HIGH SPATIAL AND TEMPORAL RESOLUTION ATMOSPHERIC MOTION VECTORS – GENERATION, ERROR CHARACTERIZATION AND ASSIMILATION

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ABSTRACT

Data from the Japanese geostationary satellite MTSAT -1R (and at times MTSAT-2) have been received at the Bureau of Meteorology (BoM) satellite groundstation at Crib Point, Victoria. Calibrated and navigated sequential radiance data have been subsequently used to calculate high density Atmospheric Motion Vectors (AMVs). These AMVs have been generated almost continuously throughout the day using sequential images separated by 15-minutes, 30 minutes or an hour. The winds have been calculated using infrared (11 µm), (high resolution) visible (0.5 µm) and water vapour absorption (6.7 µm) band images. The AMVs have been error characterized with error characteristics including the correlated error, the length scale of the correlated error, the Expected Error and Quality Indicator being estimated. These AMV data are important for operational NWP, research and particularly for severe weather forecasting, including tropical cyclone track forecasting. The data have been used in real time data assimilation experiments and their benefit to the operational LAPS (Limited Area Prediction System) regional Numerical Weather Prediction (NWP) system at the BoM has been documented.

The near continuous generation of winds has also been taken advantage of using 4D-VAR and their utility for regional forecasting has also been recorded. Their utility for tropical cyclone prediction has already been demonstrated in a number of studies. In recent studies using the Australian Community Climate Earth-System Simulator (ACCESS), which is the Bureau of Meteorology's new operational NWP system, locally generated high spatial and temporal resolution (hourly) AMVs from MTSAT-1R have been used with 4D-VAR (four dimensional variational assimilation) and their beneficial impact , in the region and with tropical cyclone track prediction, has been recorded.

Background

The location of Australia in the data sparse great southern oceans has resulted in dependence on satellite remote sensing and satellite data assimilation for high quality analysis and NWP in our region. AMVs make an important contribution to the satellite data base, for example being one of the most important satellite observations for tropical cyclone track prediction. To provide accurate, high density and timely winds for operational NWP and climate studies in the Australian Region, AMVs have been operationally calculated locally, from sequential GMS images (Le Marshall et al., 1994, 2002), GOES-9 images (Le Marshall et al., 2004b), and now MTSat-1R images (Le Marshall et al., 2008). The operational processing and operational use of hourly winds was introduced in 1996 (Le Marshall et al., 1996). MTSat-1R has been used to provide AMVs at 15-minute intervals, four times daily, and half hourly or hourly for the rest of the time. Winds have been generated using infrared (11 µm), visible (0.5 µm) and water vapour absorption (6.7 µm) band images. Here we examine the generation, quality control and application of winds generated from triplets of 15-minute interval infrared imagery every six hours and from triplets of images separated by one hour. The hourly generation of winds has allowed their use in 4D-Var where for example their utility for tropical cyclone prediction has already been demonstrated (Le Marshall et al.,1996, 2000a; Leslie et al.,1998).

The methods used at the Bureau, to estimate AMVs, from GMS S-VISSR data, are largely covered in Le Marshall et al. (1999, 2000b). Sequential infrared (IR), visible (VIS) or water vapour (WV) band images (a triplet), usually separated by an hour or half an hour were used for velocity estimation. As a result, high density winds were generated continuously at hourly or half hourly intervals. Selected targets in the imagery were tracked automatically using a lagged correlation technique, which minimised root mean square (RMS) differences in brightness from successive pictures to estimate the vector displacement.

Cloud height assignment used forecast temperature profiles. The cloud height assigned for low-level clouds was that of the cloud base (following the work of Hasler et al. (1976, 1977)). The benefit of cloud base height assignment is shown in Le Marshall and Pescod (1994). Height assignment involved fitting Hermite polynomials to smooth raw histograms of brightness temperature, enabling estimation of cloud base altitude from cloud base temperature. Upper level AMVs were assigned to the cloud top altitude which was estimated using 11 and 12 µm split window observations (Le Marshall et al, 1998). For water vapour AMVs, height assignment of the upper and middle-level AMVs in clear conditions was described in Le Marshall et al. (1999).

During the generation of the AMVs, their error characteristics were also determined and each vector has been assigned several error indicators, including the Expected Error (EE) and Quality Indicator (QI). Their correlated error and length scale of the correlated error (Le Marshall et al., 2004a) has also been provided.

