RECENT ADVANCES IN THE GENERATION AND ASSIMILATION OF HIGH SPATIAL AND TEMPORAL RESOLUTION SATELLITE WINDS

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ABSTRACT

This paper reviews work related to the generation and assimilation of high spatial and temporal resolution winds from GMS-5 Stretched VISSR data. It notes the physical basis used in the wind estimation and the accuracy of the resultant vectors. Winds are currently generated from tracers selected in 11µm, 12µm, 6.7µm and low and high resolution 0.5µm images. They are estimated hourly and, four times per day half-hourly. Height assignment uses the GMS-5 IR channels. The gains made in wind yield using a special experimental set of winds from 15-minute observations provided over the Southern Hemisphere by the Japanese Meteorological Agency will also be shown. For the first time, these experimental data provide an indication of the increased yields in Australian Region wind data expected from MTSAT.

The winds have been used in a series of (real time) data assimilation experiments and have been shown to have positive impact on both Regional and Global operational Numerical Weather Prediction (NWP) using intermittent data assimilation methods. The use of the winds has also been extended to include very high resolution 4D variational assimilation which has been employed to forecast tropical cyclone characteristics. Use of hourly and half-hourly high spatial resolution cloud and water vapour drift winds via high resolution 4-D variational assimilation at 15 km or higher resolutions (up to 1 km) has been found to provide tropical cyclone track forecasts which are more accurate than those produced by the current operational forecast system. In the cases examined, use of very high resolution (5 km or better) 4-D variational data assimilation in conjunction with hourly and half-hourly high spatial resolution cloud and water vapour drift wind data has also provided improved estimates of tropical cyclone intensity. Work underway related to cloud drift wind generation from FY-2 is also noted.

1. Background

In the Australian Region, observations taken from polar orbiting and geostationary satellites are vital to sub-synoptic scale analysis and forecasting (Le Marshall et al. 1997). Estimates of temperature, moisture, total ozone and wind are made from real time radiance observations, taken by the NOAA polar orbiting satellites and from the Geostationary Meteorological Satellite which is situated at 140°E, over the Australian Region. These data are pivotal for both analysis and forecasting in the Australian Region. In particular, the benefits obtained from using the almost continuous wind observations, available from the GMS-5 satellite for operational forecasts, have been quantified. In addition, benefits obtained using these winds, in combination with modern 4-D variational continuous data assimilation methods, are significant (Leslie et al. 1998, Le Marshall and Leslie, 1998, Le Marshall and Leslie, 1999). The anticipated improvement in data distribution, expected to result from the introduction of 15-minute observations by MTSAT, is also demonstrated using data from a special observation period in April 1999.

2. High spatial and temporal resolution winds

Hourly and, four times per day, half-hourly, GMS-5 Stretched VISSR (S-VISSR) infrared, water vapour and high-resolution visible images are received in Melbourne, navigated and calibrated and stored in cyclic data sets in the Australian Region McIDAS system at the Bureau of Meteorology (BoM). From these images, targets are selected automatically, using specific gradient criteria for each of the image types used in tracking (Le Marshall et al. 1994, Le Marshall et al. 1999).

After selection, the targets are tracked automatically, using a model forecast to initiate the search for selected targets on sequential images. A lag correlation technique is used to estimate the vector displacement. Pressure altitude assignment to the motion vectors is similar to that described in Le Marshall et al. 1994, with refinements to allow for the changes in the spectral response functions and calibration associated with the new GMS-5 S-VISSR data. In particular, the operational system used by the Bureau of Meteorology uses both the dynamic calibration associated with the GMS-5 imagery and data from the split window channel for pressure altitude assignment (see, for example, Le Marshall et al. 1998). For the visible winds, the altitude assignment uses infrared imagery at the central time of the image triplet used for wind estimation. Water vapour cloud wind altitude assignment is similar to that for upper level infrared vectors while for mid-level, clear air water vapour motion vectors, it uses the mean temperature of the tracers (Le Marshall et al. 1999). After velocity and altitude assignment, quality control produces winds with expected errors assigned according to several objective criteria (Le Marshall et al. 1994).

Currently, in operational mode, the system generates winds, four times per day, from sets of three infrared images, separated by half an hour. It also produces visible, high resolution visible, and water vapour-based winds from half-hourly images, four times per day. Hourly infrared, visible, high resolution visible and water vapour images are used to produce hourly wind data. These data are distributed to the National Meteorological Operations Centre (NMOC), Regional Forecast Centres (RFCs) and Tropical Cyclone Warning Centres (TCWCs). A summary of the winds produced is given in Table 1.

