Improved Weather Forecasts from the Continuous Generation and Assimilation of High Spatial and Temporal Resolution Winds

J. Le Marshall, N. Pescod, R. Seecamp, C. Spinoso and A. Rea

Bureau of Meteorology, Melbourne, Australia

ABSTRACT

Since 1992, the Bureau of Meteorology has produced high resolution cloud drift winds in real time for operational application over the Australian Region. The benefit of these winds to regional numerical weather prediction is well-documented and is the prime raison d'être for this activity. From 1993, these winds have been generated in real time on an hourly basis. Hourly winds have been provided to Regional Forecast Centres, Tropical Cyclone Warning Centres and the National Meteorological Operations Centre for operational evaluation and have been used in a number of data assimilation experiments. In particular, they have been used for tropical cyclone track forecasting where they have been demonstrated to be of considerable benefit. After the launch of GMS-5 in 1995, the number of channels observing the earth/atmosphere system increased to 4, allowing generation of hourly winds using visible, infrared and water vapour channel observations. The impact of both the 6-hourly and hourly local wind data sets from GMS-5 on operational forecasts in the Australian Region has been documented. The impact of the hourly winds on tropical cyclone track forecasting, using a high resolution numerical weather prediction model and a variety of assimilation techniques, has been also recorded. From these experiments, it has been found that the initialisation provided by continuous assimilation (namely, 4-D variational or 1-hourly nudging), combined with a substantial high spatial and temporal resolution data base and high resolution modelling, has shown a capacity to improve the accuracy of tropical cyclone track forecasts over the data-sparse oceans. This procedure has also provided evidence of an ability to estimate tropical cyclone intensity.

1. INTRODUCTION

Sequential GMS-5 observations, received directly at the Bureau of Meteorology (BoM), provide an opportunity to continually monitor the data-sparse regions of the Tropics and the Southern Hemisphere. In fact, continual full-disc imagery from the Japanese Geostationary Meteorological Satellite and sounding data from the NOAA polar orbiting satellites have significantly ameliorated the data sparsity problem in meteorological analysis on both global and regional scales. In this regard, hourly infrared, visible and water vapour imagery-based winds have been generated locally in the Bureau of Meteorology to augment the real time data base available to the operational regional forecast system within its stringent cutoff times. This has resulted in higher spatial and temporal resolution winds than was otherwise available for use in both routine operational regional forecasting and for tropical cyclone track prediction within the Australian Region.

This paper will briefly describe the generation of the various cloud and water vapour drift wind types and their application to regional analysis and prediction. It also summarises their utility in tropical cyclone track forecasting.

2. WINDS

Hourly and, four times per day, half-hourly, GMS S-VISSR infrared (IR), water vapour (WV) and visible (VIS) images are received in Melbourne and stored in cyclic navigated and calibrated data sets in the Australian Region McIDAS (Le Marshall et al. 1987). Targets are selected and tracked automatically using a model forecast to initiate the search for the selected targets on subsequent

Table 1 Improvement of Dynamic Calibration over Fixed Calibration (IRIFT) and use of the Split Window (IR1/IR2) MMVD = Mean Magnitude of Vector Difference (m/s)

Type	High		Middle		Low	
	IRlFT	IRl/IR2	IRIFT	IRl/IR2	IRlFT	IRl/IR2
Num.	200	185	151	86	949	992
MMVD (m/s)	7.45	7.28	5.49	4.70	3.30	2.94

images. A lag correlation technique is used to estimate the vector displacement. Altitude assignment is similar to that in Le Marshall et al. (1994) with refinements to allow for the changes in spectral response functions and calibration for the new GMS-5 VISSR. An example of the benefits of dynamic calibration and use of the split window channels (IR1, IR2) for water vapour correction and height assignment is seen in Table 1.

Table 2. Cloud drift wind types generated in the Bureau of Meteorology

Wind type	Image res.	Freq.	Time (UTC)	Wind triplet (ΔT)
Op. IR, WV, LR VIS, (HR VIS)	5, 5, 5, (1.25) km	6 hr.	05, 11, 17,23	30 min.
IR, WV, LR VIS, (HR VIS)	5, 5, 5, (1.25) km	1 hr.	00, 01, ... 23	1 hour

Op. = Operational; LR = Low Resolution; HR = High Resolution IR = Infrared
VIS = Visible WV = Water Vapour

For VIS winds, the altitude assignment uses the IR imagery at the central time of the image triplet used for wind estimation. After velocity and altitude assignment, quality control produces winds with expected errors assigned according to several objective criteria (Le Marshall et al. 1994). WV cloud wind altitude assignment is similar to that for upper level IR vectors while for middle-level clear air water vapour motion vectors it uses the mean temperature of the tracers.

