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High resolution space based wind observations estimation and application – A Review

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सार – अंतरिक्ष से अवरक्त और दृश्य विकिरणित प्रेक्षणों के आकाशीय, स्थापना और स्पैक्ट्रल विभेदन के उन्नत होने के परिणामस्वरूप वायुमंडलीय गति के आकलन और विशेष रूप से संख्यात्मक मौसम पूर्वानुमान (एन.डब्ल्यू.पी.) करने के लिए उनके लाभ की उपयोगिता में वृद्धि हुई है। इन आँकडों के उपयोग को बढ़ी हुई कम्पयूटर की शक्ति, संशोधित संख्यात्मक मौसम पूर्वानुमान निदर्शों और संशोधित किए जा रहे आँकड़ों को समाविष्ट करने की तकनीकों के उपयोग से भी सहायता मिल रही है।

इस शोध–पत्र में वायुमंडलीय गतिवेक्टरों (ए.एम.वी.) के बनने और उसके अनुप्रयोग के इतिहास को भी संक्षेप में प्रस्तुत किया गया है, जिसमें उच्च आकाशीय और स्थानिक विभेदन वाले वायुमंडलीय गतिवेक्टर संसाधन का विवरण भी संक्षेप में समाहित किया गया है। सभी वायुमंडलीय गतिवेक्टरों के डाटा टाइप उपयुक्त हैं और अब इनका प्रयोग प्रचालनात्मक क्षेत्रीय और भूमंडलीय संख्यात्मक मौसम पूर्वानुमान के लिए किया जाता है तथा इन आँकड़ों का चयन और संख्यात्मक मौसम पूर्वानुमान के लिए आवश्यक गुणवत्ता नियंत्रण विषयों का विवेचन किया गया है। भविष्य के लिए नवीनतम उपस्करों को तैयार करने से संबंधित परीक्षण की भी संक्षेप में चर्चा की गई है।

ABSTRACT. As the spatial, temporal and spectral resolution of visible and infrared radiance observations from space has improved, their utility for estimating atmospheric motion, and, in particular, their benefit to Numerical Weather Prediction (NWP) has increased. The utility of these data has also been aided by increased computer power, improved NWP models and the use of improving data assimilation techniques.

This review provides a brief history of the generation and application of Atmospheric Motion Vectors (AMVs), including a short description of high spatial and temporal resolution AMV processing. All AMV data types are both suitable and now used for operational regional and global NWP and the data selection and quality control issues important to NWP are discussed. A brief examination of preparations for future advanced instruments is also undertaken.

Key words – Cloud drift winds, Atmospheric motion vectors, Data assimilation, Remote sensing.

1. Introduction

Wind is a primary variable for the representation of atmospheric state. Accurate estimation of the wind field in areas where no conventional data are available is essential for operational weather forecasting. Measurement of wind from geostationary platforms is important, as it provides near continuous data where conventional observations are lacking, particularly over the data-sparse oceans. Studies as early as Bauer (1976) showed that AMVs have a capacity similar in several aspects to that of radiosondes for representing atmospheric flow.

This review summarises the development of AMV estimation and data impact studies using these vectors. It discusses quality control and data selection issues because of their importance in NWP, particularly with the high spatial and temporal resolution vectors now available. Global and regional data assimilation experiments which have successfully applied high-resolution visible, infrared and water vapour band image-based motion vectors to

NWP are noted. As an illustration, the utility of AMVs for tropical cyclone forecasting is also documented.

2. Atmospheric motion from sequential satellite observations

From the early 1970s, wind has been estimated routinely from space using sequential imagery from geostationary satellites. Early work is reported in Fujita *et al*. (1968) and Young *et al*. (1972). Hubert and Whitney (1971) identified and tracked passive tracers from ATS-1 to determine cloud motion and hence wind velocity. Endlich *et al*. (1971) referred to the digitisation of ATS data and computer tracking of cloud targets to estimate atmospheric motion velocities. Leese *et al*. (1971) and later Endlich and Wolf (1981) used cross-correlation and pattern matching methods for identifying targets in different images.

Intervals between images, from rapid scan, *e.g.* 1 minute (Purdom 1996) up to 3 hrs (Eigenwillig and Fischer 1982) have been used to estimate AMVs. In 1974, the Synchronous Meteorological Satellite (SMS-1) was launched and provided images at 5-minute intervals which enabled shorter-lived clouds to be studied. It had a visible channel with 0.8 km sub-satellite resolution and an infrared channel. The high spatial and temporal resolution of SMS-1 was useful in thunderstorm environments (Tecson *et al*. 1977). The characteristics of vectors from rapid scan imagery were summarised in Johnson and Suchman (1980).