When GOES-9 replaced GMS-5 in 2003, methods similar to those employed at NESDIS (Daniels et al. 2000) and also at the Bureau (Le Marshall et al. 2000b) were used to generate AMVs from GOES-9 GVAR data received at the Bureau's groundstation at Crib Point (Le Marshall et al., 2004b). In this system, target selection began with a search for tracers using bidirectional brightness temperature gradients in 15 x 15 pixel boxes. Gradients were examined to ensure that cloud edges were being tracked and prospective targets were subjected to a spatial coherence analysis (Coakley and Bretherton, 1982) and tracked using a lagged correlation technique. After tracer selection, three sequential GOES-9 infrared images were carefully navigated using matching of land features to ensure that there was consistency between the images used for estimating cloud displacement.

The height assignment method used for upper level AMVs was based on Schmetz et al. (1993). The technique employed was the H_2O-intercept method, using 11 µm (channel 4) observations and the 6.7 µm (channel 3) observations. Radiances from the infrared and water vapour channels were measured and compared to calculate Planck blackbody radiances as a function of cloud top pressure. The cloud top altitude was then inferred from a linear extrapolation of radiances onto the calculated curve of opaque cloud radiances, providing the target altitude. The approach was described in Nieman et al. (1993). The low-level AMV altitude assignment technique was similar to that developed in the Bureau of Meteorology (Le Marshall et al. 2000b) where cloud altitude was assigned to the cloud base for low-level vectors. As with the GMS-5 , the error characteristics of these vectors were determined and each vector was associated with error indicators such as the EE and QI as well as with a correlated error and the length scale of the correlated error.

MTSat-1R Atmospheric Motion Vectors

When MTSat-1R replaced GOES-9 in 2005, again, methods similar to those employed at NESDIS (Daniels et al. 2000, Velden et al. 2005) and also at the Bureau (Le Marshall et al. 2000b) were used to generate AMVs from the MTSat-1R HIRID data received at the Crib Point groundstation. Three sequential images from MTSat-1R were navigated using land features to ensure that there was consistency between images used for estimating cloud displacement. In this system, target selection for infrared (11 µm) targets, commenced with a search for tracers, using bidirectional brightness temperature gradients in 15 x 15 pixel boxes. As in the case of GOES-9, targets with gradient features were subjected to a spatial coherence analysis (Coakley and Bretherton, 1982) and tracked using lagged correlation.

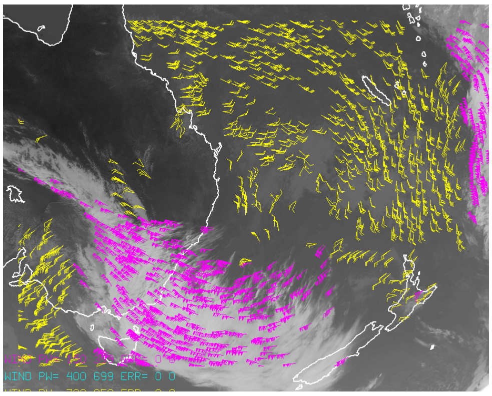


Fig. 1(a) MTSat-1R IR1 AMVs generated around 06 UTC on 17 September 2009. Magenta denotes upper level tropospheric vectors, yellow, lower level tropospheric vectors.

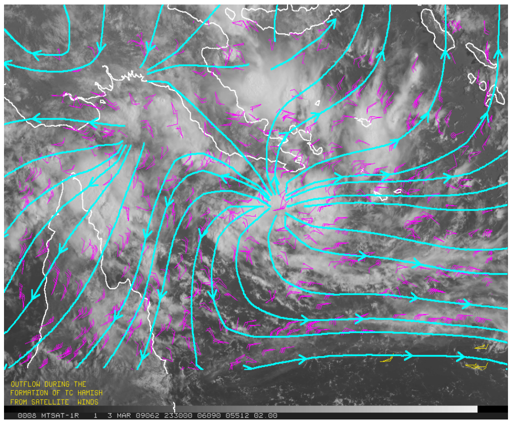


Fig. 1(b) Upper level streamline analysis (100-300HPa) from local MTSAT-1R AMVs during the formation of TC Hamish at 2330UTC on 3 March 2009.

Height assignment methods were similar to those employed for GOES-9. Figure1(a) is an example of the local MTSat-1R IR AMVs generated for 06 UTC on 17 September 2009. Figure 1(b) shows usage of local MTSAT-1R AMVs to produce an upper level streamline analysis (100-300hPa) during the formation of TC Hamish at 2330UTC on 3 March 2009. The schedule for generating these MTSat-1R based winds in the Southern Hemisphere can be seen in Table 1.

