THE ESTIMATION AND UTILITY OF HIGH SPATIAL AND TEMPORAL RESOLUTION WINDS DERIVED FROM GMS-5 OBSERVATIONS

J.F. Le Marshall[1], N.R. Pescod[1] and C. Spinoso[2]

Bureau of Meteorology Research Centre
GPO Box 1289K, Melbourne, Victoria, 3001, Australia

[2]Dept. of Land Information, RMIT
Melbourne, Victoria, 3001, Australia

ABSTRACT

The direct readout of Stretched VISSR data from the GMS has allowed the local generation of cloud and water vapour drift winds, at high resolution, in real time over the Australian Region. The techniques used in the derivation of these data and an indication of their quality and utility are contained in this document.

After the recent launch of GMS-5, cloud drift winds, calculated using infrared channel 1 (IR-1), have been generated in the Bureau of Meteorology, Melbourne and used for operational purposes in the Australian Region. In addition, winds have been generated, in real time, on an hourly basis, from infrared and visible imagery. These data have been used with the Australian Bureau of Meteorology's next generation operational forecast model and have been shown to have the potential to positively impact operational 24-hour forecasts in the Australian Region.

Further experiments have also been carried out to examine the application of high temporal and spatial resolution winds using conventional intermittent assimilation, nudging and variational techniques. A brief summary of these experiments is provided, along with an indication of the utility of these various approaches in numerical weather prediction, particularly for tropical cyclone track forecasting.

1. INTRODUCTION

Sequential geostationary meteorological satellite observations provide a unique opportunity to monitor atmospheric motion over the data sparse regions of the Southern Hemisphere, in particular, over the southern oceans. Initial methodologies for deriving IR image based cloud motion vectors every six hours in the Australian Region, and their impact on operational atmospheric analysis and forecasting are well-documented (e.g. Le Marshall et al., 1992, 1994). With the availability of hourly data, the recent expansion of the number of channels and changes in the spectral content of the channels used to observe the atmosphere from geostationary orbit, there has been an increase in the observational power of these satellites which is reflected in the increased accuracy and utility of the derived geophysical data.

In the Bureau of Meteorology (BoM) , cloud and water vapour drift winds have been generated at high spatial and temporal resolution using both visible (VIS) and infrared (IR) imagery (Le Marshall et al., 1996). In the case of IR image-based cloud drift winds (CDWs), full-resolution 5 km imagery has been used, while for VIS image-based CDWs, full-resolution 1.25 km and re-sampled 5 km sub-satellite (IR) resolution imagery has been used. CDWs are generated at high temporal resolution from hourly and half hourly IR and, during daylight hours, VIS images.

This paper records the impact of six hourly IR image based GMS-5 CDWs on operational NWP in the Australian Region and also records the potential utility of hourly GMS-5 VIS and IR image based winds in operational NWP in the Australian Region. In this regard, present methods of CDW generation, the wind accuracy and a quantitative measure of their benefits in numerical weather prediction (NWP) are recorded. Current methods for using CDWs in NWP are briefly noted and two experiments involving the assimilation of CDWs into a limited area numerical forecast system, using 6-hour intermittent assimilation are given. The first involved taking 6-hourly wind estimates, generated from triplets of sequential IR-1 (10.1 - 11.7 μm) imagery, separated by half an hour, and examining their utility in local operational NWP, using 6-hourly intermittent assimilation. The second involved taking the hourly winds generated in the BoM, from triplets of sequential GMS-5 VIS and IR data, separated by one hour, and testing them in a 6-hourly intermittent assimilation experiment to determine if any benefit could be gained from the use of these data in comparison with a forecast system which already contained the local 6-hourly IR CDWs. The results of these experiments are recorded and a discussion of the use of the winds via conventional assimilation, nudging and a full variational approach in terms of the spatial and temporal data distribution is also provided.

