HIGH DENSITY ATMOSPHERIC MOTION VECTORS AND THEIR APPLICATION TO OPERATIONAL NUMERICAL WEATHER PREDICTION

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ABSTRACT

As the spatial, temporal and spectral resolution of observations from space has improved, their benefit to numerical weather prediction (NWP) has also 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 paper provides a brief historical overview of the impact of atmospheric motion vectors (AMVs) on NWP, a description of high resolution AMV processing at the Bureau of Meteorology (BoM) and some previously unreported data impact results for the Australian region. It also discusses preparations for advanced sounders.

1. Introduction

Wind is a primary variable for describing atmospheric state, and accurate depiction of the wind field in areas where no conventional data is available is essential for operational weather forecasting and initialisation of NWP models. 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 AMVs have a capacity similar in several aspects to that of radiosondes for representing atmospheric flow.

Use of AMVs is now widespread. Applications include nowcasting, global and regional NWP, tropical cyclone forecasting and climatological applications.The characteristics of the winds and their impact on medium-range global NWP was summarised in Kallberg et al. (1982), Kelly (1993), Kallberg and Uppala (1998) and Bouttier and Kelly (2001). Their impact in regional forecasts has been well documented, for example, in Le Marshall et al. (1992, 1994, 1996 and 1999) and Velden (1996). The utility of AMVs for forecasting tropical cyclone tracks can be seen in Velden et al. (1992, 1998), Velden (1996), Le Marshall et al. (1996a, 2000), Leslie et al. (1998) and in Le Marshall and Leslie (1998). Their use for this application is summarised in Le Marshall (1998).

2. Atmospheric Motion Vector Derivation at the Bureau of Meteorology

2.1 Vector Velocity Estimation

Imagery was navigated using orbit, attitude and landmark data from the GMS-5 Stretched Visible and Infrared Spin Scan Radiometer (S-VISSR) transmission together with refinements which included statistical correction of the navigation information. The system used 3 sequential infrared (IR), visible (VIS) or water vapour (WV) band images (a triplet), separated by an hour or half an hour. These images were searched for potential target areas of 20 x 20 pixels (30 x 30 for WV imagery) by examining maximum and minimum pixel values and brightness temperature gradient maxima. The size of the potential target areas for each wind type was determined by detailed systematic testing. Selected targets were tracked automatically using a lagged correlation technique.

2.2 Height Assignment

AMV height assignment for VIS and IR targets used forecast temperature profiles. Initially, height assignment involved fitting Hermite polynomials to smooth raw histograms of brightness temperature. This enabled estimation of cloud base altitude from cloud base temperature using the forecast temperature profile. The cloud height assigned for the low level winds was that of the cloud base following the field work of Hasler et al. (1979). The benefit of height assignment to the cloud base has been documented previously (Le Marshall and Pescod 1994). Upper level AMVs were assigned to the cloud top. The cloud top level was initially estimated by an examination of the cold tail of the upper cloud population, assuming the cloud temperature for the winds to be just above the coldest 5.5% of the cloud population. The methodology has been subsequently tuned using observational studies matching AMVs with radiosonde data (Le Marshall et al. 1994).

The current system, now uses dynamic calibration, and 11 and 12 µm split window observations (Le Marshall et al. 1998). Using this system, *a check was made for the presence of transmissive cirrus* at high levels and *cloud top temperature was subsequently estimated using these two channels*. Lower level heights were estimated, using the split window to take into account the effects of water vapour on brightness temperature, when calculating the cloud base temperature. In the case of water vapour motion vectors, the height assignment of the upper-level cloud vectors and middle-level vectors in clear conditions is described in Le Marshall et al. (1999).

2.3 AMV Quality Control

Local Methods: During quality control (QC), winds are accepted if their (expected) error level allows them to improve the assimilation system forecasts. Here, wind data were accepted and errors assigned based on several criteria. These included the correlation between the brightness temperature arrays of the search and target areas. The differences in meridional (and zonal) wind components of the two vectors from a tracer tracked in pairs of adjacent images and the deviation of the calculated AMVs from the first guess field. The weights assigned to the wind data in the assimilation process are dependent on their expected error. To assist this process, the quality control method cited above provided an expected error, based on previous collocation statistics. This was not a static system but changed with the assimilation system and the accuracy of the background field.

