Shorter contribution

The contribution of GOES-9 to operational NWP forecast skill in the Australian region

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The GOES-9 satellite was moved along the Equator to 155°E, 0°S in 2003 and has operated over the Western Pacific, Asia and the Australian region as the primary geostationary meteorological satellite by the joint effort of the Japan Meteorological Agency (JMA) and the National Oceanic and Atmospheric Administration/ National Environmental Satellite, Data and Information Service (NOAA/NESDIS). Since 22 May 2003, GOES-9 GVAR data have been received via direct readout by the Bureau of Meteorology (hereafter referred to as 'the Bureau'), Victoria, and the calibrated and navigated radiance data (imagery) has subsequently been used to calculate atmospheric motion vectors (AMVs). These operational AMVs are important to Australian region numerical weather prediction (NWP) as no other AMV data are available within operational cut-off times. The method used to determine atmospheric motion differs from that usually employed for GOES series satellite data, particularly in height assignment, error characterisation and quality control. The method resulted from a detailed study of errors in height assignment in the initial experimental system. The AMV data have been used in a real-time trial to gauge their impact on operational regional NWP. Their clear benefit is described below. As a result of this trial these vectors are now being used in the National Meteorological and Oceanographic Centre (NMOC) for operational regional NWP.

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Background

Australia's position in the data-sparse southern oceans has resulted in dependence on satellite remote sensing for maintaining high quality analysis and numerical weather prediction. For a long time, satellite imagery has contributed to analysis and forecast preparation in the Australian region (Guymer 1978) and manually prepared pseudo-observations are still expected to contribute a small positive impact to southern hemisphere forecasts (Seaman et al. 1993). Atmospheric motion vectors also make an important contribution to the database (Le Marshall et al. 1994). To provide high-quality winds in a timely fashion for operational NWP in the Australian region, AMVs have been calculated locally, initially from sequential GMS image data and, recently, from GOES-9 images.

The methods used at the Bureau, to estimate AMVs, from GMS S-VISSR data, are summarised in Le Marshall et al. (1999, 2000). Sequential infrared (IR), visible (VIS) or water vapour (WV) band images (a triplet), 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 forecast winds, then a lagged correlation technique, which minimised root mean square (RMS) differences in brightness from successive pictures was used to estimate the vector displacement. Cloud-height assignment used forecast temperature profiles. The cloud height assigned for the low-level clouds was that of the cloud base (following the field work 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 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 motion vectors, height assignment of the upper-level cloud vectors uses a method similar to that associated with the determination of height for GMS-5 local 11 μm cloud-drift winds with some modification to allow for changes in the spectral response function and calibration. For middle-level AMVs associated with clear conditions the brightness temperature associated with the feature tracked is used to assign the pressure altitude. These methods are described in Le Marshall et al. (1999).

GOES-9 atmospheric motion vectors

After GOES-9 replaced GMS-5, methods related to those employed at NESDIS (Daniels et al. 2000) and also at the Bureau (Le Marshall et al. 2000) have been used to determine AMVs from GOES-9 GVAR data received at the Bureau's groundstation at Crib Point, Victoria. In this system, target selection commences with a search for tracers in the 11 μm (channel 4) infrared images using bidirectional brightness temperature gradients in 15 x 15 pixel boxes. Gradients are examined to ensure that cloud edges are being tracked. Prospective targets are subjected to a spatial coherence analysis (Coakley and Bretherton 1982) and then tracked using a lagged correlation technique. After the tracers are selected, the three sequential GOES-9 infrared images are carefully navigated using matching of land features.

The height assignment method used for upper-level AMVs is similar to that of Schmetz et al. (1993). The technique employed is 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 are measured and compared to calculate Planck black-body radiances as a function of cloud-top pressure. The cloud-top altitude is then inferred from a linear extrapolation of radiances onto the calculated curve of opaque cloud radiances, providing the target altitude. The approach is described in Nieman et al. (1993) and the temperature profile used in this process comes from the operational regional forecast model. No subsequent adjustment (autoediting) of the vector altitude occurs for GOES-9 AMVs to make them more consistent with the information in the forecast field guess fields.

The low-level AMV altitude assignment technique is similar to that developed in the Bureau of Meteorology (Le Marshall et al. 2000) where cloud altitude is assigned to the cloud base for low-level vectors. Again the temperature profile used comes from the operational regional forecast model and no subsequent adjustment (autoediting) of the vector altitude occurs for GOES-9 AMVs to make them more consistent with the information in the forecast first-guess fields.