2. THE CLOUD DRIFT WINDS

2.1 Wind Estimation

GMS Stretched-VISSR images are received every hour or half hour at the BoM, and are calibrated, navigated and stored on cyclic data sets in the Australian Region McIDAS system (Le Marshall *et al.*, 1987). The images are scanned to determine suitable cloud fields for automatic tracking, using forecast winds from the operational Regional Assimilation Prognosis (RASP) system to provide a first guess displacement. The new GMS-5 based operational CDW system uses three sequential GMS IR channel 1 (10.1 - 11.7 μm) (IR-1) images, separated by half an hour. A lagged correlation technique which minimises root mean square differences in brightness from successive pictures is used to estimate the vector displacement.

The height assignment methodology for the VIS and IR winds uses an IR histogram and is based on observational studies (Hasler *et al.*, 1979). Height assignment involves estimating the cloud population, which is determined by smoothing the raw histogram of population versus brightness temperature and then fitting Hermite polynomials, generated by up to 8 cumulants, to the distribution. The methodology for determining cloud height from these data is similar to that described in Le Marshall *et al.* (1994), with some modifications to allow for the change in spectral response functions and calibration characteristics of the new GMS-5 instrument.

After automatic velocity estimation and height assignment, quality control results in the wind data being accepted and errors assigned, based on several criteria, including the correlation between images, the zonal and meridional velocity changes between sequential image pairs and the zonal and the meridional velocity component deviation from the first guess (see Le Marshall et al., 1994). In practice, the derivation of quality control methods has relied heavily on comparison of wind data from collocated radiosondes and CDWs, and an examination of the impact of the wind data on the operational regional forecast system. Real time test systems now have several enhancements such as the correction or elimination of poorly height assigned transmissive cirrus using brightness temperature, diferences between IR1 and IR3 versus IR2, and using a velocity test which checks the level of best fit. Each observation in this system has an error flag with an associated bias and root mean square error, derived from extensive radiosonde and CDW comparisons (Le Marshall et al., 1994).

Table 1 : Cloud drift wind types generated 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 (ΔT).

Wind type	Image resolution	Frequency/ Times (UTC)	Wind image triplet (ΔT)
Operational IR	5 km	6 hourly - 05, 11, 17, 23	30 minutes
Research low-res. VIS	5 km	6 hourly - 05, 23	30 minutes
Research high-res. VIS	1.25 km	6 hourly - 05, 23	30 minutes
Research Water Vapour	5 km	6 hourly - 05, 11, 17, 23	30 minutes
Research IR (hourly)	5 km	hourly - 00, 01, 02, ... 23	1 hour
Research low-res. VIS (hrly)	5 km	hourly - 00, 01, 02, ... 23	1 hour
Research high-res. VIS (hrly)	1.25 km	hourly - 00, 01, 02, ... 23	1 hour
Research Water Vapour (hrly)	5 km	hourly - 00, 01, 02 ... 23	1 hour

2.2 Wind Types

As noted earlier, operational IR winds are generated routinely from 5 km resolution IR images, every 6 hours, using 3 images separated by 30 minutes. These winds are produced at 0500, 1100, 1700 and 2300 UTC, each day. In research mode and in real time, winds are also produced using both IR and VIS imagery.

The IR images are used to produce hourly winds, while the visible images are used to produce hourly and 6-hourly wind sets during daylight hours based on images of 5 km and 1.25 km resolution. A summary of the wind types and their characteristics is given in Table 1.

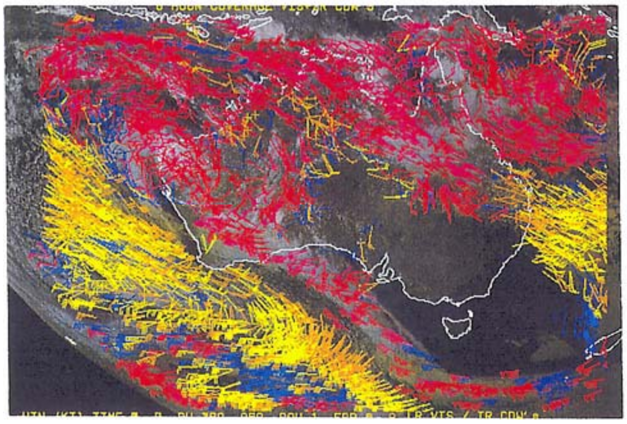


Figure 1 : A 6 hour collective of low error category IR and low resolution VIS image-based CDWs generated over the Australian Region around 05 UTC on 25 February, 1996. Yellow, cyan and magenta wind barbs denote low, middle and upper level winds