Quality Indicator (QI): Recently, a Quality Indicator (QI), Holmlund (2001) has been estimated and associated with each AMV in addition to the local error estimate. International use of the QI is intended to allow optimal use of high density winds, often from different producers, by allowing consistent estimation of the anticipated error associated with each vector. Using methods similar to Rohn et al. 1998, the QI has been provided for all AMV types generated at the BoM. Plots of QI versus RMS difference for both low level, infrared and high resolution visible AMVs are seen in Fig. 1. The QI information associated with the local AMVs is not currently used operationally in the BoM. In the Region, QC is still more efficient using local methods. That is, local methods currently provide more vectors with errors up to a given rms error level, than does use of the QI, employing currently published weights. Testing, however, is underway to tune the QI and to use it with other quality measures such as the RFF (Holmlund et al. 2001). It should be noted that, if QI rather than the expected error is to be used globally, calibration curves (see Fig. 1) need to be estimated for each vector type or a 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.*

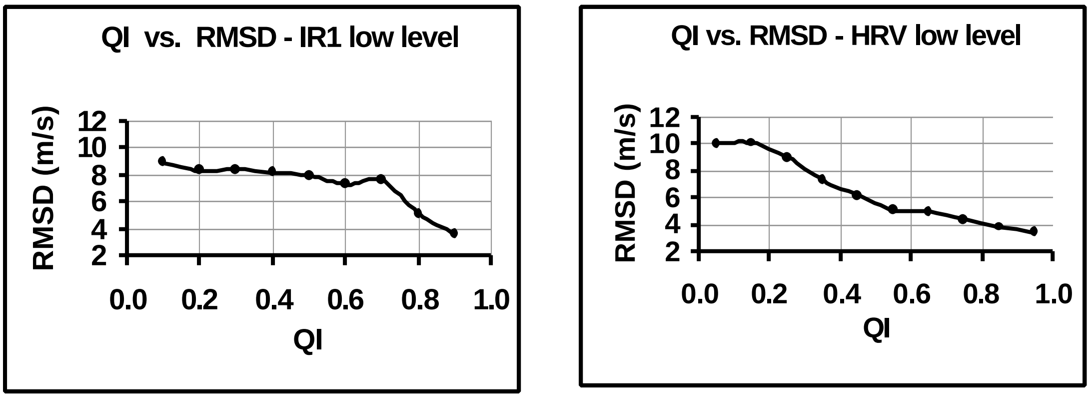

Fig. 1. Quality Indicator (QI) versus r.m.s. difference (RMSD) with radiosondes within 150 km for low level (left) IR and (right) high resolution VIS AMVs for 28 April, 2000 to 29 April 2001.

2.4 AMV Accuracy

The wind types generated by the BoM's operational Australian region forecast system and their characteristics are listed in Table 1.

Wind type	Image resolution	Frequency/ Times (UTC)	Wind image triplet (? T)
IR, Low res. VIS, WV	5 km	6 hourly - 05, 11, 17, 23	30 minutes
High-res. VIS	1.25 km	6 hourly - 05, 23	30 minutes
Low res. VIS (hrly)	5 km	Hourly - 00, 01, 02, ... 23	1 hour
High-res. VIS (hrly)	1.25 km	Hourly - 00, 01, 02, ... 23	1 hour

Table 1. Cloud drift wind types generated operationally in the BoM. The table indicates wind type, sub-satellite image resolution, frequency of wind extraction, time of wind extraction and the separation of the image triplets used for wind generation (? T).

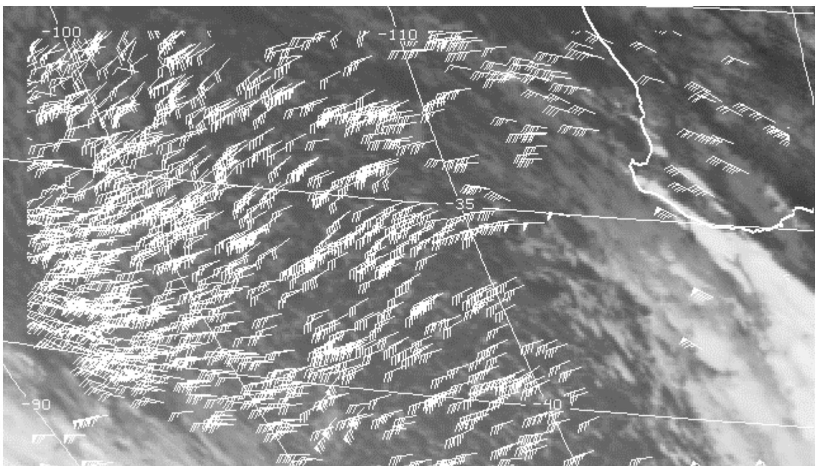

Figure 2. Local cloud and water vapour AMVs for 0500 UTC on 07 May 2001.