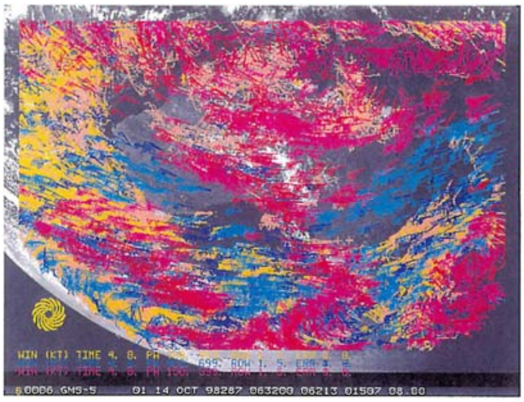

Fig. 1 (a) Cloud and Water Vapour motion vectors 05 - 07 UTC on 14 October 1998. Yellow/cyan/magenta vectors represent low/middle and high level winds

Fig. 1 (b) As in Fig. 1 (a) but expanded around 34 °S, 109 °E

At the Bureau of Meteorology (BoM), the current operational system generates winds from sets of 3 IR images, separated by half an hour, four times per day. It also produces VIS, high resolution visible (HRVIS) and WV image-based winds from half-hourly imagery four times per day. IR, VIS, HRVIS and WV image-based winds are also produced hourly and are distributed to the National Meteorological Operations Centre (NMOC), Regional Forecast Centres and Tropical Cyclone Warning Centres.

A summary of winds produced is given in Table 2. An example of these winds generated between 05 - 07 UTC on 14 October 1998 is seen in Fig. 1 (a) and (b).

3. IMPACT OF THE WINDS ON REGIONAL NWP

A series of real time data assimilation experiments was undertaken to examine the utility of local cloud and water vapour motion vectors in operational numerical weather prediction over the Australian Region. In these experiments, the operational Limited Area Prediction System (LAPS) system (Puri et al. 1998) has been used as the *control*. The *experimental* system has been a parallel near real time LAPS run, identical to the operational system, except for the addition of local real time cloud and water vapour motion vectors to the data base.

The analyses on which the forecasts reported here are based start with a BoM 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 twenty four and forty eight hour forecasts are run. Forecasts are nested in fields from the most recent BoM global model forecast. The LAPS analysis and forecast models have the same latitude/longitude/sigma coordinate system with 160 x 110 gridpoints at 0.75º 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 multivariate statistical interpolation analysis (Seaman et al. 1995). The forecast model is described in Puri et al. 1998 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 and the digital filter initialisation of Lynch and Huang (1992).

The first of these real time data impact studies was to gauge the impact of local cloud drift winds, estimated using the 11 μm window channel on the operational LAPS (Le Marshall et al. 1996). The winds were estimated from triplets of half-hourly GMS-5 imagery at 05, 11, 17 and 23 UTC. The NMOC operational forecast system (LAPS) and the operational data base (including NESDIS TOVS data and local TOVS data (Le Marshall et al. 1994) and available JMA cloud drift winds) was the *control*. The *experimental* system employed an identical forecast system with the addition of local cloud drift winds to the data base. The SI skill scores (Teweles and Wobus, 1954), tabulated on the official NMOC verification grid, for the local cloud drift wind system (LAPS + CDWs) and the matching NMOC forecasts (LAPS) are seen in Fig. 2 (a). It can be seen that, overall (19 cases), local cloud drift wind data have a modest but positive impact on forecasts.

A second real time data impact study gauged the impact of local hourly cloud drift winds, on the operational Australian Region prediction system (Le Marshall et al. 1996). The winds were estimated from triplets of hourly GMS-5 imagery centred within an hour of 05, 11, 17 and 23 UTC. The NMOC operational forecast system (LAPS) and the operational data base (here including NESDIS TOVS data, *local cloud drift wind data (from triplets of half-hourly imagery)* and available JMA cloud drift winds) was the *control*. The *experimental* system again employed an