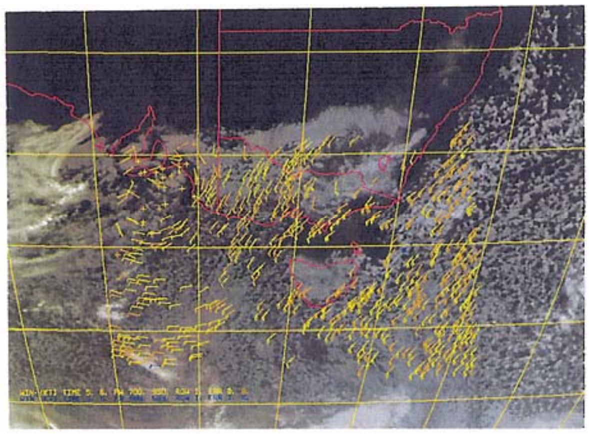


Figure 2 : A typical example of wind vectors over S.E. Australia, based on three high resolution VIS images, separated by half an hour. Colour coding as in Fig. 1.

In the case of VIS image-based winds, target selection uses the visible images while height assignment uses the IR channel 1 imagery associated with the central time of the image triplet under examination and the techniques already described. Figure 1 provides an example of a 6 hour collective of hourly and 6-hourly low resolution VIS and IR winds generated at 05 UTC around 25 January 1996. A typical example of wind vectors over S.E. Australia, based on half-hourly high resolution VIS imagery can be see in Figure 2.

Table 2 : Verification statistics (mean speed, bias and mean magnitude of vector difference (m/s)) from August and September 1995, for VIS and IR-based vectors within 100 nautical miles of a radiosonde. Images used have 5 km resolution.

Wind Level	Type	No. Obs.	Mean Speed	Speed Bias	Mean |Vec. Diff.|
Low	IR	2214	8	-0.4	4.08
	VIS	572	6	-0.72	4.19
Middle	IR	206	16	0.19	5.72
	VIS	60	12.5	-3.84	7.67
High	IR	428	20	-2.67	6.77
	VIS	84	18	-1.9	5.62

Table 3 : Mean speed, bias and mean magnitude of vector difference statistics (m/s) for vectors derived from high resolution visible images, August and September, 1995, at the 05 and 23 UTC

Wind Level	No. Obs.	Mean Speed	Speed Bias	Mean |Vec. Diff.|
Low	754	8.0	-0.36	4.24
Middle	112	13.0	1.4	4.26
High	266	21.0	-1.34	5.13

2.3 Verification

Verification statistics for the various wind types, compared with radiosondes and the first guess wind fields, have been measured. Verification statistics from comparisons with radiosonde data for the lowest error category VIS and IR winds, generated from 3 images, separated by half an hour, can be seen in Tables 2 and 3.

The mean magnitude of the vector difference compared to radiosondes for high resolution half hourly (1.25 km) VIS image-based winds is shown in Table 3. In this sample, it can be seen that the accuracy of the winds and the speed bias are comparable with the winds derived from lower resolution half hourly IR or VIS imagery. It should be noted, however, that in very cloudy areas, half-hourly, high resolution VIS images produce many times the density of winds generated from the corresponding half-hourly IR and low resolution VIS images.

Statistics for both IR and VIS hourly CDWs can be seen in Table 4. It would appear that although hourly winds do not provide the same spatial density as half-hourly winds, their general accuracy is similar to half hourly winds at upper, middle or at lower levels. It can also be seen that the yield of visible image based winds is less than that of the corresponding IR based vectors, this being a function of both illumination and quality control.