The first Geostationary Operational Environmental Satellite (GOES-1) was launched in 1975. The first AMV system for GOES was similar to that described by Hubert and Whitney (1971) and Young (1975). The first European MeteoSat and Japanese Geostationary Meteorological Satellite (GMS) satellites were launched in 1977. Routine production of AMVs from GMS began in 1978 with manual target selection and tracking of high-level winds and automatic tracking of low-level winds. Imagery from the water vapour absorption band of MeteoSat-1 became available in 1977. Early work in the generation of AMVs from absorption channel imagery was reported by Allison *et al.* (1972) and by Steranka *et al*. (1973). They both examined the application of the Nimbus 4 Temperature and Humidity Infrared Radiometer (THIR) 6.7 μm channel observations to the determination of the moisture distribution and wind flow near the 400 hPa level. Almost a decade later, Kästner *et al*. (1980) reported using overlapping swaths of consecutive Nimbus 5 orbits to derive wind velocities from water vapour imagery in another pre-Meteosat study. Their work demonstrated the feasibility of using sequential water vapour images for wind determination. Subsequent work by Fischer *et al*. (1981), Eigenwillig and Fischer (1982), Stewart *et al*. (1985) using the McIDAS system (Suomi *et al*. 1983), Hayden and Stewart (1987), Velden *et al*. (1992) and Le Marshall *et al*. (1985) described the use of this imagery for deriving mid-tropospheric wind vectors by tracking water vapour features. These works further refined the procedures for generating water vapour winds and gave an initial indication of their utility for NWP in particular for tropical cyclone track forecasting where they can provide important information around the 'steering level'.

By the 1990s, infrared, visible and water vapour motion vectors were included in experimental and operational data bases. In 1992, a fully automatic (no manual quality control) operational cloud drift wind processing system was established in the Bureau of Meteorology, Australia (Le Marshall *et al.* 1992). Later, hourly AMV data was routinely generated (Le Marshall *et al.* 1996) and high resolution visible imagery provided high density wind data and was a good source of low-level cloud drift wind data (Le Marshall *et al*. 1996, Schmetz *et al*. 1996). Derivation of wind vectors from water vapour imagery was further studied by Holmlund (1993), Uchida (1993), Laurent (1993) and others. Inoue and Smith (1994) tracked low-level moisture patterns between the surface and 700 hPa using water vapour imagery and split window infrared brightness temperature differences. A considerable body of work was produced, in the mid-nineties, on the generation and application of these winds by Velden and associates (Velden 1996, Velden *et al*. 1997, 1998).

Incorrect altitude assignment has always been a major source of error in satellite wind measurement (Hubert and Whitney 1971). Important fieldwork in addressing this problem was undertaken by Hasler *et al*. (1976, 1977, 1979). Szejwach (1982) developed a method for estimating the temperature of cirrus clouds using both the IR window channel and water vapour absorption band data. Menzel *et al*. (1983) used the VAS sounder to assign cloud heights. In the 1990s, many studies focussed on improving altitude assignment (Schmetz and Holmlund 1992, Le Marshall *et al*. 1992, Nieman *et al*. 1993). Hayden (1993) described an auto-editor which included an adjustment for speed bias and allowed altitude reassignment when necessary. Research into experimental stereoscopic altitude assignment techniques for cloud drift wind derivation by interactive methods and the use of polar orbiting satellites was conducted by Purdom and Dills (1994). Recently, Campbell (1998), Campbell and Breon (2000) and Campbell and Holmlund (2000) have also demonstrated the utility of these stereoscopic methods.

(a)

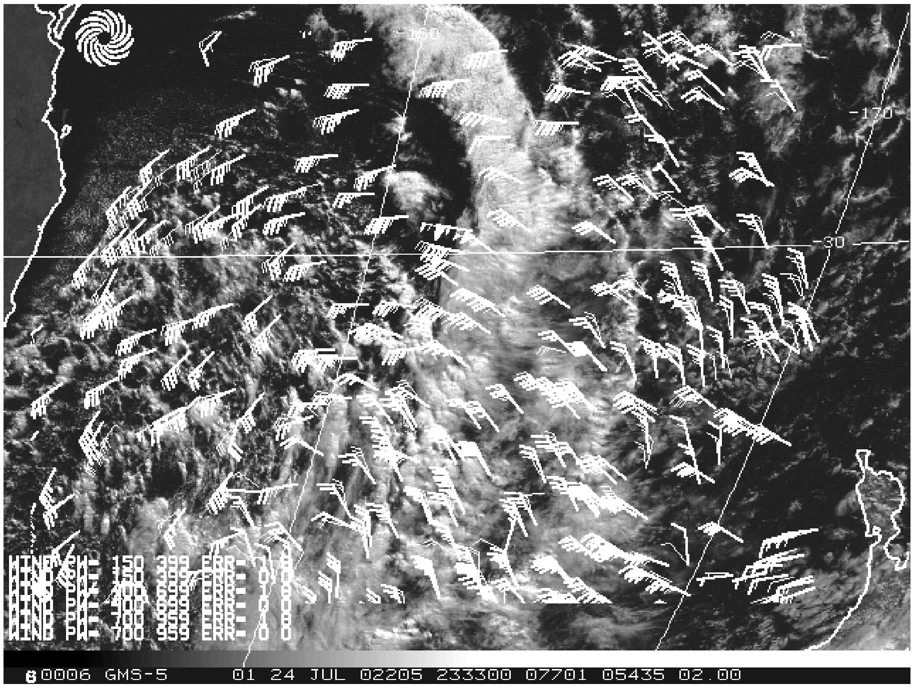


Fig. 1 (a). GMS-5 cloud and water vapour motion vectors over the Tasman Sea for 2300 UTC on 24 July 2002