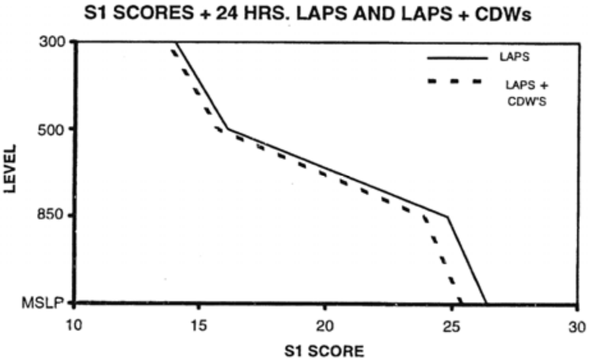

Fig. 2 (a) Twenty four hour forecast skill scores for LAPS versus LAPS with CDWs

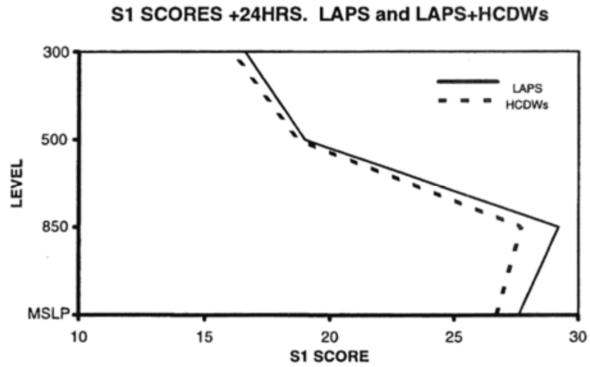

Fig. 2 (b) As in 2 (a) but skill scores for LAPS versus LAPS with Hourly Winds

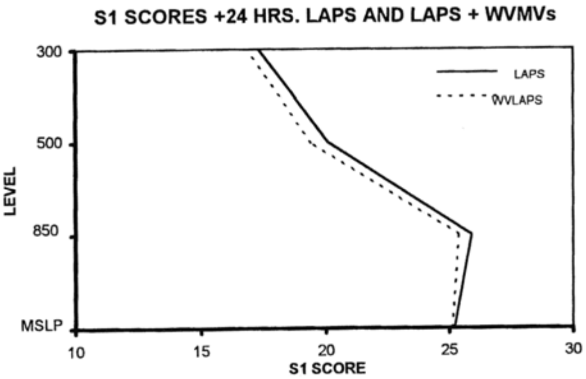

Fig. 2 (c) As in 2 (a) but skill scores for LAPS versus LAPS with Water Vapour Winds

Fig. 2 (d) A histogram showing the SI skill score impact of water vapour winds at 300 hPa at +24 hrs.

identical forecast system with the local hourly cloud drift winds added to the data base. The S1 skill scores for the local hourly cloud drift wind system (HCDWs) and the matching NMOC (LAPS) forecasts for the period are seen in Fig. 2 (b). In this case, it can be seen that, overall (23 cases), the local hourly cloud drift wind data again have a modest but positive impact on the forecasts.

In a third study, impact of water vapour motion vectors on operational Australian Region forecasts was gauged (Le Marshall et al. 1998a). The water vapour motion vectors were estimated from triplets of half-hourly water vapour absorption band imagery at 05, 11, 17 and 23 UTC. Over thirty forecasts, mainly for March 1998, were examined. This experiment again contrasted the NMOC *control* with an identical *experimental* system with local water vapour winds added to the NMOC data base (which contained NESDIS and local TOVS, JMA and *local cloud drift winds).* Results are in Fig. 2 (c), indicate that water vapour motion vectors have provided, on average, a modest forecast improvement. Fig. 2 (d) shows a histogram of skill score impact for this experiment.

In summary, evidence provided by regional forecast trials over extended periods indicate that use of cloud and water vapour drift wind data, calculated locally from GMS-5 imagery, provide, on average, a modest but sometimes significant improvement in forecast accuracy.

4. IMPACT OF THE WINDS ON TROPICAL CYCLONE TRACK FORECASTING

A series of data assimilation experiments was undertaken to assess the utility of hourly cloud and water vapour drift winds on tropical cyclone track prediction (Le Marshall et al. 1996a; Leslie et

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al. 1996; Le Marshall and Leslie, 1998). The results from nine sets of forecasts in the Australian Region which were generally deemed difficult are summarised here. The forecast problem has been addressed in three ways. Modelling and data assimilation have been performed at high (15 km, 5 km for some intensity studies) resolution. A newly developed data source, namely, high spatial and temporal resolution cloud drift winds, has been used to augment the often quite poor data base upon which forecasts are based and, in one case, these winds have been augmented with scatterometer-based surface winds. In addition, a range of continuous assimilation techniques, including recently developed 4-D variational assimilation and hourly nudging have been tested. The assimilation methodology is described in Le Marshall and Leslie (1998), and is summarised below.