Table 4 : Mean speed, speed bias and mean magnitude of vector difference (MMVD) statistics (m/s) for vectors derived from hourly IR and VIS (5 km resolution) images, August and September, 1995, around 05 and 23 UTC

Wind Level	Type	No. obs.	Mean Speed	Speed Bias	Mean |Vec. Diff.|
Low	IR	892	2.0	-0.69	4.13
	VIS	186	5.0	-0.98	4.01
Middle	IR	62	18.0	1.2	5.38
	VIS	14	9.0	-2.83	5.49
High	IR	156	18.0	-1.6	5.46
	VIS	8	3.0	-1.26	5.71

3. THE ASSIMILATION OF CLOUD DRIFT WIND DATA IN THE AUSTRALIAN REGION

The most common data assimilation method used currently in the BoM, as in most operational NWP centres, is still intermittent assimilation or cycling where, usually, a 6-hour forecast is used as a first guess to an analysis scheme, often multivariate statistical interpolation, commonly followed by some form of initialisation prior to generation of a forecast. At NMC, Washington, 3-dimensional variational analysis techniques are now used, while at ECMWF, 3-dimensional variational analysis techniques were introduced operationally in early 1996 and 4-dimensional variational techniques are planned to be introduced late in 1996. The advantages of variational techniques, particularly in relation to high density asynoptic data, are noted later.

Here, we report recent data assimilation experiments, completed in the BoM, which used conventional assimilation techniques, namely 6-hour cycling with both 6-hourly and selected hourly CDW data. We also discuss the use of nudging and variational assimilation with these data. Summarised below are the characteristics of the data assimilation systems, the methodologies used and the results from these CDW data impact studies.

3.1 The six-hourly Assimilation CDW Impact Experiments

In these studies, the data assimilation process, used to provide the analysis on which the 24-hour forecasts studied here are based, starts with a BoM global analysis, valid at 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 subsequently used as a first guess to the final analysis from which the twenty four hour forecasts are run. All forecasts are nested in fields from the most recent BoM global model forecast.

3.1.1 The Analysis and Forecast System The Limited Area Prediction Scheme (LAPS) used in these experiments is undergoing real time trials in the BoM Research Centre prior to testing in the National Meteorological Operations Centre for operational use. As such, the control system was run with operational data cut-offs, and thus its performance is that which would be experienced operationally. Both analysis and forecast models are new, and are described in detail elsewhere, however, a brief description of these two systems is provided.

Both analysis and forecast models have the same latitude/longitude/sigma coordinate system. The configuration used in this study consisted of 160 x 110 gridpoints at 0.75° spacing in the horizontal, and 19 levels in the vertical, with an upper level of sigma = 0.05. The analysis system is a limited area adaptation of the global multi-variate statistical interpolation (MVSI) analysis described in some detail by Seaman et al. (1995).

The forecast model is described in Puri et al, 1996 and is a hydrostatic model formulated in latitude/ longitude/sigma coordinates on the Arakawa "A-grid". It uses high order numerics and includes a comprehensive physics package (Hart et al, 1990), and the digital filter initialisation of Lynch and Huang (1992).

3.1.2 Real Time Impact Studies with Operational Six hourly GMS-5 IR Winds

The aim of these data impact studies was to gauge the impact of current local GMS-5 CDW data on operational numerical forecasts in the Australian Region. Earlier impact studies, based on GMS-4 observations and performed using the operational RASP system (Mills and Seaman, 1990), were described in Le Marshall et al. (1992; 1993, 1994). With the advent of GMS-5, again, an operational CDW system to produce winds for operations at six-hourly intervals from triplets of half-hourly IR-1 imagery was developed. These winds were used in a limited area impact study with the BoM's Limited Area Prediction Scheme (LAPS).