Table 1. Real time schedule for MTSat-1R Atmospheric Motion Vectors at the Bureau of Meteorology. Sub-satellite image resolution, frequency and time of wind extraction and separations of the image triplets used for wind generation (ΔT) are indicated.

Wind Type	Resolution	Frequency-Time (UTC)	Image Separation(ΔT)
Real Time IR	4 km	6-hourly – 00, 06, 12, 18	15 minutes
Real Time IR (hourly)	4 km	Hourly – 00, 01, 02, 03, 04, 05, . . . , 23	1 hour

Accuracy and Quality Control

Careful quality control (QC) and error characterisation ensure the AMVs have a beneficial impact on NWP (Le Marshall et al. 2004a). Error characterisation used the Bureau's initial error flag (ERR), which involved a number of basic checks (first guess departure check, vector pair acceleration check, tracer constancy check etc.) , the Quality Indicator (QI), (Holmlund et al. 1998) and the more recent Expected Error (EE), (Le Marshall et al. 2004a).

These error indicators are used to effectively thin the AMVs and to ensure good data coverage with average separations consistent with the Length Scale of the Correlated Error. The thinning methodology has also ensured that the errors are not significantly larger than the background error field of the forecast model as measured at radiosonde sites. The approach is detailed in Le Marshall et al. (1994a). The EE now has several components, the total root mean square (rms) error (m/s) currently used operationally, the meridional and the zonal error components (m/s) and the AMV height error (hPa). The total rms error component of the EE has been used in this study. A typical comparison of the EE with the actual error for MTSat-1R IR winds is seen in Figure 2.

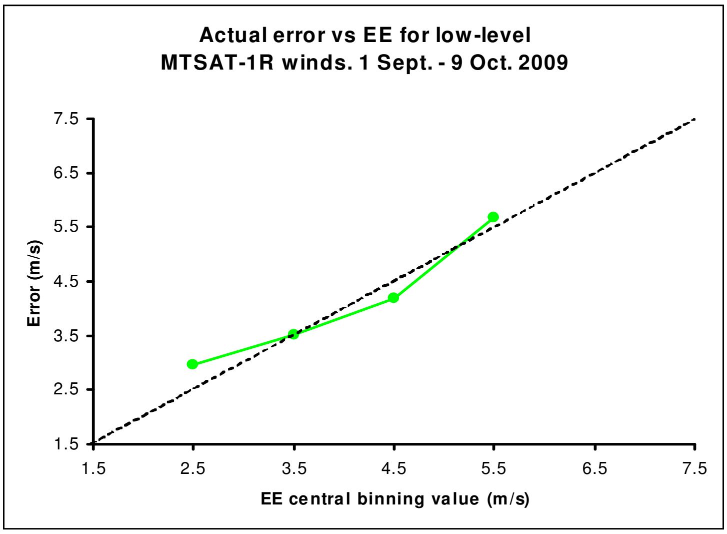


Fig. 2 Measured error (m/s) versus EE for low-level MTSAT-1R IR winds (1 September – 9 October 2009).

Here, the root mean square error component of the EE has been compared to the actual rms error determined using contemporaneous radiosonde data within 150 km of the AMVs and is seen to be an effective tool for selecting high quality AMVs. The figure shows statistics for the current ACCESS based AMV system.

Quality control of AMVs to provide low, middle and high level data in the BoM system has used all 3 error indicators (EE, QI, ERR). Typical accuracy of the AMVs available for NWP is given in Table 2, which shows the Mean Magnitude of Vector Difference (MMVD) and Root Mean Square Vector Difference (RMSVD), between MTSat-1R AMVs used in the assimilation study reported later and radiosondes winds in the Australian Region, for 1 September to 9 October 2009.

Table 2. Mean Magnitude of Vector Difference (MMVD) and Root Mean Square Difference (RMSD) between MTSAT-1R IR1 AMVs, forecast model first guess winds and radiosonde winds for the period 1 September to 9 October 2009.

