise the potential of the AMVs.

In this thesis, the current state of the art methods for derivation of AMVs has been presented. The versatility of the existing schemes lends themselves easily to use with higher temporal and spatial resolution imagery data. The basic approach is straight-forward and is composed of five major steps; target extraction, image enhancement, tracking, height assignment and quality control. Schemes based on those presented in this thesis are currently implemented at all satellite centres that produce AMVs operationally. At the present time the single main source of error is the height assignment. With the advent of new instruments like Meteosat Second Generation (MSG) further improvements in the area of height assignment are expected. In particular the capability to derive heights using different methods simultaneously will provide an unprecedented opportunity to derive information on the reliability of these estimated heights for each individual vector. Until these new instruments are launched the estimation of the reliability of the AMVs is mainly based on temporal and spatial characteristics of the vectors themselves.

The main part of this thesis concentrates on the reliability aspect of the Atmospheric Motion Vectors. Based on the presented AMV extraction schemes and bearing in mind the current and future requirements on the quality of the derived vectors, a method to derive Quality Indicators (QIs) for Atmospheric Motion Vectors has been developed and presented. This scheme uses statistical properties of the derived vectors and the vector field itself to estimate how well this data can be used as single point measurements of the atmospheric state. One of the main components of the Automatic Quality Control (AQC) scheme that provides the QIs is the derivation of consistency parameters, calculated with respect to temporal and spatial variations as well as with respect to background data. These are typically NWP (Numerical Weather Prediction) fields or wind vectors derived from different spectral bands. The presented AQC scheme also takes into account natural variability in the atmosphere, hence allowing the derived vectors to deviate in time and space from other measurements. It therefore provides denser vector fields than the early quality control methods that were based on simple acceleration checks. Finally the AQC-scheme normalises all individual tests with respect to expected distributions of the individual test results, thereby enabling the combination of the individual test results into a final Quality Indicator (QI).

The performance of the scheme presented has been extensively validated against NWP and radiosonde data as well as against other AQC schemes. It has shown to have an almost linear relationship to the measured RMS error of the AMVs, hence providing reliable error estimates of the derived vectors. For more than 35% the developed AQC scheme assigns a quality indicator value higher than 0.7 to the derived vectors. This can for high level winds be translated roughly to a RMS error of 9 m/s for a mean wind speed of 24 m/s. These numbers should be compared to the old AQC-scheme that rejected any wind that showed some inconsistency in any wind component. The old scheme provided slightly lower RMS values of the order of 8.5 m/s for the same mean wind speed of 24 m/s, but retained only 10% of the total wind field. Furthermore, e.g for high level winds, the mean quality of the 10% best winds with the new scheme is between 0.20 and 0.25. This translates to a RMS less than 6 m/s for a mean wind speed of 24 m/s, clearly showing the benefits of the new AQC scheme; it provides more winds with a smaller error than the old approach.

The capability of the new scheme to provide reliable estimates of the quality of the AMVs has already been exploited in several different disciplines. The main use of Atmospheric Motion Vectors is in NWP. At ECMWF (European Centre for Medium range Weather Forecasting) the Quality Indicators (QIs) are currently used to select the most appropriate part of the disseminated vector fields. Data screening in areas where high-density vector fields have been produced has been especially successful. The QIs disseminated together with each individual vector, in conjunction with the new assimilation schemes that are able to make more efficient use of the AMVs, have now for the first time shown positive impact in the northern hemisphere following assimilation AMVs. This positive result at ECMWF has also contributed towards the initiation of a globally unified approach for derivation of QIs. The presented methodology is already used operationally in NOAA/NESDIS (National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service) and is currently under implementation at BoM (Bureau of Meteorology/Australia) and JMA (Japan Meteorological Association).

The derived Quality Indicators (QIs) can also be used in other applications, in conjunction with the derived wind field. A further application is the utilisation of the QIs in a Barnes interpolation scheme, enabling the derivation of higher quality interpolated wind fields. These wind fields are not suitable for assimilation in NWP, but can be used in nowcasting and to study upper tropospheric circulation and climate. The use of the QIs in a Barnes interpolation scheme maintains a better description of the true flow where good quality vectors have been retrieved. It puts more weight to the high quality vectors and limits the impact of poor vectors. The interpolated wind field is therefore better suited for further applications than a simple interpolation scheme.

Currently two main areas of use have been developed. At the Finnish Meteorological Institute AMVs are derived from composite radar echo data. These AMVs are used to derive improved interpolated wind fields that are then used to extrapolate observed precipitation fields. These advected precipitation fields are produced semi-operationally and are already now established as a highly desired product, reliable for up to three hours ahead. Further developments in this field include investigations into the capabilities of the QIs for estimation of the probability of rain at the advected locations.

The second application is the derivation of upper tropospheric divergence fields from Water vapour wind vectors. Due to the poor performance of the old quality control and traditional interpolation methodologies, early studies that looked into the interaction between upper tropospheric circulation and humidity had to rely on monthly mean fields. These investigations demonstrated the connection between these two quantities, but were not able to look in detail at differences and smaller time scales. With improved interpolation methodology it is now possible to derive these divergence fields from instantaneous vector fields enabling a more thorough investigation into the complex interaction in the upper troposphere, especially in the vicinity of large mesoscale systems.

The Atmospheric Motion Vectors derived from consecutive geostationary satellite images are currently an integral part of the global observing system. This thesis has shown that the utilisation of these vectors can be improved with the derivation of reliable error estimates attributed to each individual vector. In order to maintain the position the AMVs have in the global observation system, further improvements are required. In particular, the derivation of quality estimates for the height assignment will play a key role in the future.

The Atmospheric Motion Vectors derived from geostationary satellite imagery data are more and more frequently complemented with wind information from other satellite instruments. Most of these are based on polar platforms and do not provide global coverage at the temporal and spatial resolution possible from geostationary orbit. It is therefore important to continue the research in the field of the AMVs, with the ultimate goal of improving knowledge of the atmosphere, weather prediction and climate. The expected improvements in the usage of the AMVs will not only come from improved derivation techniques. A major impact will also originate from improved Automatic Quality Control (AQC) procedures. The AQC scheme presented in this Thesis has proven to be robust and easily adaptable to different satellites and scanning strategies, and therefore it may form a common baseline for further development.

Acknowledgements

I would like to express my gratitude to everybody who has helped me to take this final hurdle in my studies. I am deeply indebted to all contributors, co-authors and reviewers, not only of the papers presented here but of all of the papers I have published either as lead or co-author. My sincere thanks go to the people supporting me in my scientific career; at the Finnish Meteorological Institute Prof. Erkki Jatila and Dr. Jorma Riissanen for introducing me into satellite meteorology; Mr. Johannes de Waard and Mr. Brian Mason for involving me with Atmospheric Motion Vector retrievals at ESOC/ESA; Prof. H. Savijärvi at the University of Helsinki; and to Prof. Tillmann Mohr and Dr. Alain Ratier for their support during my career at EUMETSAT. My special gratitude for their continuous support and encouragement to take this final step go to Dr. habil. Johannes Schmetz and Dr. Paul Menzel.

I also wish to lovingly thank my parents, brother, sisters and to my numerous friends for all the love and support they have given to me in my life. Finally, I would like to express my warmest thanks to my sons Kristian, Mikael and Niko who have given my life its purpose; to Rose for teaching me to dream again; and to Birger and Linnea Holmlund who have never stopped believing in me and have taken a special place in my life. Mina käraste tack går till Birger och Linnea för den plats Ni har fyllt i mitt liv, för Er kärlek och understöd i alla dessa år.