Table 1. Cloud and water vapour drift wind types generated in the BoM. Type (Op. = Operational, LR = Low Resolution, HR = High Resolution, IR = Infrared VIS = Visible, WV = Water vapour), Image resolution, Frequency, Time of wind extraction and the separation of image triplets (T) are included.

Wind type	Image res.	Freq.	Time (UTC)	Wind triplet ((T)
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

An example of the winds produced between 05 and 07 UTC on 25 March 1999 is seen in Figure 1 and a diagram of the differences between the motion vector winds and those taken from radiosondes within 150 km are seen in Figure 2.

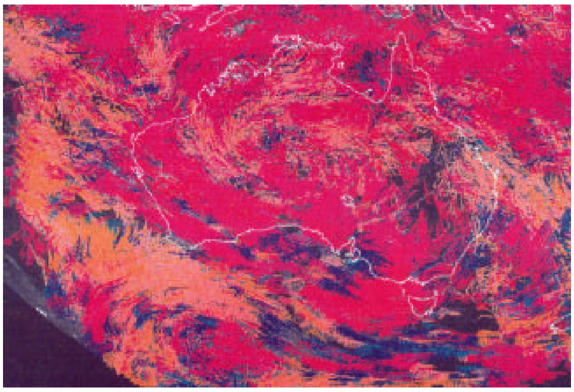

Figure 1. Local cloud and water vapour drift winds generated around 06 UTC on 25 March 1999 from visible, high resolution visible, infrared and water vapour absorption band images.

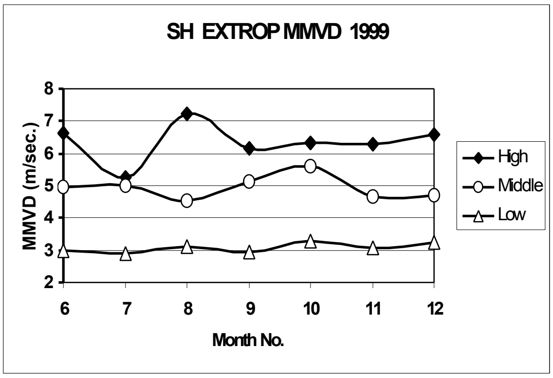

Figure 2. The mean magnitude of vector difference (MMVD) for local Southern Hemisphere extra Tropical IR cloud drift winds compared to radiosondes within 150 km June to December 1999

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3. The 1999 special observation period

As a prelude to the launch of a replacement satellite for GMS-5, the Japanese Meteorological Agency (JMA) and the Bureau of Meteorology (BoM) undertook a collaborative project to observe the Australian Region at higher temporal resolution than had been undertaken before. In addition to the usual observation sequence, undertaken by the GMS-5 satellite, images were taken over the Southern Hemisphere on the 7, 20, 21, 22 and 23 April 1999 at 0330, 0345 and 0400 UTC, providing 15-minute observations of the southern section of the full-earth disc.

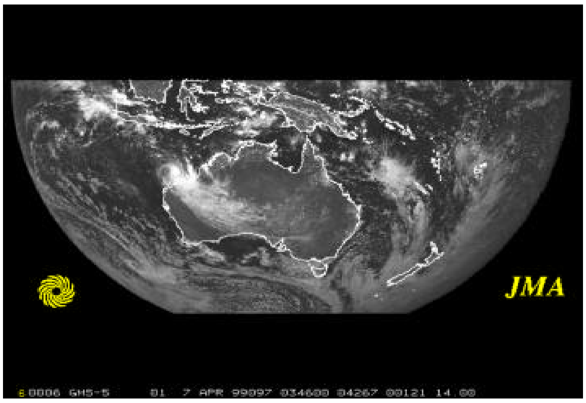

Figure 3 (a). Coverage during the Southern Hemisphere Special Observing Period - April 1999.