A selection of winds, estimated by the operational AMV system is shown in Fig. 2. The local (11 µm) system alone can provide up to 400 wind vectors around Australia at 05, 11, 17 and 23 UTC. The accuracy of the local wind system during a recent impact study described in the next section is seen in Table 2. It shows the mean modulus of the vector difference (MMVD) of the AMVs from radiosondes within 150 km over the Australian Region.

Type		IR1	VIS.	HR VIS.	WV
Low (950 – 700 hPa)	No. of obs.	500	190	994	---
	MMVD (m/s)	3.33	3.49	3.33	---
Middle (699 – 400 hPa)	No. of obs.	8	---	6	254
	MMVD (m/s)	6.46	---	5.38	5.44
High (399 – 150 hPa)	No. of obs.	622	116	398	1896
	MMVD (m/s)	5.79	6.45	5.51	6.34

Table 2. Comparison of AMVs and radiosonde winds using CGMS criteria [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})]

3. Atmospheric Motion Vectors in Regional NWP

A number of data assimilation experiments over the Australian region using local AMVs has been completed. In three experiments, different *types* of AMVs were added individually to the BoM's operational data base to gauge their impact on operational Regional NWP (Le Marshall et al. 1994, 1996, 1999). After these experiments, *all* vectors were used together with the BoM's real time data base to gauge their combined impact on the operational Regional NWP model, (LAPS (Puri et al. 1998)).

3.1 Recent Studies

The first study gauged the impact of local six-hourly GMS-5 IR-1 AMV data on operational NWP in the Australian Region. The local AMV system provided winds at six-hourly intervals from triplets of half-hourly GMS-5 IR1 imagery. LAPS was employed with 6-hour cycling and the operational database (including NESDIS and local TOVS data and JMA AMVs available at the operational cutoff time of +6 hrs. for the 06 and 18 UTC based forecasts and +1.5 hrs. for the 12 and 00 UTC based forecasts) to provide the control forecasts. In parallel, using the same assimilation system, the local IR1 AMVs were added to the operational data base for real time assimilation runs. The S1 skill scores (Teweles and Wobus, 1954), tabulated on the official National Meteorological and Oceanographic Centre (NMOC) verification grid, for 24 hour forecasts from the local AMV (LAPS + IR) and matching control forecasts (LAPS) are shown in Table 3 (a).

Level	(LAPS)-S1	(LAPS + IR)S1
MSLP	26.4	25.4
850 hPa	24.8	23.9
500 hPa	16.1	15.7
300 hPa	14.0	13.7

Table 3. (a) 24 hr forecast verifications (S1) for the operational regional model (LAPS) and LAPS with local GMS-5 IR-1 AMVs (LAPS + IR) for 20 June to 18 August 1995 (19 cases).

Level	(LAPS + IR)S1	(LAPS + VIS/IR/Hrly) S1
MSLP	27.6	26.7
850 hPa	29.2	27.7
500 hPa	19.0	18.7
300 hPa	16.6	16.1

(b) 24 hr forecast verifications (S1) for the control (LAPS) and the control plus hourly/six hourly IR and VIS AMVs (LAPS + VIS/IR-Hrly) for 5 September to 4 December 1995 (22 cases)

Level	(LAPS) S1	(LAPS + WV) S1
MSLP	25.2	25.1
850	25.9	25.4
500	20.1	19.4
300	17.3	16.8

(c) 24 hr forecast verification (S1) for the control (LAPS) and LAPS with water vapour motion vectors (LAPS + WV) for March 1998 (33 cases)

A second experiment (Le Marshall et al. 1996) used hourly IR and VIS winds added to the (operational) control data base (which now included *local 6-hourly IR winds*). Winds generated from image triplets centred within one hour of analysis time were used in this study. The S1 skill scores for the control 24 hour forecasts (LAPS) and for the matching forecasts with VIS and IR AMVs (LAPS + VIS/IR-Hrly) are in Table 3 (b). These indicate that the additional winds had the potential to improve operational regional forecasts, even when 6-hourly local IR AMVs were in the control data base.