(b)

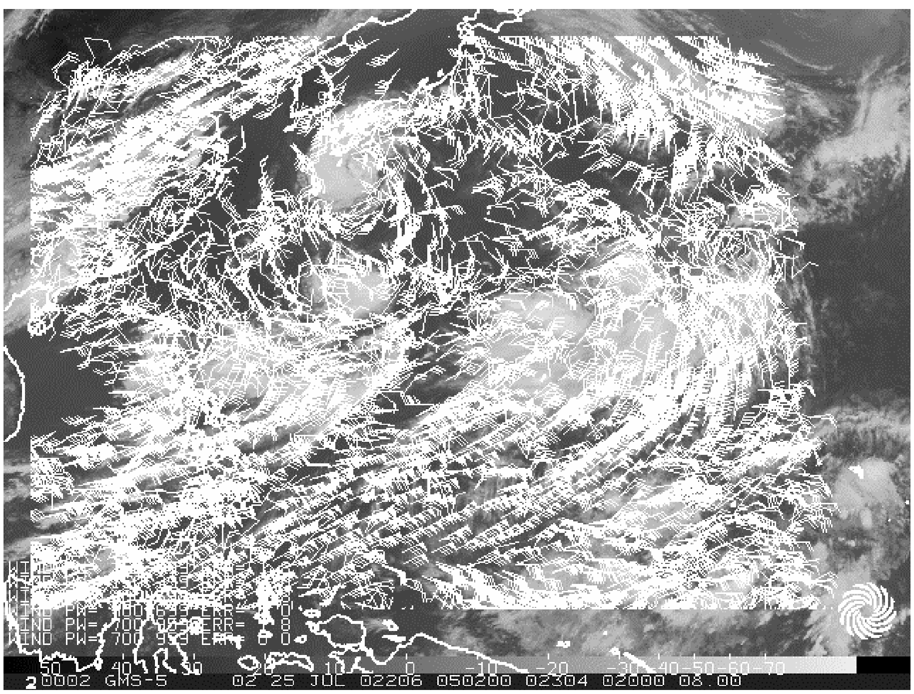


Fig. 1 (b). AMVs around Tropical Cyclones Feng Shen and Fung Wung in the NW Pacific around 0500 UTC 25 July 2002

2.1. *Current AMV derivation methods*

Agencies currently generating winds for operational use are the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (Rattenborg 2000), the National Oceanic and Atmospheric Administration / National Environmental Satellite Data and Information Service (NOAA/NESDIS) (Daniels *et al.* 2000), the Japanese Meteorological Agency (Tokuno 2000), the Indian Meteorological Department (Khanna *et al*. 2000) and the Bureau of Meteorology, Australia (Le Marshall *et al*. 2000).

At NOAA/NESDIS infrared, water vapour, visible and sounder water vapour winds (7.4μm and 7.0μm) are produced from the GOES I/M series satellites generally three hourly, with image intervals ranging from 60 minutes for sounder water vapour winds, through 30 minutes for infrared and water vapour winds, to 15 or 7.5 minutes for visible cloud drift winds (Daniels *et al*. 2000). Low level height assignment is at cloud base level and uses the method developed at the Bureau of Meteorology, Australia. Upper level vectors are height assigned using the IR window and water vapour intercept method and quality control involves use of an 'auto-editor' and now a Quality Indicator (QI) (Velden *et al*., 1998, Nieman *et al*., 1993). At EUMETSAT, cloud tracked winds generated from infrared, water vapour and low resolution visible imagery are distributed every 90 minutes. Clear sky Water Vapour (WV) winds from cloud free areas are also distributed every 90 minutes. High resolution visible image based winds are also produced every three hours from 0600 UTC to 1800 UTC (Rattenborg, 2000). Low level height assignment is to the cloud base level. Radiance slicing is applied to segments before tracking to enhance the highest cloud layer (Schmetz *et al*., 1993), and cloud tracking is automatic, using a cross correlation technique, with tracking aided by use of an ECMWF forecast. A semi-transparency correction is applied using infrared and water vapour data. Quality control is fully automatic and a quality indicator (QI) is appended to the vectors.