Level	Data Source	Bias (m/s)	MMVD (m/s)	RMSVD (m/s)
High – up to 80 km separation between radiosondes and AMVs	**AMVs**	-0.65	3.31	3.92
	Background	-0.30	3.48	4.09
Low - up to 150 km separation between radiosondes and AMVs	**AMVs**	0.17	2.86	3.36
	First Guess	0.18	2.67	3.14
Low – up to 30 km separation between radiosondes and AMVs	**AMVs**	0.22	2.26	2.51
	First Guess	-0.24	2.30	2.57

Correlated Error

As with earlier geostationary satellite local AMV systems, the correlated error has been analysed for the Bureau produced MTSat-1R winds. The correlated error and its spatial variation (length scale) were determined using the Second Order Auto Regressive (SOAR) function :

$$R(r) = R_{00} + R_0(1 + r/L) \exp(-r/L) \quad (1)$$

where R(r) is the error correlation, R_0 and R_{00} are the fitting parameters (greater than 0), L is the length scale and r is the separation of the correlates. Thus, the difference between AMV and radiosonde winds (error) has been separated into correlated and non-correlated parts. The parameters of the SOAR function which best fits the data is shown in Table 3. These length scales may be compared to those from GMS-5, namely, 123 km and 73 km, for low and high levels respectively, where the GMS-5 vectors were subjected to a quality control regime close to that of EE < 6.

Table 3: Parameters of the SOAR function (Equation 1) which best model the measured error correlations for the MTSat-1R AMVs listed in the left column of the table. (February – April, 2007).

MTSat-1R IR1 AMVS	R_{00}		R_0		L (km)	
	Low	High	Low	High	Low	High
EE < 6	0.006	0.370	0.460	0.460	86.000	99.900
EE < 8	0.066	0.052	0.640	0.440	122.700	110.900

AMV Assimilation Trials

The 2007 LAPS Based Assimilation Trial

Before local MTSat-1R data were introduced into the Bureau's 2007-2010 operational NWP suite, real time assimilation trials using MTSat-1R infrared channel 1 (IR1) AMVs were undertaken using the operational 2007 LAPS system configured to run at 0.375° horizontal resolution with 61 levels in the vertical. The assimilation system and methodology are described below. The results from the trial were similar and consistent with earlier results from assimilation of GMS-5 and GOES-9 local AMVs (e.g. Le Marshall et al., 2002; Le Marshall et al., 2004b).

The assimilation system

The assimilation methodology employed the real time operational NMOC regional Limited Area Prediction System, using all available data (including all available AMVs from the Japanese Meteorological Agency (JMA)) as the control. The analyses on which the forecasts reported here were based started with a BoM Global Analysis and Prognosis System (GASP) global analysis (Seaman et al. 1995), valid 12 hours prior to the forecast start time. This was used as a first guess to the regional analysis which then provided the base analysis for an initialised six hour forecast, a subsequent analysis and a further initialised six hour forecast. This forecast was then used as a first guess to the final analysis from which the 24 and 48 hour forecasts were run. Forecasts were nested in fields from the most recent GASP forecast (Bourke et al. 1995). The analysis and forecast models used in this trial are described in Le Marshall et al. (2008).

Method

In the 2007 real time trial MTSAT-1R AMVs, generated using 11 µm (Channel IR1) and 6.7 µm (Channel IR3) imagery were added to the 2007 operational regional assimilation system. The system already contained AMVs from the JMA, available up to the operational cut-off time (analysis time + 1.75 hours; 0.75 hours when daylight saving applies), which can preclude on time vectors. In the study, local quality control methods were used to provide vectors with an expected error consistent with the error levels anticipated for AMVs in the operational analysis. The data used for this operational trial was generated from triplets of IR and WV images centred at 00, 06, 12 and 18 UTC where the images used were separated by 15 minutes. The system provided AMV coverage and accuracy consistent with the length scale of the correlated error, the analysis background error and the resolution of the data assimilation system.

A series of parallel *real time* forecasts was run using the late 2007 operational forecast system with the AMV data added to the operational database. The period studied was from *1 September to 8 October 2007* (72 cases). For these real time forecasts, the S1 skill scores (Teweles. and Wobus, 1954) were calculated on the NMOC operational verification grid using 00 UTC and 12 UTC analyses. The verification grid consists of 58 points within the domain 90° E to 170° E, 15° S to 55° S. The exact grid is seen in Bennett and Leslie (1981).

Results

The S1 skill scores for 24-hour forecasts resulting from using, local MTSAT-1R AMV data plus the operational data base, in the operational (L61) LAPS model were compared to the skill scores of the control, which used the operational data base only (see Table 4). The statistics were consistent with those recorded in earlier impact studies with GMS-5 (Le Marshall et al. 2002) and GOES-9 (Le Marshall et al., 2004) where a modest positive impact, mainly in the lower levels, was recorded. The results showed that real time MTSAT-1R IR and WV image based AMVs, were of an accuracy which could benefit operational NWP in the Australian Region. Addition of the vectors to the operational regional forecast system which already contains some JMA AMVs, provided both improved data coverage of the region and small average forecast improvement. These results and their consistency with previous studies led to operational use of these local AMVs.