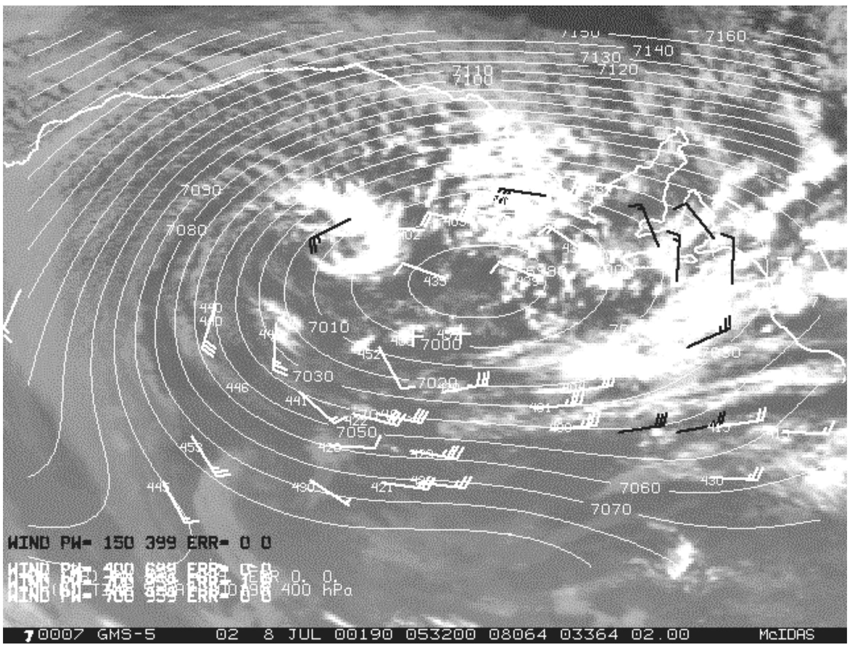

Fig. 3 GMS-5 Water Vapour AMVs with pressure heights displayed over an 0530 UTC GMS-5 6.7 µm image on 8 July 2000 with the NMOC 400 hPa analysis for the same time.

In a third experiment (Le Marshall et al. 1999), WV AMVs calculated four times per day from three images, separated by 30 minutes, were added to the operational data base.

Thirty three forecasts were examined and the results are summarised in Table 3 (c). On average, at all levels examined, a modest improvement in the twenty four hour regional forecasts.

Individual improvements, however, can be quite significant, for example, up to five points during this trial. In some cases, water vapour motion vectors can clearly be seen to contain important information for analysis. Figure 3, for example, shows a GMS-5 WV image for 0530 UTC on 8 July 2000 overlaid by the operational 400 hPa analysis for the same time. In this case, WV AMVs indicate that the low centre in the operational analysis at 400 hPa, which had no access to these AMVs, should be further to the south west.

3.2 The Operational Trial : The Application of Infrared, Visible and Water Vapour Image based Winds in the Australian Region

In a recent experiment, *all* the wind types employed in the previous experiments were added at the same time to the operational regional assimilation system. The assimilation methodology was largely unchanged from that used previously, however, there were some changes in the analysis and prognosis system, in particular, a move from 0.75° to 0.375° horizontal resolution and 19 to 29 vertical levels.

The accuracy of the real time AMVs used in this experiment in late 2000 is sumarised in Table 2. The statistics correspond to an expected RMS difference (error) threshold in the case of lower level IR1 winds, of around 4 ms^{-1} (or a QI threshold of 0.83). The data insertion methodology used for this operational trial which employed 6-hourly intermittent data assimilation, is summarised in Fig. 4.