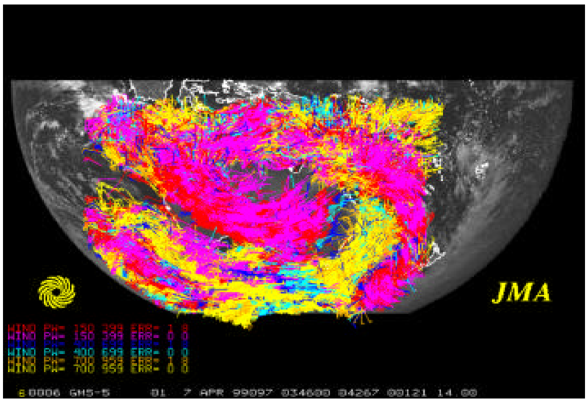

Figure 3 (b). Winds generated using 15-minute imagery on 7 April 1999.

The coverage provided during this observing period is shown in Figure 3 (a). Winds generated using these 15-minute observations on 7 April 1999 are shown in Figure 3 (b). These winds include 11µm infrared, low-resolution visible, high-resolution visible and water vapour image based motion vectors. The numbers of winds/high quality winds generated from these 15-minute observations as compared to those from hourly and half-hourly observations have been examined, as has the variation in wind numbers as visible image resolution is increased from 5 km to 1.25 km. In the case of observations taken on 7 April 1999, the area around Tropical Cyclone Gwenda has been examined in detail. Vectors generated in a 900 by 1280 pixel box, centred on the tropical cyclone, have been calculated at hourly, half-hourly and 15-minute intervals. The total number high resolution visible (HRVIS) vectors generated in the box, centred on Tropical Cyclone Gwenda, at different time periods on 7 April 1999, is displayed in Figure 4.

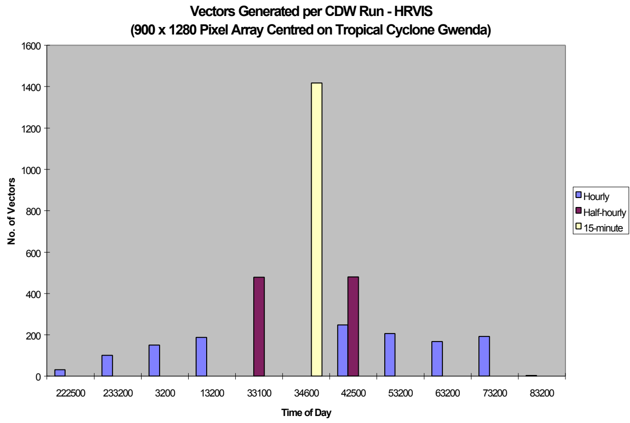

Figure 4. The variation in vector numbers for a high resolution visible image 900 x 1280 pixel box around TC Gwenda for different image frequencies (1/4, 1/2 and 1 hour).

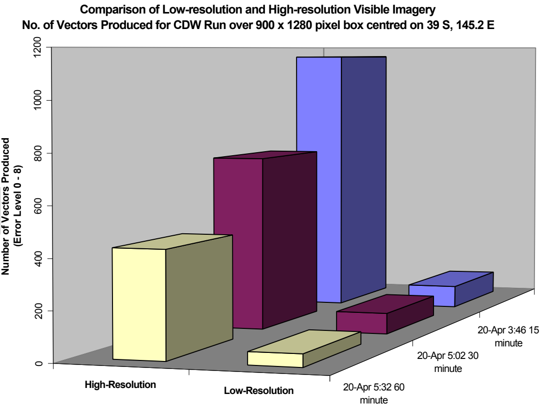

Figure 5. Comparison of low and high resolution visible imagery vectors mproduced in a 900 x 1280 pixel box centred on 39 °S, 145.2°E.

There is a significant gain in the numbers of vectors at higher temporal resolution, for this high-resolution image based data. The 15-minute observations provide significantly more data than the half-hourly and hourly observations. The influence of solar illumination is also clearly seen in these observations where the rising and setting of the Sun are clearly defined.

The effect of image resolution and target selection in the local system is seen in Figure 5 where high quality vector numbers calculated from high and low resolution visible images (1.25 km, 5 km respectively), separated by ¼, ½ and 1 hour over a 900 x 1280 pixel box centred on 39°S, 145.2°E over South Eastern Australia are shown. The total numbers of high quality vectors over the southern portion of the full-earth disc observed at different temporal resolutions are shown in Figure 6. An increase in high quality vector numbers with increased temporal resolution is seen for low resolution visible winds and, to a diminishing extent, for the infrared and water vapour winds.The winds generated from these SOP images are being used with other wind data from 7 April 1999 in a study of TC Gwenda. Preliminary results are shown later.