Table 4: 24 hour forecast verification S1 Skill Scores for the late 2007 operational regional forecast system (L61 LAPS) and L61 LAPS with IR, 6-hourly image based AMVs for 1 September to 8 October 2007 (72 cases).

LEVEL	(LAPS) S1	(LAPS + MTSAT-1R AMVS) S1
MSLP	20.24	19.15
1000 hPa	20.06	19.13
900 hPa	18.65	17.75
850 hPa	17.41	16.69
500 hPa	12.41	11.73
300 hPa	10.49	9.76
250 hPa	12.41	11.90

The 2009 ACCESS Based Assimilation Trial

To test the utility of assimilating continuous wind observations using 4D-VAR in the BoM's new operational ACCESS regional NWP system (ACCESS-R), hourly and four times a day (00, 06, 12 and 18UTC) fifteen minute local MTSat-1R AMVs were used. The operational ACCESS-R system of 2009 had a 0.375° horizontal resolution with 50 levels in the vertical. The assimilation system and methodology are described below. The results from the trial were again consistent with earlier results from assimilation of GMS-5, GOES-9 and MTSat-1R local vectors (e.g. Le Marshall et al., 2002; Le Marshall et al., 2004b; Le Marshall et al., 2008 respectively) and showed improved forecasts in the lower, middle and upper troposphere.

The Assimilation System

The assimilation system used was similar to the real time operational NMOC regional ACCESS-R system, which used all available data, including all available JMA AMVs. The analysis methodology on which the forecasts reported here were based, was 4D-VAR. The analyses were performed at 00, 06, 12, and 18UTC and the time window for the analyses was +3 to -3 hours. The forecast system was warm run and forecasts were nested in fields from the most recent ACCESS-G forecast. The ACCESS-R system is a regional implementation of the United Kingdom Meteorological Office Unified Model (UKUM). The configuration consists of 220 x 320 gridpoints at 0.375° spacing in the horizontal and 50 levels (50L) in the vertical. The analysis is undertaken on a 110 x 160 grid with 0.75° spacing in the horizontal. The model and analysis timestep is 15 minutes. Lateral boundary conditions for the forecast model are derived from the N144L50 ACCESS-G global forecast model. A summary of the characteristics of the ACCESS-R forecast system is seen Table 5.

Table 5: The Characteristics of the ACCESS-R Forecast System.

DOMAIN : AUSTRALIA REGION	65.0°S TO 17.125°N, 65.0°E TO 184.625°E
UM Horizontal Resolution (lat x lon)	220x320 (0.375°)
Analysis Horizontal resolution (lat x lon)	110x160 (0.75°)
Vertical Resolution	L50
Observational Data Used (6h window)	AIRS, ATOVS, Scat, AMV, SYNOP, SHIP, BUOY,AMDARS, AIREPS, TEMP, PILOT
Sea Surface Temperature Analysis	Daily 1/12° SST analysis
Soil moisture analysis	N144L50 soil moisture field SURF once every 6 hours
Model Time Step	15 minutes (96 time steps per day)
Analysis Time Step	15 minutes
Nesting	Lateral Boundary Condition derived from N144L50

Method

The assimilation methodology employed a system, similar to that of the operational NMOC regional ACCESS-R system. The *control* forecast used all available data, including all available JMA AMVs. The *experimental* system was similar but had local MTSAT-1R AMVs added to the operational/control data base.

The local MTSAT-1R AMVs were both 15 minute and hourly IR and VIS image based AMVs. The AMVs were generated in real time using 11 μm (Channel IR1), 0.55-0.9 μm (Channel VIS) and 6.7 μm (Channel IR3) imagery. The wind generation system used the ACCESS-G system for a number of tasks including tracking, height assignment and quality control. The characteristics of the real-time IR1 image based AMVs generated from 15 minute interval images, available every six hours is shown in Table 2. The characteristics of the IR1 image based AMVs generated from hourly imagery were similar, but the hourly images produced fewer vectors. The visible image-based winds also appeared to have similar characteristics to the IR1 winds for the September/October 2009 period studied. Again, local quality control methods were used to provide vectors with a coverage and accuracy consistent with the length scale of the correlated error, the analysis background error and the resolution of the data assimilation system.