An example of the wind observations generated around 2200 UTC on 2 July 2003 in the Australian Region is seen in Fig. 1. An enlarged section giving a

Fig. 1 **A selection of GOES-9 AMVs calculated around 2200 UTC on 2 July 2003. Magenta denotes upper-level tropospheric vectors (above 500 hPa), yellow lower-level tropospheric vectors (below 500 hPa).**

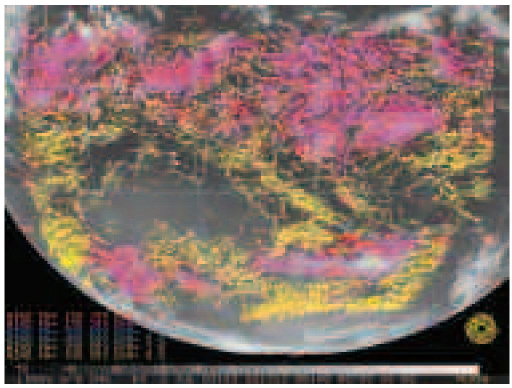

Fig. 2 **GOES-9 AMVs calculated around 2200 UTC on 2 July 2003. Magenta denotes upper-level tropospheric vectors, yellow lower-level tropospheric vectors.**

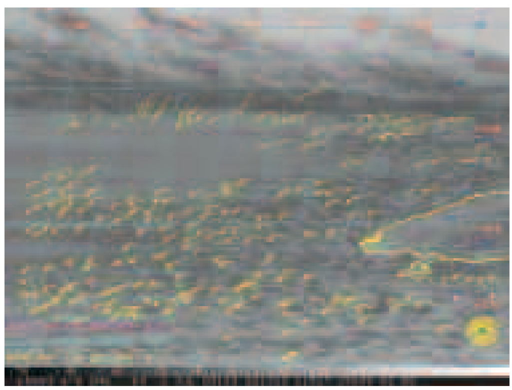

Table 1. Real-time schedule for GOES-9 Atmospheric Motion Vectors (AMVs) at the Bureau of Meteorology. Sub-satellite image resolution, frequency and time of wind extraction and separations of the image triplets used for wind generation (ΔT) are indicated.

Wind type	*Resolution*	*Frequency-times (UTC)*	*Triplet (ΔT)*
Real Time IR	4 km	6-hourly – 05, 11, 17, 23	36 minutes
Real Time IR (hourly)	4 km	Hourly – 00, 01, 02, . . . , 23	1 hour

more complete display of data coverage (near New Zealand) is seen in Fig. 2. The schedule for generating these winds is recorded in Table 1.

Accuracy and quality control

Since the operational use of locally generated atmospheric motion vectors began at the Bureau in 1991, careful quality control (QC) and error characterisation have played important parts in ensuring that the vectors have a beneficial impact on numerical weather prediction (Le Marshall et al. 2004).

The AMVs used in this study have been quality controlled using a variety of tests. A local error index (ERR), the Quality Indicator QI, the RFF and RFI (Holmlund et al. 2000) and the Expected Error (Le Marshall et al. 2004) are generated for each GOES-9 AMV and used in quality control and error estimation. Using this information the winds are effectively thinned by quality measures to ensure good data coverage with average separations around the length scale of the correlated error (see Bormann et al. 2003, Le Marshall et al. 2004). The thinning methodology and quality control result in errors not significantly larger than the background error of the forecast model, measured at radiosonde sites. The approach used is detailed in Le Marshall et al. (1994, 2004).

The operational trial

The assimilation system

The assimilation system employed was the real-time operational NMOC regional Limited Area Prediction System (LAPS). The analyses on which the forecasts reported here are based start with a Bureau of Meteorology global analysis (Seaman et al. 1995), valid 12 hours prior to the forecast start time. This is used as a first guess to the regional analysis which then provides the base analysis for an initialised six-hour forecast, a subsequent analysis and a further initialised six-hour forecast. This forecast is then used as a first guess to the final analysis from which the 24 and 48-hour forecasts are run. Forecasts are nested in fields from the most recent Bureau global model forecast (Bourke et al. 1995).

Table 2. The mean magnitude of vector difference (MMVD) between GOES-9 AMVs and radiosonde winds within 150 km in the Australian region for 9 June to 30 June 2003, the period used for the data assimilation experiment.

GOES-9	*No. Obs*	*MMVD ($m\ s^{-1}$)*
Low 950 – 700 hPa	431	3.64
Middle 699 – 400 hPa	82	4.00
High 399 – 150 hPa	1759	4.58

The analysis and forecast models

The LAPS analysis and forecast model uses a common latitude/longitude/sigma coordinate system. The configuration consisted of 320° x 220° grid-points at 0.375° spacing in the horizontal, and 29 levels in the vertical, with an upper level of sigma 0.05. The analysis system was a limited area adaptation of the global multivariate statistical interpolation analysis (Seaman et al. 1995). The errors assigned to the atmospheric motion vectors in the operational analysis scheme are 3 m s^{-1}, 4 m s^{-1} and 5 m s^{-1} for low, middle and high-level vectors respectively. These numbers are consistent with the errors of 3 m s^{-1} assigned to local middle and high-level radiosonde observations and the differences between collocated local AMVs and radiosonde wind estimates usually recorded at the Bureau of Meteorology. The forecast model is described in Puri et al. (1998) and is a hydrostatic model using high-order numerics and including a comprehensive physics package and the digital filter initialisation of Lynch and Huang (1992).