Overall, a clear increase in the density and coverage of high quality winds available from the system is evident with these higher temporal resolution observations. This is a clear indication of the improved observational capability associated with MTSAT, which, in principle, will allow five minute observations, defining wind fields in increased detail by tracking, for example, features in clouds associated with tropical cyclones right up to the inner core.

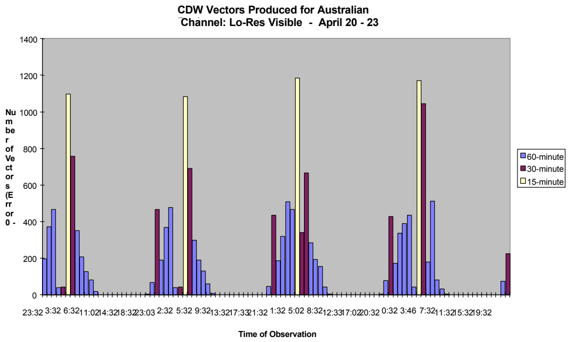

Figure 6 (a). Vector numbers for Low Resolution 5km) Visible Image based winds over the Australian Region (20 - 23 April 1999).

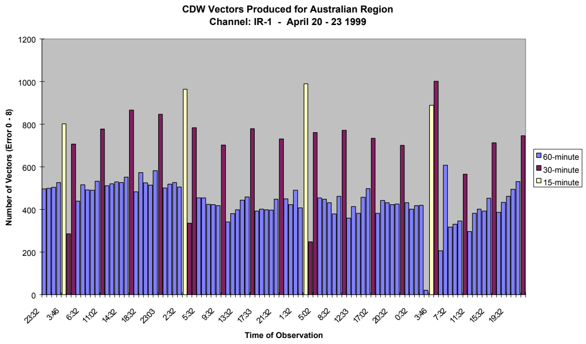

Figure 6 (b). Vector numbers for IR1 (11µm, 5km) Image based winds over the Australian Region (20 - 23 April 1999).

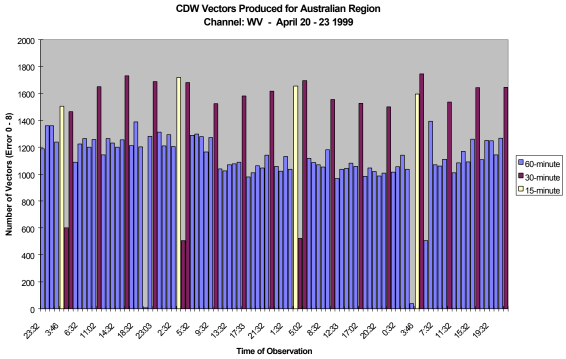

Figure 6 (c). Vector numbers for Water Vapour Band (6.7µm) Image based winds over the Australian Region (20 - 23 April 1999).

4. Intermittent assimilation of motion vector data

Real time data assimilation experiments, documenting the utility of local cloud and water vapour motion vectors for operational numerical weather prediction (NWP) over the Australian Region are complete. The operational Limited Area Prediction System (LAPS, Puri et al. 1998) has been used as the control. The experimental system employed has been a parallel, near real time LAPS system run, identical to the operational system, apart from 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 before the forecast start time. This is used as first guess to the Regional Analysis which then provides a base analysis, an initialised 6-hour forecast, a subsequent analysis and a further initialised 6-hour forecast. This forecast is then used as a first guess to the final analysis from which 24-hour forecasts have been run. The forecasts are nested in fields of the most recent Bureau of Meteorology Global Model forecast. The LAPS analysis and forecast models have the same latitude/longitude/sigma co-ordinate system of 160 x 110 grid points at 0.75° spacing in the horizontal and 19 levels in the vertical. The upper sigma level is at 0.05.

Three experiments have been completed. The first gauged the impact on the operational regional forecast system of local IR1 cloud drift winds, based on the 11µm window channel imagery. It was reported in Le Marshall et al. 1998. The winds were estimated from triplets of half-hourly GMS-5 imagery at 05, 11, 17 and 23 UTC. The NMOC operational forecast system and the operational data base included NESDIS TOVS, local TOVS and available JMA cloud drift winds. The second experiment gauged the impact of local hourly cloud drift winds on the operational prediction system (Le Marshall et al. 1998). This experiment was performed after the local 11µm winds had been introduced into the operational system. The third experiment gauged the impact of local water vapour image based motion vectors on the operational system (Le Marshall et al. 1999). The results of these three experiments are seen in Figure 7 which shows the improvement in regional S1 skill scores estimated on the official NMOC verification grid. It is interesting to note that most impact is seen at lower levels except in the water vapour wind study where the upper and mid-level vectors have provided most benefit at upper levels.