4.1 The Assimilation Methodology

The *control* forecast (M) used the forecast component of the variational assimilation system initialised with the BoM's Tropical Analyses (Davidson and McAvaney 1981). All forecasts were nested in the BoM's TAPS (Tropical Analysis and Prediction Scheme - Puri et al. 1992). *Hourly Nudging* was performed using 6-hour nudging from T = -24 to T = 0 and then analysing the hourly CDWs into the hourly fields generated during this process. The model was again started at T = -24 and the evolving forecast nudged towards these hourly analyses as it progressed through the 24-hour time period. Divergence damping (Haltiner and Williams 1980) was used during this process to suppress spurious generation of gravity waves before the 48-hour forecast, based on the evolved state at T = 0. The final forecast generated in these experiments was a *4-D variational assimilation* forecast. Details of this system are given in Bennett et al. (1996). It uses Tropical Analyses from T = -24 to T = 0. Forecast boundary conditions were derived from the TAPS and 24 hours of hourly visible and infrared winds were incorporated asynoptically during the 4-D variational model initialisation. Where scatterometer wind data were used, the penalty functional (similar to 2.21 in Bennett et al. (1993)) had an additional term $\mathbf{S} \circ \mathbf{W}_{SS} \circ \mathbf{S}$ added, where the weight $\mathbf{W}_{SS}$ is a suitably defined inverse of the scatterometer wind residual covariance and **S** is the initial scatterometer wind residual at T = 0. Here, the weights were chosen so that the position of the surface centre was determined by the scatterometer data. The model configuration in these studies was 25 levels, 15 km resolution and 180 x 180 grid points.

4.2 Results

Five studies examining tropical cyclones Beti, Olivia, Ethel and Justin - 2 cases (Le Marshall et al. 1996a, Le Marshall and Leslie, 1998) have been performed. These contrasted a control run from the operational Tropical Analysis, 6-hourly nudging, 1-hourly 3-dimensional variational assimilation, 1-hourly nudging and full 4-dimensional variational assimilation, using the

Table 3 Tropical Cyclone Track Forecast Errors for the Control (M),CLIPER (CL), 1-hourly nudging (1HN) and 1-hourly 4-D variational (1H4D) forecast systems

Cyclones	24 hr. Forecast				48 hr. Forecast			
	M	CL	1HN	1H4D	M	CL	1HN	1H4D
Beti, Olivia, Ethel, Justin (2 cases)	291	179	108	115	478	598	146	111

initialisation method of Bennett et al. (1996). The results are summarised in Table 3, which gives the relative accuracy of control run (M), CLIPER (CL) (Morison 1993)., 1-hourly nudging (1HN), and 4-D variational assimilation (1H4D). It is important to note that the hourly nudging and 4-D variational assimilation are clearly the most accurate forecast methodologies and although 4-D variational assimilation requires an increase of 2 orders of magnitude in resources, it shows a far less significant increase in forecast accuracy.

Because of the practical advantages of 1-hourly nudging, three further experiments were run for TCs Justin, Drena and Rachel and used to contrast the control, CLIPER and 1-hourly nudging. The results from these and the earlier 1-hourly nudging cases are summarised in Table 4. Again, the control and CLIPER forecasts were clearly inferior to the 1-hourly nudging forecasts.

Table 4 Tropical Cyclone Track Forecast Errors for the Control (M),CLIPER (CL) and 1-hourly nudging (1HN) forecast systems

Cyclones	24 hr. Forecast			48 hr. Forecast		
	M	CL	1HN	M	CL	1HN
Beti, Olivia, Ethel, Justin (3 cases), Drena, Rachel	269	160	107	432	498	142

In another example, surface scatterometer data was used in an attempt to reduce initial position errors for TC Justin forecasts from 12 UTC on 16 March 1997. Fig. 2 (a) shows an example of the satellite-based wind data base. The results in Table 5 clearly show that significant benefit is gained from the use of hourly winds, and a more accurate starting position for the cyclone is obtained from the use of the scatterometer winds.