Method

The operational regional forecast system was employed as the control and used all available data, including JMA winds which were usually available up to the second last analysis in the cycle. The experimental forecast system was the same, with the addition of GOES-9 AMVs (generated using 11 μm (channel 4) and 6.7 μm (channel 3) images) in that case. The methodology was similar to that used in Le Marshall et al. (2002).

A series of parallel real-time forecasts were run using the operational forecast system. The difference between operational and experimental real-time systems was that local GOES-9 AMVs were added to the database in the experimental system (It should be noted JMA winds were not available in time for the final operational analysis.) The experimental period was from 0000 UTC on 9 June to 0000 UTC on 30 June 2003 (36 cases). The experimental period was not overly long but encompassed a wide variety of synoptic patterns in the Australian region from zonal flow to highly unusual blocking sequences, including a Tasman Sea cut-off low. For these real-time forecasts, the S1 skill-scores (Teweles and Wobus 1954) were calculated on the NMOC operational verification grid using 0000 UTC and 1200 UTC analyses.

Results

The S1 skill-scores for 24-hour and 48-hour forecasts for the Australian region using GOES-9 AMV data are compared to the operational skill scores in Figs 3 and 4.

Figure 3 shows a plot of the operational (control) skill scores versus those from the operational system with GOES-9 AMVs in the database. Points below the diagonal indicate an improvement in accuracy. It can be seen that a clear majority of points lie below the line and, in particular that most improvement occurs at the higher values of the S1 skill-score, i.e. in the lower atmospheric levels and for poorer forecasts.

Fig. 3 **The S1 skill-score from Operations versus the S1 skill-score from the operational system, including GOES-9 winds, 9 June to 30 June 2003.**

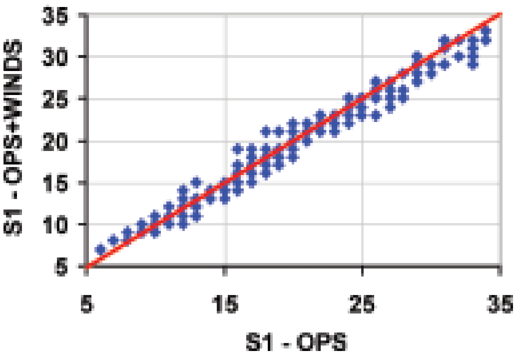

Fig. 4 **S1 skill-score versus pressure for real time 48-hour forecasts (right-hand pair) and 24-hour forecasts during the period 9 June to 30 June 2003.**

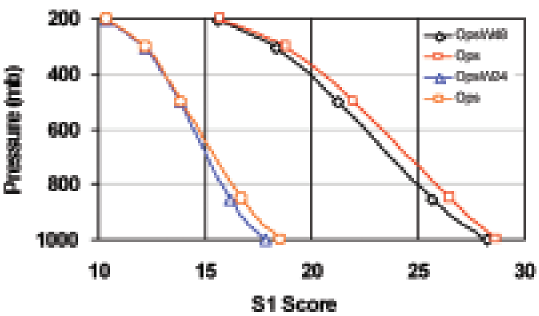

Figure 4 also shows the skill-score improvement due to the AMVs, during the data assimilation experiment. The plot shows the S1 skill-score versus pressure level for 48-hour (right-hand pair) and 24-hour (left-hand pair) real-time forecasts. It shows that the addition of these data has improved the real-time forecast at all levels at both times, with greater impact in the lower troposphere. Overall, it is clear these winds are beneficial to the forecast process. In essence, we have shown that real-time GOES-9 IR and WV image-based AMVs, are of an accuracy which benefit operational NWP in the Australian region. Addition of the vectors to the operational regional forecast system has provided both improved data coverage of the region and forecast improvement. The results also show that there is not only a general improvement in forecast accuracy but that the impact is to ameleorate larger forecast errors particularly in the lower levels. As a consequence of this trial, these winds have been used in NMOC, Melbourne, since early August 2003, in the operational regional forecast system.

Summary and conclusions

The local estimation of real time operational GOES-9 AMVs and their impact on regional NWP has been described. Experiments using these data in a real-time NWP trial have been summarised. The clear benefit of these data to operational regional NWP has been recorded. These results have led to the introduction of these winds into NMOC's operational database and their use in operational regional NWP since August 2003. The results reported here are similar to those recorded in earlier impact studies with GMS-5 AMVs (Le Marshall et al. 2002). This suggests that navigation and height assignment accuracy in the new GOES-9 system is similar to that of the mature GMS-5 system.

Looking ahead, the continuing trend towards 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 particular, the prospects of significant benefits from the use of sequential observations from MTSat-1R, which will have similar observational capability and new generation ultra-spectral instruments such as the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) (Smith et al. 2000) are very good.

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