The methodology employed in this study was to use the LAPS in the manner described above with 6-hour cycling and the operational data base (including low resolution TOVS data, high resolution local TOVS data and JMA CDWs 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). This system provided the control forecasts with verification results, denoted as LAPS in Table 5. In parallel, using the same system, the local 6-hourly IR image-based CDW data, produced at the BoM using full-resolution GMS-5 half-hourly image triplets, were added to the operational data base for real time assimilation runs. The SI skill scores (Teweles and Wobus, 1954) for 24 hour forecasts from the local CDW assimilation (CLAPS1) and matching control forecasts (LAPS) are shown in Table 5. In this case, it can be seen that the local CDW GMS-5 IR channel 1 based data have a consistent positive impact on the forecasts (around 1 skill score point near the surface), a result consistent with that found for GMS-4 (Le Marshall *et al.*, 1994).

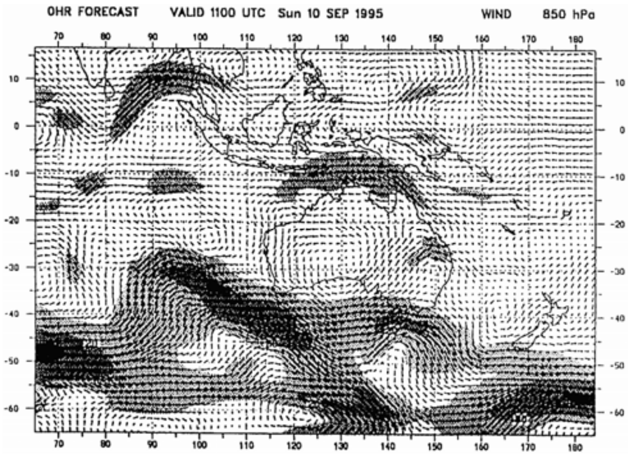
Table 5 : The impact of CDWs generated from GMS-5 IR channel 1 on the BoM's next generation operational regional forecast model. LAPS denotes the control +24 hour forecast skill scores, and CLAPS 1 the +24 hour forecast skill scores for the system with local 6-hourly GMS-5 IR channel 1 CDWs for the period 20 June to 18 August 1995.

Level	MSLP		850 hPa		500 hPa		300 hPa	
Assimilation Type	LAPS	CLAPS1	LAPS	CLAPS1	LAPS	CLAPS1	LAPS	CLAPS1
No. of cases	19	19	19	19	19	19	19	19
Skill scores	26.4	25.4	24.8	23.9	16.1	15.7	14.0	13.7

3.1.3 Real Time Impact Studies with Hourly GMS-5 VIS and IR Winds

A second experiment was undertaken in September and early December, 1995, where hourly IR and VIS winds were added to the (operational) control data base, which included JMA wind data available at the operational cutoff time *and local 6-hourly IR winds*. The hourly winds include a full regional coverage of 5 km resolution IR and VIS winds and a reduced coverage of 1.25 km resolution VIS winds over S.E. Australia as generated for a trial in the Victorian Regional Office. The area over S.E. Australia covered by the high resolution VIS image based winds can be seen in Figure 2, which provides a good example of winds in a post-frontal cumulus field. Winds generated from image triplets centred within one hour of analysis time were used in this study. Differences resulting from the use of these hourly winds were evident in the resulting analyses. For example, the wind field at 850 hPa at 1100 UTC on

10 September 1995 (Fig. 4) shows differences in wind maxima and directions, south and southwest of Australia when comparing analyses with and without hourly CDWs. These differences were due to differences in data at analysis time and also to differences in data available in the two preceding assimilation cycles which provide the analysis with first guess fields.