Table 5. Position errors for TC Justin forecasts from 12 UTC on 16 March 1997. Forecasts are the Control, with Cloud Drift Winds (CDW), with Water Vapour Winds (WVW) and for All data (CDW, WVW and surface scatterometer winds)

Date/Time	Forecast	Control	CDW	WVW	All
12 UTC 16/03/1997	+0 hrs.	55	40	50	25
12 UTC 17/03/1997	+24 hrs.	509	180	192	167
12 UTC 18/03/1997	+48 hrs.	598	174	185	120

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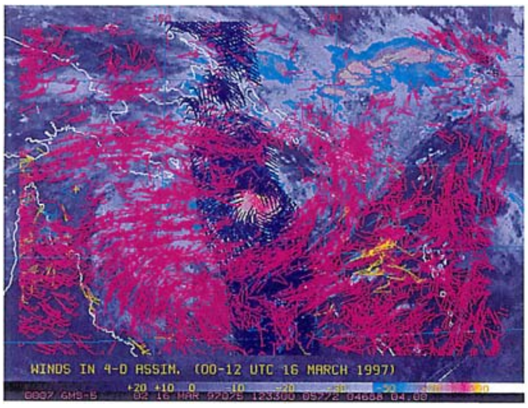

Fig. 3 (a) Hourly CDWs and WVWs for 00 to 12 UTC on 16 March 1997 and ERS-2 scatterometer winds (12 UTC) over the image of TC Justin for 12 UTC. (Low error category vectors shown)

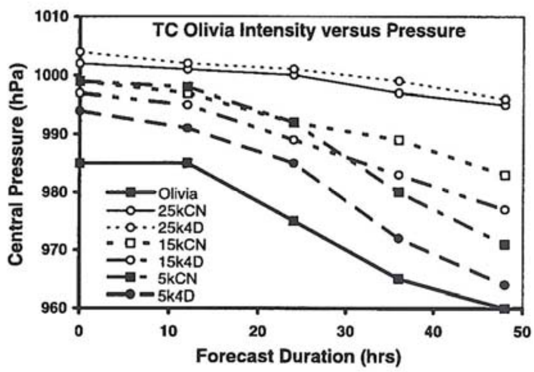

Fig. 3 (b) Forecast intensities for TC Olivia from 12 UTC on 6 April 1996 with varying grid resolution for the control and 4-D var. (5kCN (4D) means 5 km resolution Control (4-D var.) forecast)

In a recent series of experiments (Le Marshall and Leslie, 1998b), the impact of data and resolution on tropical cyclone forecasting has also been examined. Using hourly cloud and water vapour drift winds, 4-D variational assimilation and resolutions ranging from 25 km to 5 km, a dependence of modelled forecast storm intensity on resolution has been recorded. It appears that in these cases, high resolution upper level motion vectors are important for depicting the upper level divergence associated with storm development. Results for TC Olivia for forecasts based on 12 UTC on 6 April 1996 are seen in Fig. 3 (b). An improvement in intensity forecasts is seen with increasing resolution and high resolution wind data, a result being examined in a series of high resolution tests now underway.

In summary, results found for TCs Beti, Olivia, Ethel and Justin (4 cases), Drena and Rachel show that there is a distinct jump in forecast accuracy (reduction in error growth) as one goes from the CLIPER to control to hourly nudging and 4-D variational assimilation. In the cases examined, it was found that initial position errors appear to be significant, and amelioration of this problem has been demonstrated in a case where surface scatterometer data have been employed.

5. CONCLUSIONS

It has been shown that GMS-5 VIS, IR and WV sequential imagery can be used to produce cloud and water vapour motion vectors on an hourly basis in addition to the usual 6-hourly vectors from half-hourly image triplets. *Six-hourly image-based winds* have been used in real time *limited area prediction* studies and have been shown to have the ability to *consistently improve operational Regional NWP.* In a similar study of 22 cases, 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. In a related study (33 cases), 6-hourly *water vapour winds* generated from half-hourly water vapour absorption band imagery have also shown *positive impact on regional forecasts.* The timely availability of these local wind data make them suitable for operational application.

It is well established that *high resolution numerical modelling and an enhanced data base are important to accurate tropical cyclone forecasts,* here, high resolution modelling, high spatial and temporal resolution data and continuous data assimilation have been combined and applied to the tropical cyclone forecast problem. This approach allows the benefits of high resolution modelling to be obtained both in the assimilation and forecast process, while continuous assimilation with a new source of high spatial and temporal resolution data has incorporated additional data at non-synoptic times and ensured an initial state which is close to dynamic balance and consistent with observations taken during the previous 24 hours.

Overall, the results obtained show that *the high resolution wind data base and continuous assimilation methodology used here reduce significantly forecast errors associated with TC track forecasting,* particularly in difficult forecast situations. The 48 hour track forecast errors are well below those now associated with operational forecasts (Gordon et al. 1998). As such, these results indicate that the prospects of reducing operational TC track forecast errors are excellent.

In addition, in just two cases, the ability of scatterometer winds to ameliorate the initial position error problem has been shown and the potential of high-resolution modelling to enhance intensity estimates has been shown .

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