A parallel *real time* forecast trial was run using the late 2009 operational ACCESS-R forecast system with the AMV data added to the operational database, which included all available MTSat-1R AMVs from JMA. The experimental period was from 1 September to 10 October 2009. For these forecasts, errors in wind, temperature and geopotential height and the S1 skill score (Teweles. and Wobus, 1954) were calculated.

Results

The RMS difference between forecast and verifying analysis geopotential height at 48 hours for the *control* ACCESS-R system (operational database) and the *experimental* ACCESS-R system (operational database plus local hourly AMVs) for the period 1 September to 10 October 2009 seen in Figure 3. In addition the RMS difference between the forecast and verifying analysis geopotential height at 48 hours are also provided for the current operational LAPS systems. It can be seen that the ACCESS-R system provides a significant increase in skill when compared to the operational LAPS system. This increase is due to improved modelling, assimilation methodology and an enhanced database. It can also be seen that addition of continuous (hourly) AMVs to the access system has also provided improvement to forecasts throughout the troposphere for the month studied.

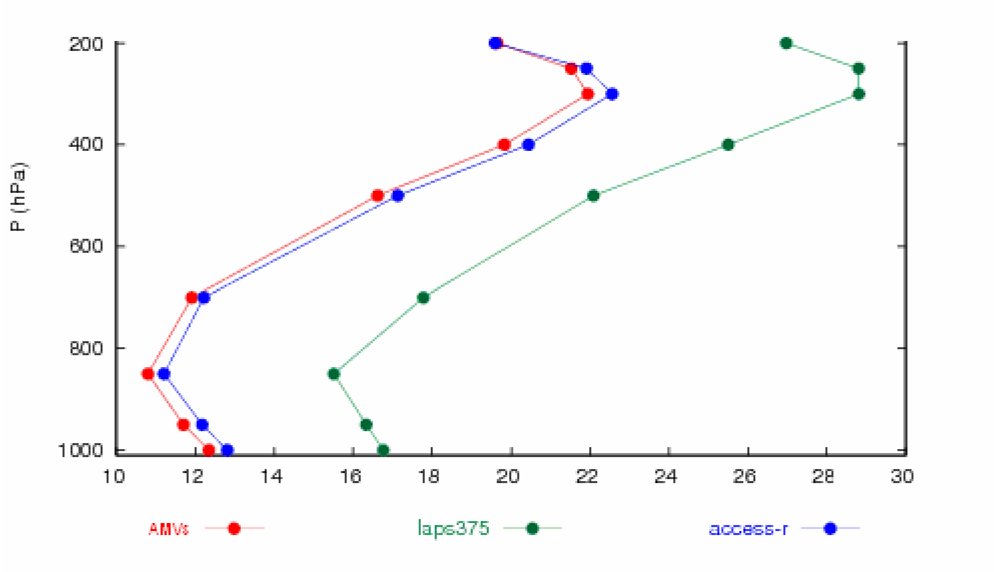


Fig.3 The RMS difference between forecast and verifying analysis geopotential height at 48 hours for LAPS375 (Green), ACCESS-R (blue) and ACCESS-R with AMVs (red) for the period 1 September to 10 October 2009.

The statistics are consistent with those recorded in earlier impact studies with GMS-5 (Le Marshall et al. 2002), GOES-9 (Le Marshall et al., 2004) and MTSAT-1R (Le Marshall et al., 2008) where a modest positive impact, through the troposphere, was recorded. The results showed that real time hourly MTSAT-1R IR, VIS and WV image based AMVs assimilated using 4D-VAR, are of an accuracy which can benefit operational NWP in the Australian Region. Addition of the vectors to the operational ACCESS-R regional forecast system which already contains some JMA AMVs, provided both improved data coverage of the region and small average forecast improvement. The results and their consistency with previous studies led to the operational use of these local AMVs.

The Future

Development work is currently proceeding in several areas. One area is the verification of cloud height determination and the improvement of cloud height estimation techniques. As part of this CLOUDSAT and CALIPSO data are being employed to produce match files which contain CLOUDSAT and CALIPSO based cloud fields, model cloud fields, AMVs and where available radiosonde data. An early example of the information contained in the CLOUDSAT and CALIPSO data sets is seen in Figure 4. These data are currently being used to improve cloud height estimation and the estimation of cloud height errors. They provide important information particularly in the area of determination of cloud base.

Another area of study is preparation for the reception and processing of MTSAT-2 observations later this year. Some experience was gained in using MTSAT-2 observations during 2009, while it was the operational geostationary satellite observing the Australian region. AMVs were generated from MTSAT-2 images and after significant testing and using information from previous tests with MTSAT-2, they were introduced into operations at the Bureau of Meteorology. An example of AMVs generated from MTSAT-2 seen in Figure 5(a), while typical operational coverage is seen in Figure 5(b).