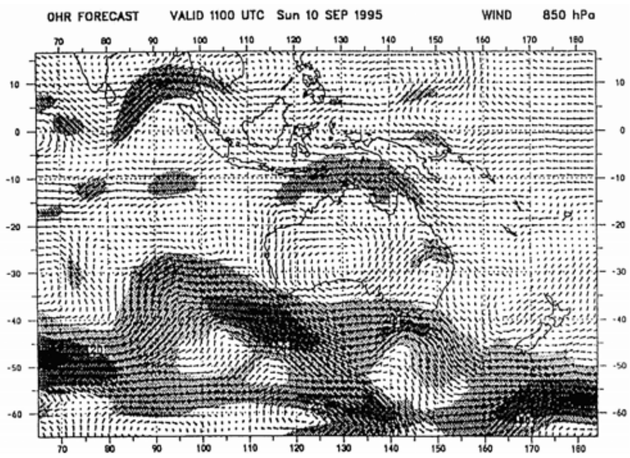


Figure 4 : (a) The 850 hPa wind analysis using 6·hourly IR CDWs for 1100 UTC on 10 September 1995. (b) As in (a) with the addition of hourly CDWs centred within 1 hour of analysis time.

The S1 skill scores for 24 hour forecasts for the hourly IR and VIS CDW *(with local 1 and 6-hourly IR winds)* assimilation (CLAPS2) and matching control forecasts (CLAPS1) *(with local 6-hourly IR winds)* are shown in Table 6. These indicate that hourly IR and VIS winds have the potential to improve operational regional forecasts, even when 6-hourly local CDWs are included in the control data base.

Table 6 : The SI skill scores for the hourly IR and VIS CDW assimilation (CLAPS2) and matching control forecasts (CLAPS1) for the period and 03 December to 08 December 1995

Period	05 September to 25 September 1995							
Level	MSLP		850 hPa		500 hPa		300 hPa	
Assim. Type	CLAPS1	CLAPS2	CLAPS1	CLAPS2	CLAPS1	CLAPS2	CLAPS1	CLAPS2
No. of cases	16	16	16	16	16	16	16	16
Skill score	27.1	26.1	28.2	27.0	18.6	18.5	16.4	16.0

Period	03 December to 08 December 1995							
Level	MSLP		850 hPa		500 hPa		300 hPa	
Assim. Type	CLAPS1	CLAPS2	CLAPS1	CLAPS2	CLAPS1	CLAPS2	CLAPS1	CLAPS2
No. of cases	6	6	6	6	6	6	6	6
Skill score	29.0	28.3	31.9	29.5	20.2	19.3	17.0	16.3

3.2 NUDGING AND VARIATIONAL DATA ASSIMILATION

In previous studies, higher spatial and temporal resolution winds, similar to those described above, have been used for predicting tropical cyclone (TC) movement. In the NW Pacific, higher spatial density CDWs, generated as part of the TCM-90 Experiment (Bennett *et al.*, 1993) have been shown to improve the accuracy of numerical cyclone track forecasting, when used with a three-dimensional variational procedure. The gains from using the variational procedure and enhanced 12-hourly wind fields were greater than those achieved from the use of nudging and

BMRC Tropical Analyses. The gains were significantly diminished if the variational procedure did not include an enhanced CDW data set but rather GTS SATOBs which were already contained in the Tropical Analysis (Le Marshall *et al.*, 1996). It has also been shown that use of the hourly GMS winds described above, through the variational technique has led to an improvement in the accuracy of tropical cyclone track forecasting in a case study of TC Rewa over the Coral Sea (Le Marshall *et al.*, 1996). In that case, the gains from the use of hourly winds with the variational approach were greater than those seen from the use of BMRC tropical analyses through the nudging technique.

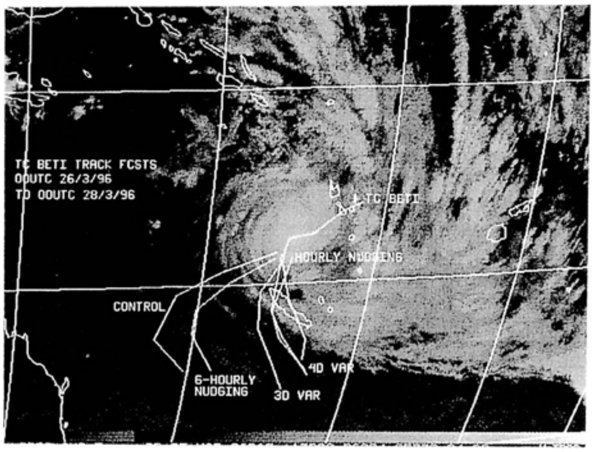


Figure 5 Control. 6-hourly and hourly nudging and 3-D and 4-D variational forecasts for TC Beti from 00 UTC, 26 March 1996. The actual track is also shown