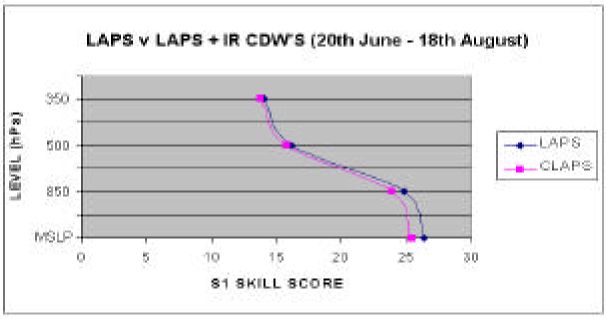

Figure 7 (a). S1 skill scores for 24-hour LAPS forecasts for Operations (Ops) and Ops plus IR1 winds.

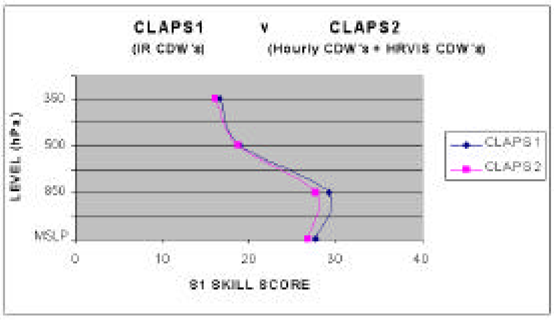

Figure 7 (b). S1 skill scores for24-hour LAPS forecasts for Operations (Ops) and Ops plus hourly winds.

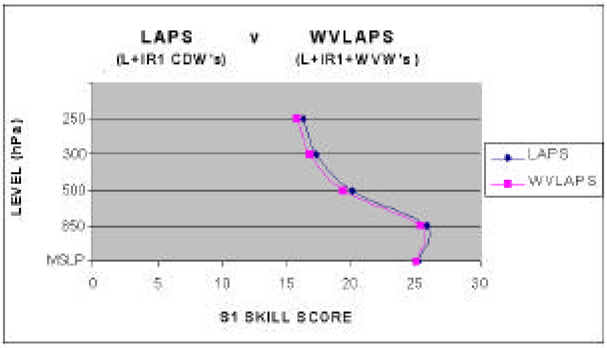

Figure 7 (c). S1 skill scores for 24- hour LAPS forecasts for Operations (Ops) and Ops plus Water Vapour winds.

5. Continuous assimilation of motion vector winds

Improvements in TC track forecasting have been made recently through the use of high resolution modelling, an enhanced data base and modern data assimilation techniques. For example, Le Marshall et al. (1996), Leslie et al. (1998) and Le Marshall and Leslie (1998) have shown that high-resolution (15 - 5 km) modelling and the use of high spatial and temporal resolution cloud and water vapour motion vector data with continuous 4-dimensional (4-D) variational assimilation (Bennett et al. 1996, 1997) has the ability to significantly improve TC track forecasting. The accuracy of eleven tropical cyclone track forecasts using high-resolution data and 4-D variational assimilation is shown in Figure 8.

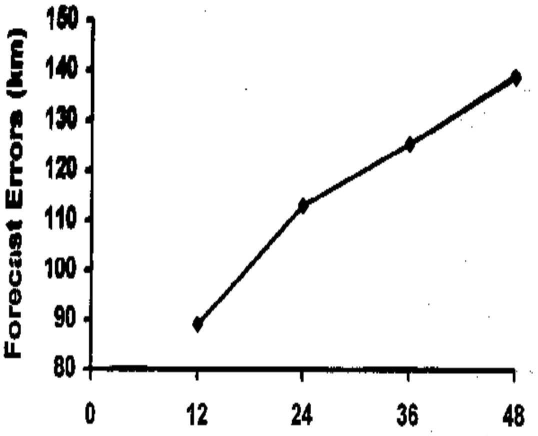

Figure 8. Forecast position error versus forecast length using 4-D variational assimilation for the eleven tropical cyclones.