Another area of activity is optimisation of the use of continuous AMVs in four dimensional variational assimilation. Continuous (hourly) AMVs have been generated from MTSAT-1R and

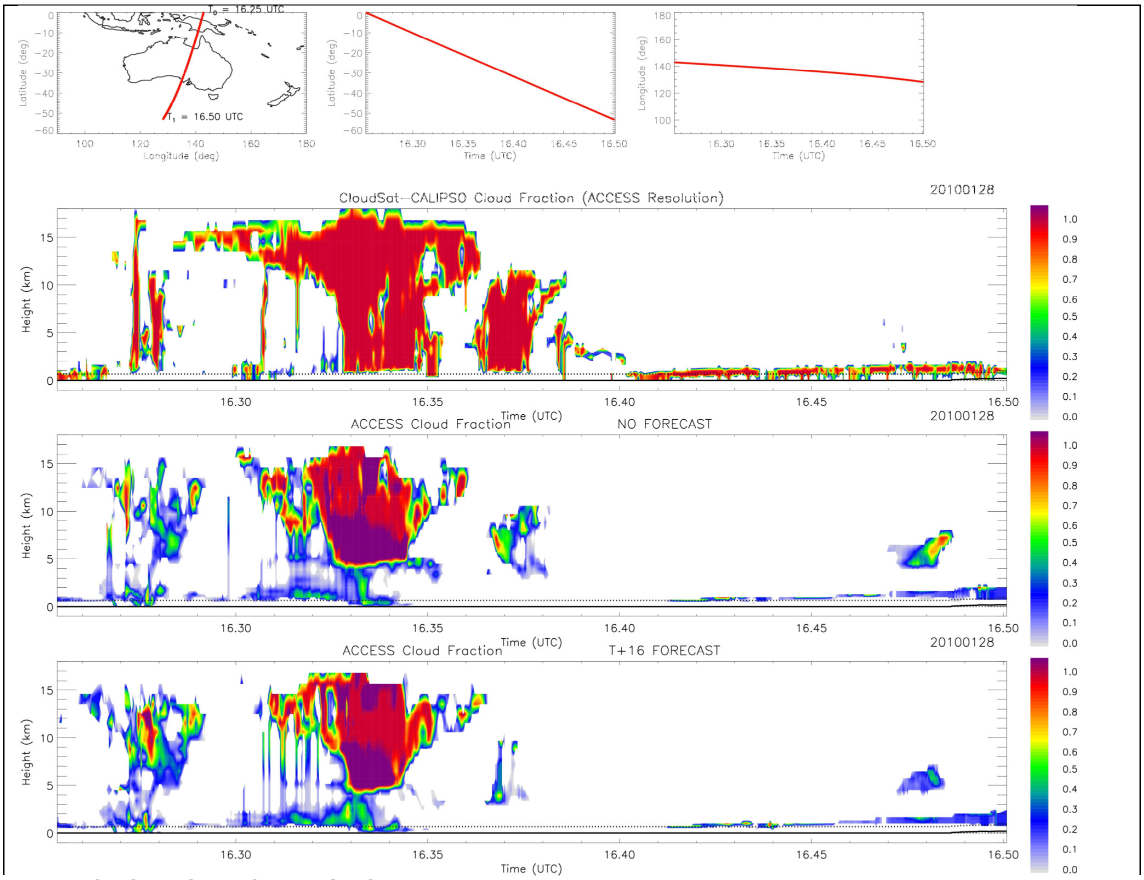
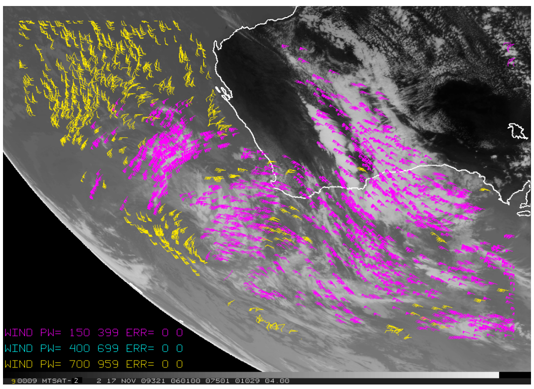


Fig.4 CLOUDSAT-CALIPSPO and a model analysis and forecast cloud fraction around 1640 UTC 28 January 2010.

used in the operational ACCESS-R system, where they have been demonstrated to improve regional forecasts. In addition a study documenting the utility of MTSAT-2 AMVs for tropical cyclone forecasting is underway. The study is examining the use of these continuous data sets in the forecasting of tropical cyclone track and intensities.