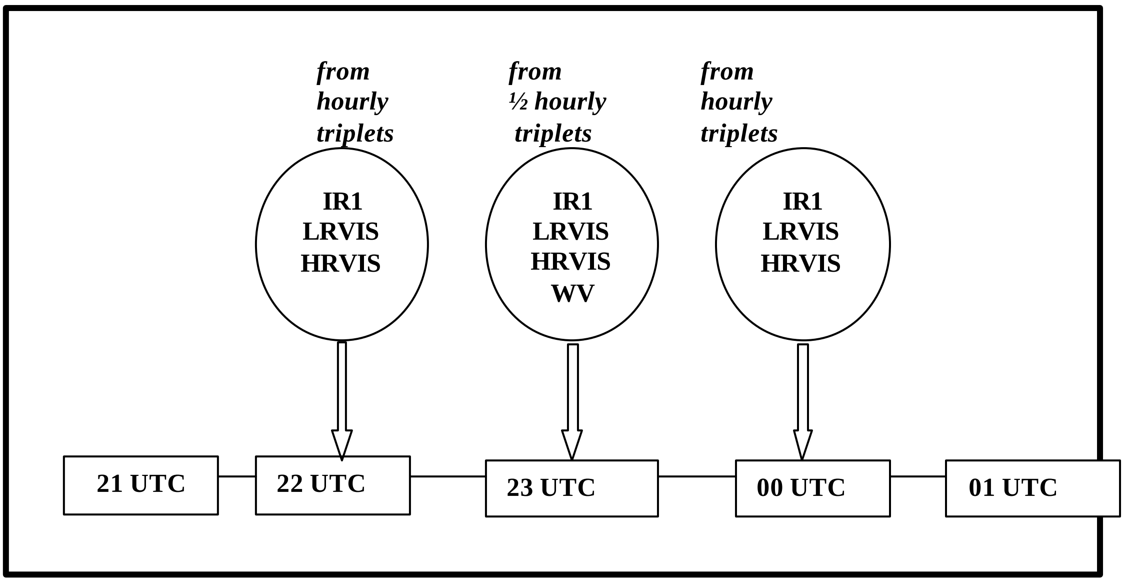

Fig. 4 Schematic diagram showing the nominal central image time of triplets used to generate AMVs in the assimilation of VIS/HRVIS, WV and IR1 image-based winds.

It shows winds generated from triplets of IR, VIS and HR VIS images, with the images separated by one or half an hour, have been used when *the image triplet is centred within one hour of the analysis time*. In the case of WV winds, only winds generated *at the analysis* time were used. This approach was found to provide effective data coverage consistent with both AMV accuracy and with the resolution and characteristics of the data assimilation system. The S1 skill scores for 24-hour forecasts from using these data are compared to the operational skill scores in Table 4. The improvement recorded is consistent with the three earlier experiments.

LEVEL	(LAPS) S1	(LAPS + VIS/IR/ WV HRLY) S1
MSLP	25.6	24.6
850 hPa	24.8	24.2
500 hPa	16.6	16.5
300 hPa	14.7	14.5

Table 4. 24 hr forecast verification (S1) for the operational LAPS and LAPS with VIS, IR and WV AMVs for 12 October - 10 November 2000 (47 cases)

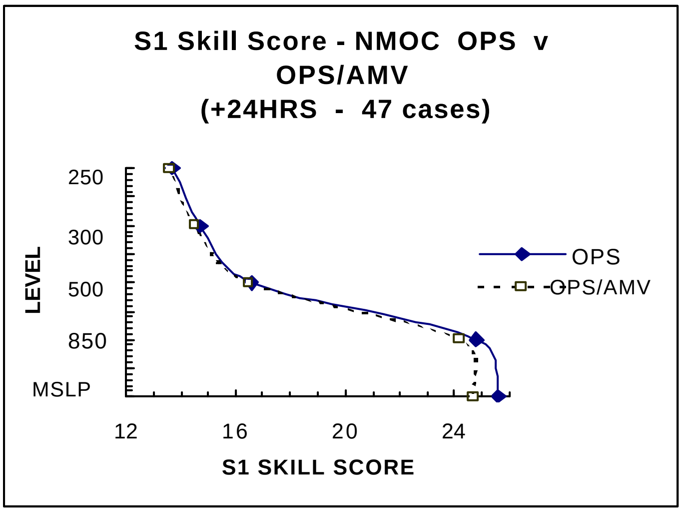

Fig 5. Skill scores (12 Oct. to 10 Nov. 2000) from 47 cases for NMOC forecasts (OPS) and OPS with IR/WV AMVs (OPS/AMV) for (47 cases)