At the Meteorological Satellite Centre (MSC) Japan, cloud and water vapour winds are produced four times per day with high density low level visible winds being produced once per day (0400 UTC) in a 20° E × 20° E box around any typhoon. For upper level vectors, areas containing cumulonimbus are excluded and the IR and WV intercept technique is used in the height assignment for non black body clouds (Tokuno 2000). Low level winds are currently assigned to fixed heights. At the Indian Meteorological Department (IMD) cloud drift winds are derived from INSAT data at 0000, 0600 and 1200 UTC using half hourly image triplets. Satellite winds at 0600 UTC are generated using visible imagery for cloud tracers while infrared imagery is used for cloud tracking at 0000 UTC and 1200 UTC. Cloud top temperatures are used for height assignment (Khanna and Prasad, 1998). Automatic quality control includes acceleration checks and use of the forecast model first guess before dissemination of the wind data on the Global Telecommunications System (GTS). A summary of recent improvements in INSAT AMVs is in Khanna *et al*., 2000.

The methods used for AMV estimation in the Bureau of Meteorology, Australia (hereafter referred to as the Bureau) are largely covered in Le Marshall *et al*. (1999, 2000). Three sequential infrared (IR), visible (VIS) or water vapour (WV) band images (a triplet), usually separated by an hour or half an hour are used for velocity estimation. High density winds are generated continuously at hourly or half hourly intervals. Selected targets are tracked automatically using forecast winds, then a lagged correlation technique, which minimises root mean square (RMS) differences in brightness from successive pictures, is used to estimate the vector displacement. Cloud height assignment uses forecast temperature profiles. The cloud height assigned for the low-level winds was that of the cloud base (following the fieldwork of Hasler *et al*. 1976, 1977). The benefit of height assignment to the cloud base has been documented in Le Marshall and Pescod (1994). Height assignment involves fitting Hermite polynomials to smooth raw histograms of brightness temperature enabling estimation of cloud base altitude from cloud base temperature. Upper level AMVs are assigned to the cloud top altitude which is estimated using 11 and 12 μm split window observations (Le Marshall *et al*. 1998). For water vapour motion vectors, height assignment of the upper-level cloud vectors and middle-level vectors in clear conditions is described in Le Marshall *et al*. (1999).

A selection of winds, estimated by the operational Bureau AMV system over the Tasman Sea (30 °S, 160 °E) is shown in Fig. 1 (a). The local IR (11 μm) system alone can provide up to 400 wind vectors around Australia at 0500, 1100, 1700 and 2300 UTC. AMVs around Tropical Cyclones Feng Shen and Fung Wung in the NW Pacific around 0500 UTC 25 July 2002 are seen in Fig 1 (b).

3. Accuracy and quality control

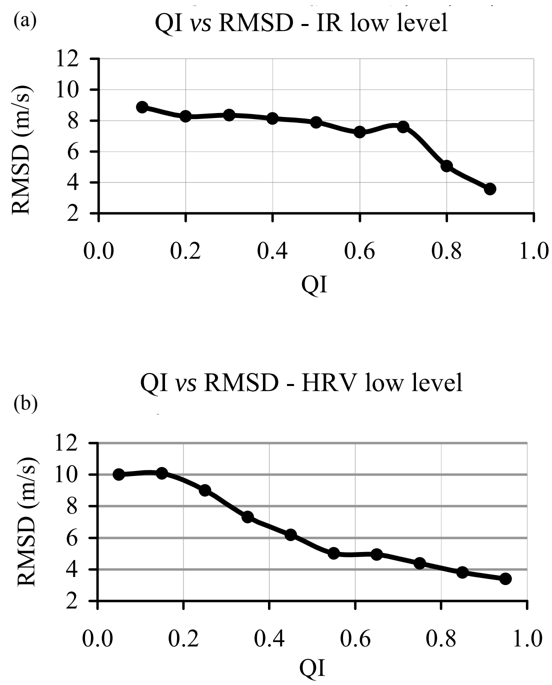
3.1. *AMV accuracy*

The accuracy of AMVs is determined by several factors. The resolution of the imagery used for tracking clearly determines the accuracy in measuring displacement of targets. The time between images is also important in that it needs to be short enough to allow features to be tracked while being long enough that the inherent errors in measuring displacement (due to image resolution) do not lead to large velocity errors. The number of vectors also depends on these factors. A summary of these influences may be seen in Jedlovec (1998) and Le Marshall *et al*. (2000). The most important factor influencing the accuracy of the AMVs is height assignment. It is well established low-level vectors need to be assigned to the level of the cloud base (Hasler *et al*., 1976, 1977, Le Marshall and Pescod, 1994). Upper

TABLE 1

Comparison of radiosonde and atmospheric motion vectors over the Australian Region using CGMS criteria, March to June 2002 inclusive. [IR1 = 11 µm imagery based winds, VIS. = Low resolution (5 km) visible winds, HR VIS. = High resolution (1.25 km) visible winds, WV = Water Vapour based winds and MMVD = mean magnitude of vector difference (ms^{-1})]