In recent studies, data assimilation using hourly winds in combination with six hourly nudging, hourly nudging, and the full three- and four-dimensional variational scheme of Bennett et al., (1993, 1996) has been examined for the case of Tropical Cyclone Beti (Le Marshall, Leslie and Bennett, 1996).

From 00 UTC on 25 March, 1996, this storm moved South and crossed New Caledonia. In this study, the data assimilation systems used the BMRC Tropical Analyses (TAs) for 00, 06, 12 and 18 UTC on 25 March and 00 UTC on 26 March and hourly CDWs. The storm trajectories from a control forecast from the 00 UTC TA on 25 March 1996, and those resulting from 6-hourly and hourly nudging using the TAs and hourly CDWs and 3-D and 4-D variational assimilation were contrasted.

In the cases of the control and 6-hourly nudging forecasts, the trajectory is poorly captured, while in the 3-D variational (Bennett et al., 1993), hourly nudging and 4-D variational assimilation (Bennett et al., 1996), the TC is modelled with increasing accuracy (see Fig. 5). These results indicate the value of both variational assimilation and hourly nudging, in combination with use of hourly data between the conventional 6-hourly data assimilation points, in establishing the appropriate model state (dynamics) before forecast initiation. A more detailed discussion of the numerical experiments may be seen in Le Marshall et al., (1996b).

4. DISCUSSION AND CONCLUSIONS

In summary, several points have been made in this paper. Firstly, it was seen that GMS-5 VIS and IR sequential imagery can be used to automatically produce both hourly and 6-hourly CDWs, the latter being generated from half-hourly image triplets. The errors associated with these winds are of a size that makes them useful for NWP.

Secondly, the 6-hourly IR winds, generated using half-hourly image triplets from GMS-5, have been used in real time regional limited area prediction studies, where they have been shown to have the ability to consistently improve operational Regional NWP. In a similar study over 22 cases, use of hourly IR and VIS winds, generated from image triplets centred within one hour of the analysis time, have also been shown to have the ability to make consistent improvement to the accuracy of operational NWP within the Australian Region. The timely availability of these local data make them suitable for operational application. We believe that this is the first time that the utility of hourly cloud drift winds for operational NWP has been documented.

From the nudging and variational data assimilation studies cited above, it would also appear that the use of local hourly and six hourly higher density CDWs has the potential to reduce mean TC track forecast errors. Although some benefit from these winds can be seen using the conventional six hour cycling approach, there are obviously problems in incorporating high spatial and temporal density wind observations into a six hourly analysis with a typical time window of ±3 hours, in such a way as to extract their full information content. In the 6-hour cycling approach, the detail of atmospheric structures, if mobile and of small zonal or meridional dimension (such as TCs) may be lost. The temporal self-consistency of hourly CDWs, for example, may be apparent only by using observation time properly in the data analysis, as is done in the hourly nudging or the four dimensional variational approach.

In conclusion it would appear that, given the forecast improvement seen using these high resolution wind data in both regional forecasting and tropical cyclone track prediction, that further work to ensure their exploitation for operational forecasting is warranted. Their application can be achieved currently using conventional assimilation, nudging, 3-dimensional variational assimilation or, more correctly, but at a great computational expense, with four dimensional variational assimilation. In the near future, the utility of GMS-5 water vapour imagery, which provides winds near the steering level of tropical cyclones, will also be quantified while hourly nudging and the four dimensional variational technique of Bennett *et al.*, 1996, which appear to be well suited to the application of these winds, will be further studied.

5. ACKNOWLEDGMENTS

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