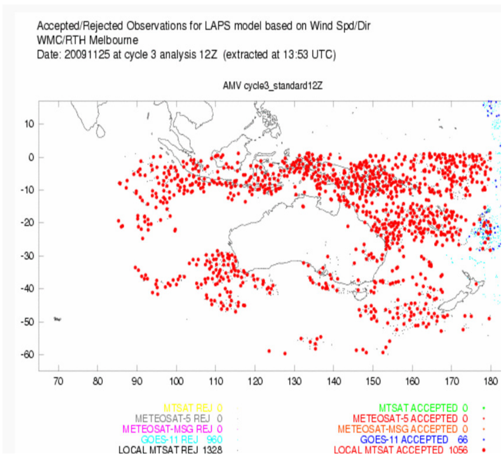


Fig. 5(a) MTSat-2 IR1 AMVs generated around 06 UTC on 17 November 2009. Magenta denotes upper level tropospheric vectors, yellow, lower level tropospheric vectors .

Fig. 5(b) MTSat-2 IR-1 AMVs generated around 012 UTC on 25 November 2010. Red denotes AMVs used by the operational analysis.

This work has involved generating large numbers of vectors which have been suitably quality controlled and use in tropical cyclone track prediction using 4D-Var.

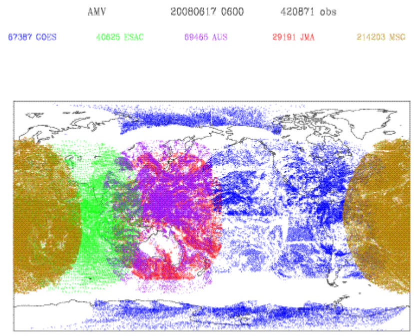


Figure 6(a) The winds generated around 06UTC on 17 June 2008. Note the more than 69,000 AMVs generated by MTSAT-1R at the time of Tropical Cyclone Feng Shen.

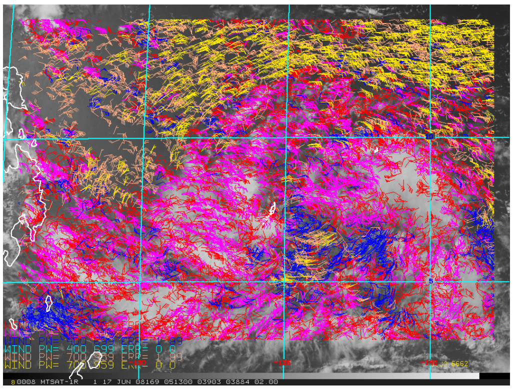


Figure 6(b) The AMV distribution around the Tropical Cyclone Feng Shen at 06 UTC on 17 June 2008.

An example of this work is seen in Figure 6(a), which shows the more than 69,000 AMVs generated by MTSAT-1R at 06UTC, 17 June 2008, around the time of Tropical Cyclone Feng Shen. Figure 6(b) shows the related AMV distribution around the cyclone, again at 06 UTC on 17 June 2008. In preliminary experiments, winds calculated during this study and used with 4D-VAR have provided promising forecasts.

Summary and Conclusions

The local estimation of real time operational MTSAT-1R AMVs and their impact on operational regional NWP has been described. Experiments using these real-time data in NWP trials have been summarized. Their benefit to current operational regional NWP, both in the LAPS and ACCESS-R system, when used with a control employing NMOC's full operational data base (including JMA AMVs), has been recorded. These results were consistent with past trials with GMS-5 and GOES-9 and have resulted in the use of these local vectors in operations.

The recent ACCESS-R trial has used continuous (at least hourly) local real time operational MTSAT-1R IR and VIS AMVs and their beneficial impact on operational regional NWP using 4D-VAR has been described.

Looking ahead, the continuing trend to space-based observations with higher spatial, temporal and spectral resolution should enable improved estimation of atmospheric motion and result in quantitative benefit to NWP. In the near future, the prospects of benefits from the expanded use of sequential observations from MTSat-2 and the Chinese satellite, FY-2 and also from next generation ultraspectral instruments such as the Geostationary Imaging Fourier Transform Spectrometer (Smith et al. 2000) are very good.

Acknowledgements

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