Types		IR1	VIS.	HR VIS.	WV
Low	No. of obs.	3084	707	2493	---
(950-700 hPa)	MMVD (m/s)	3.33	3.32	3.27	---
Middle	No. of obs.	26	3	7	464
(699-400 hPa)	MMVD (m/s)	5.26	3.31	5.20	4.21
High	No. of obs.	1644	327	879	6182
(399-150 hPa)	MMVD (m/s)	5.59	5.57	5.47	5.36



Figs. 2(a&b). Quality Indicator (QI) *versus* Root Mean Square Difference (RMSD) with radiosondes within 150 km for low level (a) infrared image based AMVs and (b) high resolution visible image based AMVs for 28 April 2000 to 29 April 2001

level targets on the other hand travel at the speed of the wind at cloud top and hence the AMVs need be associated with the cloud top altitude. The assignment of low level AMVs to cloud base is first described in Le Marshall *et al*. (1992) and later in Schmetz *et al*. (1996). Different methods employed for the height assignment for upper level vectors are described in the references cited in Section 2. These methods are designed to take into account variations in cloud emissivity in the estimation of cloud top altitude by using multi-pixel, statistical and multi-channel approaches. Typical verification results from the application of these multi-channel height assignment methods to 11µm infrared (IR1), low resolution (5 km) visible (VIS) and high resolution (1.25 km) visible (HRV) imagery over the Australian Region are seen in Table 1.

3.2. *AMV quality control*

AMV rejection and expected error determination are usually based on several criteria. These include the correlation between the brightness temperature arrays of the search and target areas, and the difference in meridional and zonal wind components of the two vectors from a tracer tracked in pairs of adjacent images. The difference thresholds for rejection are usually situation dependent (near a jet stream, low level, etc.), and typically require the winds to be within 5 and 7 ms^{-1} for the zonal and meridional components respectively. The deviation of the calculated wind vectors from the first guess field is also an important consideration. The acceptable deviation is usually situation dependent (near a jet stream, low level, etc.) and zonal and meridional wind thresholds are typically less than around 10 and 7 ms^{-1} respectively. The weights assigned to AMVs during assimilation are dependent on their expected error. To enhance the use of AMVs in assimilation, the quality control (*qc*) elements cited above can provide both data selection and be used to estimate expected error, based on previous collocation statistics generated from coincident radiosondes and AMVs. These elements therefore allow selection of vectors with errors appropriate to the assimilation system. It is important to note that in practice the *qc* system should not be static but changes, for example, with the assimilation system and the accuracy of the background field, *i.e.* changes, for instance, where the forecast model in the assimilation system is improved. As the accuracy of the background field improves, the ability to distinguish between reliable wind estimates and erroneous data is enhanced.

Recently, a Quality Indicator (QI), Holmlund (1998) and Holmlund *et al*. (2001) has been introduced and associated with each AMV in the BUFR product from EUMETSAT and NESDIS. The QI for each AMV is calculated by estimating direction consistency, speed consistency, vector consistency, spatial consistency and consistency with the operational forecast. The degree of compliance with these five tests is then used to form a single QI. The QI is intended to allow optimal use of high-density winds, by giving a consistent estimation of the expected error associated with each vector. Using methods similar to Rohn *et al*. (1998), the QI has been provided for

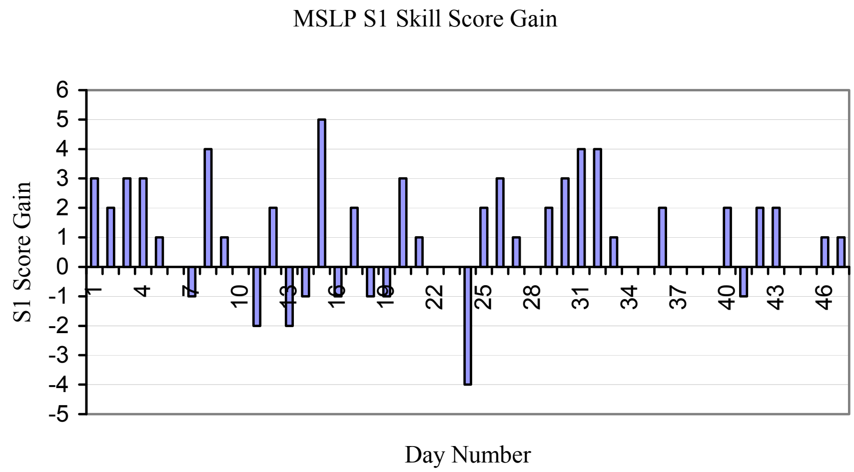


Fig. 3. Skill score gain for 24 hr forecasts at MSLP with use of the VIS, IR and WV AMVs (12 September - 30 October 2000)

all AMV types generated at the Bureau. Plots of QI *versus* RMS difference between AMV's and radiosondes within 150 km, for both low level infrared and high resolution visible AMVs, estimated using one years data (April 2000 – April 2001), are seen in Fig. 2. The use of the QI for data selection (error estimation can be improved by using it in conjunction with other quality measures such as the Recursive Filter Flag (RFF) (Holmlund *et al*. 2001).