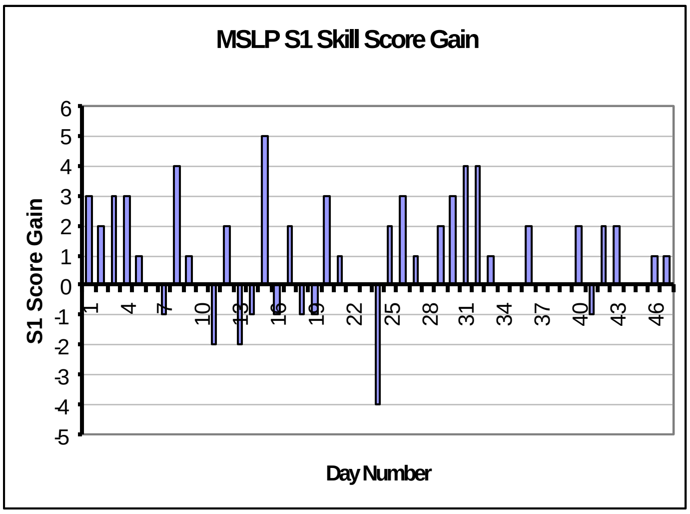

Fig. 6 Skill score gain for 24 hr. forecasts at MSLP with use of the VIS, IR and WV AMVs (12 October - 10 November 2000)

The results are also illustrated in Figs 5 and 6. Fig. 5 shows that these data on average, improved the real time forecast at all levels with greater impact in the lower troposphere. Fig. 6 shows the individual S1 skill score gain each day at MSLP. It is clear that these winds are beneficial to the forecast process. In summary, the IR, VIS, HR VIS and WV image based AMVs, generated in real time from GMS-5 S-VISSR images, are of an accuracy which is of benefit to operational regional NWP. *As a result of this trial, all of these wind types have been employed in the operational regional forecast system in NMOC, Melbourne since November 2000*.

4. Preparation for Advanced Imagers

The trend to space-based observations with higher spatial, temporal and spectral resolution 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 resolution comes the opportunity to exploit 3-D and 4-D variational assimilation (3-D and 4-D VAR.). The potential benefits from the use of AMVs on local scales using 4-D VAR. can be seen in experimental studies of Le Marshall et al. (1996b) and Le Marshall and Leslie et al. (1998) where the methods of Bennett et al. (1996) were employed. In those studies, use of near time continuous, real time winds and 4-D VAR for forecasting tropical cyclone tracks has been shown to have the potential to be very effective (Le Marshall and Leslie 1998), reducing 48-hour forecast errors to well below 200 km for the 11 cases studied. The benefits of the AMVs at global scales from the use of 4-D VAR. can be seen in studies of Bouttier and Kelly (2001) using the operational ECMWF 4-D VAR system. They have summarised the impacts of SATOBs showing small positive impact over the Southern Hemisphere mid-troposphere and mixed impact in the Tropics at 1 to 3 days.

Of considerable benefit to science, meteorology and operational forecasting in the Australian region 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 part of its lifetime near Continental US and later over the Indian Ocean. 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 GIFTS will allow the estimation of AMVs from both cloud tracking and from the tracking of features in the water vapour fields.

Several methods will be employed at SSEC Wisconsin and later at the BoM for estimation of 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 band 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. This method has already been demonstrated at SSEC Wisconsin and later in the BoM. Another approach is to use either sequential moisture (or radiance) observations as input for 4-D VAR. and rely on the initialisation to provide consistent velocity and moisture estimates. Initial studies examining this methodology using NAST-I (NPOESS Airborne Sounder Test-bed Interferometer) data from the CAMEX-3 experiment near Andros Is., in September 1998 have been undertaken (Leslie, Le Marshall and Smith, 2001). They found, using 4D-VAR 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.

5. Summary and Conclusions

A brief history of the use AMVs in NWP has been given. The estimation of local AMVs and their impact on Regional NWP has been described. Experiments using these data in regional NWP have been described and the benefit of these data to regional NWP clearly recorded. *These results have led to the introduction of all these wind types into NMOC's operational data base since November 2000.* Preparations for the use of observations from the revolutionary GIFTS have been noted. Overall, it would appear that the higher spatial, temporal and spectral resolution satellite observations soon to be available, should enable improved estimation of atmospheric motion and result in quantitative benefit to NWP.

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