Four-dimensional variational assimilation with the new high spatial and temporal resolution data source has incorporated additional data at non-synoptic times and assured an initial state which is in dynamic balance and is consistent with the observations taken during the previous 24 hours. It has produced 48-hour track forecast errors considerably below those now associated with operational forecasts (Gordon et al. 1998). Although these experiments are representative of recent increases in the accuracy of forecasting tropical cyclone tracks, the prediction of tropical cyclone intensity is still a vexing issue. We have extended the strategy employed above and have used high spatial and temporal resolution satellite data with very high resolution continuous assimilation and modelling. The wind-field associated with the tropical cyclone has again been depicted by several thousand wind observations over a 24-hour period prior to forecast start. These winds generally in the 200 - 3000 km range from the cyclone describe both the cyclone and the environment into which it moves. They also help define the upper level divergence associated with these storms, aiding the estimation and prediction of intensity (Bosart et al., 1998). We have used 4-dimensional variational assimilation to ensure that these data are incorporated correctly at non-synoptic times and we have assimilated both the data and modelled the cyclone at 5 km resolution to allow an adequate depiction of both cyclone structure and intensity. Five kilometres resolution appears to be within the range required to resolve adequately the area of maximum wind speed and provide a realistic depiction of storm dynamic and thermodynamic structure.

The model configurations used in these studies were 25 levels, 25 km resolution (180 x 180 grid points), 15 km resolution (301 x 301 grid points) and 5 km resolution (601 x 601 grid points). The early stages of two tropical cyclones are shown. The first was Tropical Cyclone Olivia which developed explosively off the NW coast of Western Australia during the forecast period. High spatial and temporal resolution cloud and water vapour winds were assimilated for 24 hours between 12 UTC on 5 and 6 April 1996 using 4-D variational assimilation. The resolution of the assimilation and forecast system was varied from 25 km, through 15 km down to 5 km. The variation of storm central pressure with time from 12 UTC on 6 April 1996 for the control and 4-D variational forecasts out to 72 hours is seen in Figure 9(a) for each resolution.

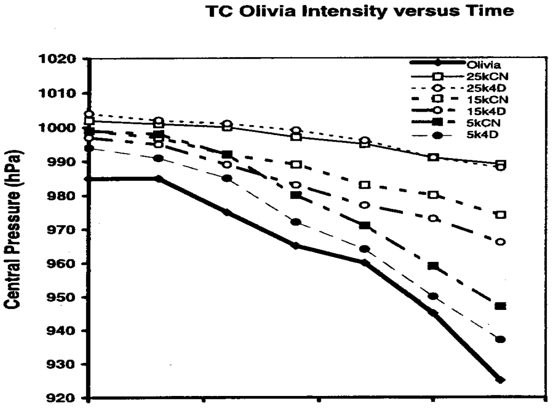

Figure 9 (a) TC Olivia intensity versus forecast period for different resolutions and data.

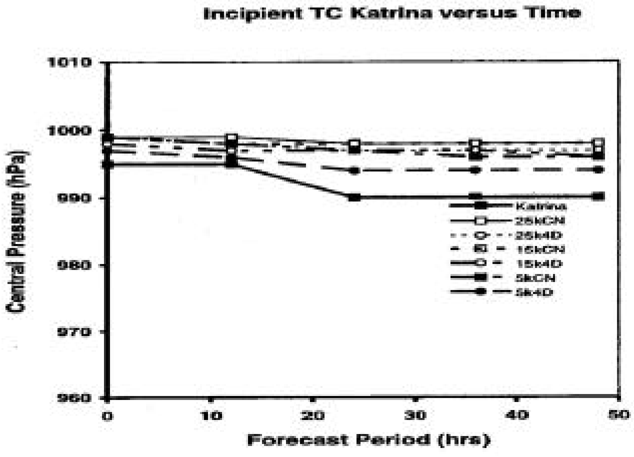

Fig. 9 (b) Forecast intensities for TC Katrina from 0000 UTC 3 January 1996 with varying grid resolutions, for the control and 4-D variational assimilation cases

Figure 9 (b). TC Katrina intensity versus forecast period for different resolutions and data..