It should be noted that, if QI rather than the expected error (EE) is to be used widely, then calibration curves (Fig. 2) need to be estimated for each vector type or an internationally consistent (normalised) QI is needed. (*i.e.* the same QI means similar error characteristics for all AMV types from different providers). It may, however, be simpler to provide the expected error with each AMV. In the Bureau for instance expected error is calculated directly using tests which include those used to estimate the QI. This direct measure of error obviates the need for a look-up table constructed from the QI *vs* RMSD as shown in Fig. 2 to estimate error.

4. Atmospheric motion vectors in NWP

Use of AMVs for applications such as nowcasting, global and regional NWP and tropical cyclone forecasting is now widespread. However despite the fact they have been used in numerical analysis and prediction since the 1970s, only a limited number of works have attested to their utility in NWP on either regional or global scales.

4.1. *Atmospheric motion vectors in regional and global NWP*

The characteristics of the winds and their impact on medium-range global NWP was summarised in Kållberg *et al*. (1982) and later by Kelly (1993), Le Marshall *et al*., (1994), Seaman *et al*. (1995), Tomassini (1996), Kållberg and Uppala (1998) and later in Bouttier and Kelly (2001). In Seaman *et al.* (1995), the impacts of the Indian geostationary satellite (INSAT) cloud drift winds upon the Bureau's global assimilation system was documented. They found, during a seven week period in 1993 and 1994, the INSAT winds had a small and systematic positive impact on background fields and initialised analyses produced by the global assimilation cycle. In Bouttier and Kelly (2001), the impact of using high density winds with the operational ECMWF 4-D VAR system has been summarised. They noted that the satellite winds showed small positive impact over the Southern Hemisphere mid-troposphere and mixed impact in the Tropics at 1 to 3 days.

The impact of AMVs *in* regional NWP has also been documented, in Le Marshall *et al*. (1994, 1996 and 1999) and Velden (1996). These studies (except Bouttier and Kelly, 2001) have generally employed 6-hourly intermittent assimilation techniques. The Tomassini (1996) and Le Marshall (1996a, 1997) papers, in particular, deal with the application of high resolution cloud motion vectors from high resolution visible images using intermittent assimilation and, in the latter case, also 4-D VAR. The application of hourly AMVs to regional numerical weather prediction using intermittent assimilation is addressed in Le Marshall *et al*. (1996, 2002).

Recently, in a regional context, during real time experiments over the Australian region, different types of local AMVs were added individually to the Bureau's operational database and their benefit to regional NWP quantified (Le Marshall *et al*. 1994, 1996, 1999). Three *experiments* recorded the impact of infrared (11 μm), hourly and water vapour (6.7 μm) imagery based winds on operational forecasts. By employing a duplicate Limited Area Prediction System (LAPS) (Puri *et al*. 1998), it was found that the addition of these local AMVs to the data base, provided, on average, a consistent small positive impact to forecasts at all atmospheric levels studied. The impact was greater than 1 Skill Score point (Teweles and Wobus, 1954) near the surface for the case of 11 μm and hourly winds. After the completion of these experiments, all AMV types were used together with the Bureau's real time database in an operational trial to gauge their combined impact on operational regional NWP. The assimilation methodology is recorded in Le Marshall *et al*. (2002). The S1 skill scores for 47 24-hr forecasts (12 September – 20 October 2000) using these AMVs were compared to the operational skill scores and the gains were consistent with those of the three earlier experiments, showing on average consistant improvement at all low, middle and upper levels studied, with an impact of about 1 skill score point near the surface. The results are illustrated Fig. 3 which shows the daily S1 skill score gain at MSLP. It is clear these winds are beneficial to the forecast process. As a result of this trial, all of these wind types have been employed in the operational regional forecast system in NMOC, Melbourne since October 2000.

4.2. *Atmospheric motion vectors in tropical cyclone forecasting*

The utility of AMVs for forecasting tropical cyclone tracks is well established. It is documented in Velden *et al*., (1984), Le Marshall *et al*. (1985), Velden *et al*. (1992, 1997, 1998), Velden (1996), Le Marshall *et al*., (1996b, 2000), Leslie *et al*. (1998) and in Le Marshall and Leslie (1998). A summary of their impact for this application is also found in Le Marshall (1998).

Early studies addressing analysis and prediction of tropical cyclones using cloud and water vapour motion vectors include Velden *et al*., (1984). Le Marshall *et al*., (1985) and Mills *et al*., (1986). Velden *et al.* (1984) used deep layer wind information, derived from GOES satellite imagery to improve tropical cyclone track prediction. The Le Marshall *et al*. (1985) study of Hurricane Debby, illustrated the utility of both VAS (VISSR Atmospheric Sounder [VISSR =Visible and IR Spin Scan Radiometer]) soundings and cloud and water vapour drift winds for analysis and prediction over the Caribbean. This early NWP study using a variational analysis and primitive equation model, indicated the potential of cloud and water vapour drift winds for numerical tropical cyclone track forecasting. Velden *et al*. (1992) demonstrated the impact of satellite-derived winds on numerical hurricane track forecasting. High density satellite-derived motion vectors from the infrared 6.7 μm and 7 μm water vapour absorption band and gradient winds derived from VAS height fields were used in two different single-level barotropic track forecasts systems and resulted in a 7% to 17% reduction in middle-to long-range (48 - 72 hrs) track forecast errors.

Bennett *et al*. (1993) published the results of tropical cyclone prediction study using a barotropic model initialised by a generalised inverse method. As part of the Tropical Cyclone Motion-90 experiment (TCM 90), this 3-dimensional variational assimilation model was initialised using a 6-hourly enhanced satellite derived wind field. Improved forecasts were produced using this variational assimilation technique with the 6-hourly wind data. Following this, the 3-dimensional barotropic model and its generalised inverse were applied to the case of tropical cyclone Rewa in the Coral Sea, near Australia (Le Marshall *et al*., 1996a). In this experiment, hourly satellite winds were used for the first time in a continuous 3-dimensional variational assimilation and the results were contrasted with those obtained using a control forecast and 6-hourly nudging. The continuous assimilation procedure used hourly data as input in the 24 hours before the forecast start. It was found in this study that the high spatial and temporal (hourly) resolution winds used with the variational approach clearly had the potential to improve the accuracy of NWP It was also noted that a full exploitation of their information content appeared to require continuous assimilation techniques such as the variational method employed there.

In Le Marshall *et al*. (1996a), a separate experiment was also undertaken to compare forecasts generated using six hourly nudging and 6-hourly 3-D variational assimilation. Twenty eight forecast cases from 11 tropical cyclones, separated by more than 30 hrs to avoid serial correlation (Neumann *et al*., 1977), were examined. There, the data base used consisted of the BMRC Tropical Analyses plus 6-hourly data insertion of CDW data (SATOBs) from the GTS. The direct forecast, nudging and the variational method were compared. At 24 hrs, an examination of position errors found that the forecasts produced by the variational method were, on average, 10% more accurate than those using the direct forecast and the forecasts produced by the variational method were, on average, only 3% more accurate than those using nudging. At 48 hrs, the variational method was, on average. 9% more accurate than the direct forecast and only 3% more accurate than nudging. Several conclusions were drawn from these studies. The variational method, using enhanced CDWs is more accurate than nudging using BMRC Tropical Analyses and the use of a direct forecast, and that the variational and nudging methods are both better than the use of a direct forecast. It would also appear than if no enhanced data are used, such as the CDWs in the original TCM-90 study, then the gains from using the variational method over the nudging technique are not large and this would have to be weighed against the large increase in computational power required to use this technique.

Bennett *et al*. (1996) described the generalised inversion of a global numerical weather prediction model. In this case, to prepare initial conditions for the model at the initial time T = 0, the inverse found a weighted least squares best fit to the dynamics for $-24 < T < 0$ hrs., for the previous initial conditions at $T = -24$ and to data at $T = -24$, -18, -12 and $T = 0$. The inverse was a weak constraint, 4-dimensional variational assimilation scheme. The model and its generalised inverse were then applied to a study of the impact of reprocessed cloud drift wind observations from the TCM 90 experiment. Use of the model with these 6-hourly reprocessed wind fields provided improved forecasts in the South China Sea at T = +48 hrs. Following this study, the primitive equation model and its generalised inverse were scaled to a 30° × 30° domain in the Australian region (Le Marshall *et al*., 1996b) and used in a series of continuous data assimilation studies. In these studies, the model was run at 15 km resolution with 25 levels and the wind data were assimilated at hourly intervals for 24 hrs. The data consisted of high spatial and temporal resolution infrared and visible cloud drift winds, generated in real time from hourly GMS 5 observations. Four Australian tropical cyclones were studied, Beti (26-28 March 1996), Olivia (9-11 April 1996), Ethel (10-12 March 1996) and Justin (10-12 March 1997). Here, hourly nudging and 4-D variational assimilation produced the best forecasts.

Velden *et al*. (1997) described the derivation of upper tropospheric winds from geostationary satellite water vapour observations and their utility in tropical cyclone track forecasts. It noted the considerable increase of viewing capability with the launch of GOES 8 and 9 and GMS 5. In fact, if the GOES, Meteosat and GMS satellites are considered together, there is almost complete global coverage. The article described the derivation of water vapour winds from the GOES 6.7, 7 and 7.3 µm channels and the GMS-5 6.9 µm channel. It illustrated water vapour motion vectors, calculated from both clear and cloudy environments and, finally, investigated the application of these data to NWP. Overall, it was found with the application of these water vapour winds to tropical cyclone forecasting during the 1994 and 1995 tropical cyclone seasons using both the Geophysical Fluid Dynamics Laboratory Hurricane model and the Navy Operational Global Atmospheric Prediction Scheme (NOGAPS), that for 24 hrs forecasts, a 6% improvement in the mean forecast errors for 24 hrs was achieved, while improvement at 48 hrs was found to be 13% and 10% at 72 hrs. The numbers referred to some 42, 36 and 30 cases, respectively.