The beneficial impact of the high resolution wind data used during initialization is evident. While there is little difference between the control and 4-D assimilation forecasts at lowest resolution, the difference progressively increase with higher model resolution. The winds associated with TC Olivia at 0000 UTC on 9 April 1996 are shown in Figure 10. This is a southwest to northeast cross section of the winds at 900 hPa. The winds are a 15 minute average. The maximum wind speed in this case is 63 m/s at 900 hPa and compares well with the NCC surface maximum winds of 46 m/s, which is close to 0.75 of the 900 hPa estimate.

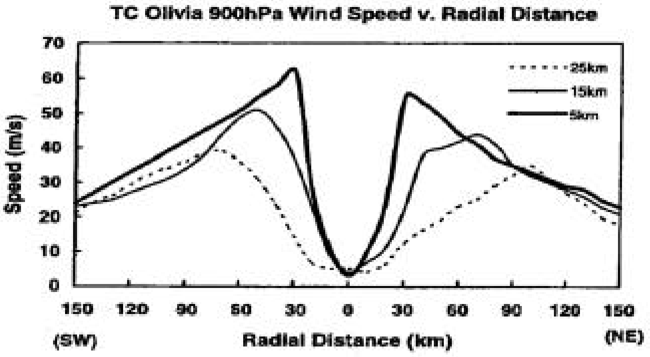

Fig. 10 A SW to NE cross-section of winds through TC Olivia at 900 hPa at 00 UTC 9 April 1996

Figure 10. A SW-NE cross-section of winds through TC Olivia at 900 hPa at 00UTC 9 April 1996.

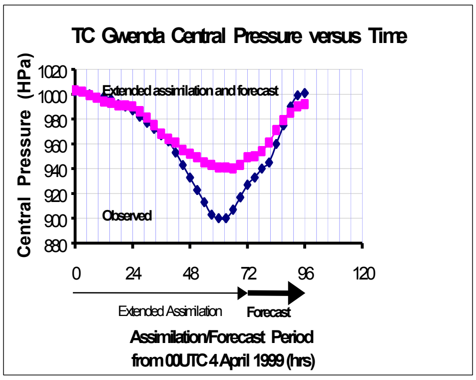

Figure 11. Modelled TC Gwenda central pressure using extended 4D variational assimilation.

The second cyclone examined in this study was TC Katrina. The time for the start of the forecasts was 00 UTC on the 3 January 1998. This cyclone formed very slowly in the Coral Sea. The intensities forecast in this case are summarised in Figure 9 (b). In recent developments, continuous data from 00 UTC on 4 April 1999, around TC Gwenda, has been used to forecast intensity. Warm running at 1 and 5 km resolution via 3 days of 24 hour 4D variational assimilation has provided a 24hr forecast (See Figure 11). Here again the benefits of very high resolution 4-D variational assimilation and modelling and high resolution data are evident.

6. Summary and Conclusions

We have briefly described the real time generation of cloud drift winds in the Australian Region from GMS-5 Stretched VISSR data. We have also used the test data available from a special observing period in April 1999 to show the improved coverage of winds expected from MTSAT. We have briefly documented the beneficial impact of the locally generated winds on regional numerical weather prediction. In relation to tropical cyclone track forecasting, while it is well established that high resolution numerical modelling and an enhanced data base are important to accurate tropical cyclone forecasts, here, we have summarised work showing high resolution modelling, high spatial and temporal resolution data and continuous data assimilation being combined and applied to the forecast problem. This approach allows the benefit of high resolution modelling to be obtained, both in the assimilation and forecast process, while continuous assimilation incorporated with the high spatial and temporal resolution data at non-synoptic times and ensured an initial state which is close to dynamic balance and consistent with observations. Although initial position errors are still a contributor to forecast errors, overall, the results show that the wind data base and the assimilation methodology adopted here have significantly reduced the forecast errors associated with tropical cyclone track prediction, , particularly in difficult forecast situations.

In relation to modelling tropical cyclone intensity, we have shown two contrasting tropical cyclones - a developing and non-developing storm. In these cases studied, horizontal resolution has been revealed to be a key element in predicting storm intensity. The winds used were mainly in the upper outflow region of the storm and had a significant impact on the overall accuracy of both the initialised fields and the subsequent forecasts. In addition to this, we have, for the first time, shown the benefits of warm running using 4-dimensional variational assimilation to enable initialisation of the model over a very intense cyclone and to successfully allow the modelling of the cyclone dissipating.

ACKNOWLEDGMENTS

Thanks are due to T. Adair for his work in the preparation of this manuscript.

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