The benefits of high spatial and temporal resolution locally generated AMVs from the use of 4-D VAR are shown in experimental studies of Le Marshall *et al*., (1996b), Leslie *et al*., (1998) and Le Marshall and Leslie (1998, 1999). In those studies, the use of these real time continuous winds with 4-D VAR in the analysis and forecasting of tropical cyclone tracks has been shown to have the potential to be very effective. In Le Marshall and Leslie, (1998), for example reducing 48 hrs forecast errors to below 150 km for the 11 cases studied. Recently, other studies have employed 4-D VAR. High spatial resolution 4-VAR has been employed by Xiao *et al*., (1999) and Zou and Xiao (1999), for tropical cyclone forecasting. Their results also demonstrate the utility of 4D-VAR. Their approach is different from that of Le Marshall and Leslie (1998) who use continuous data assimilation (hourly high-resolution GMS-5 AMVs) over the 24 hrs prior to forecast time (Le Marshall *et al*, 1996, Leslie *et al*, 1998) to define the cyclone and its environment. Xiao and Weng (1999) and Zou and Xiao (1999) have used repeated assimilation of high-resolution AMVs plus bogus data in the half-hour prior to forecast time.

5. The future

The continuing trend to space based observations with higher spatial, temporal and spectral resolution will greatly influence the generation of AMVs. In the Australian Region, for example the Geostationary Meteorological Satellites, GMS-4 and GMS-5 have provided increased temporal (now hourly) and spectral (now from bands near 0.7 µm ,6.7 µm, 11 µm and 12 µm) resolution, compared to their predecessors. As expected (Jedlovec 1998), this has resulted in the ability to generate winds of greater density and accuracy than those from earlier spacecraft, with attendant improvements in NWP capability.

With increasing spatial and temporal resolution, there also comes the opportunity to exploit the advantages of 3-D and 4-D VAR. The potential benefits from the use of AMVs on local scales using 4-D VAR have been noted for example, Leslie *et al*. (1998). Benefits were also reported in Bouttier and Kelly (2001) using the operational ECMWF system.

Of considerable potential benefit to meteorology over the Indian Ocean will be the launch of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) in 2005 (Smith *et al*. 2000). This instrument on the EO-3 Satellite will spend a year and a half of its lifetime near Continental US and the balance over the Indian Ocean. There, it will provide 3000 - 6000 channel observations of the full earth disc, centred at 75 °E. The sub-satellite resolution of the observations will be 4 km in the IR and 1 km in the visible. The use of detector arrays will allow, for example, the estimation of 16,384 soundings with 1 K accuracy, every 10 seconds, and the estimation of AMVs from both cloud tracking and from the tracking of features in the water vapour field generated using the thousands of channels available for this purpose.

Several methods will be employed for estimation of operational AMVs from this ultra-spectral sounder. The tracking of cloud features in sequential observations will be undertaken with the height assignment being improved by the thousands of channels provided by the instrument (Smith and Frey, 1991). In relation to the AMV estimation using features in cloud-free sequential WV channel observations, several techniques are available. One is to derive the moisture fields on pressure levels and then track features in those fields whose pressure altitude is already known. Another approach is to use either moisture or radiances from sequential GIFTS observations and rely on 4-D VAR initialization to provide consistent velocity and moisture movement estimates from the sequential observations. Initial studies employing this methodology using NAST-I (NPOESS Airborne Sounder Test-bed Interferometer) data from the CAMEX-3 experiment near Andros Is. in the Bahamas, in September 1998 have been undertaken (Leslieet *et al.,* 2002). They found, using the 4D-VAR approach at 1 km resolution, that the mass and wind fields were adjusted during a six hour initialisation with 3000 NAST-I temperature and moisture observations, to provide a field which was consistent with the limited AMV data available in the region.

6. Summary and conclusions

A brief history of AMV derivation and their application to NWP has been provided. The generation of AMVs from infrared and visible imagery has been documented. Experiments using these data in global and regional NWP and in Tropical Cyclone forecasting have been described and the benefit of these data to NWP clearly recorded. These results have led to the introduction of all Atmospheric Motion Vector types into operational data bases around the world. In addition, it would appear that the higher spatial, temporal and spectral resolution observations soon to be available will provide considerable improvement in AMVs. This improvement is anticipated to be of quantitative benefit to NWP. In particular, the prospects of significant benefits from the use of sequential observations from new generation ultra-spectral instruments such as GIFTS appear to be significant.

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