

Shorter contribution

Modelling tropical cyclone intensity

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Introduction

Significant gains have been made recently in tropical cyclone (TC) track prediction, by use of high spatial and temporal resolution data, high-resolution modelling and modern continuous data assimilation techniques such as four-dimensional variational assimilation and one-hourly nudging. However, advances in forecasting tropical cyclone intensity have been limited. In this study very high resolution numerical modelling and four-dimensional variational assimilation (up to 5 km) and high spatial and temporal resolution satellite wind data are used in determining the initialised tropical cyclone intensity and also the subsequent forecast intensity, up to 72 hours ahead.

It is found that model resolution is a key element in predicting storm intensity and as it is increased to 5 km a far more realistic depiction of storm intensity and structure is obtained. This result is not surprising as higher resolution provides more detailed modelling of the comparatively small areas of very high wind speed associated with the storm. Higher resolution also allows increasing tangential wind speed in the converging low-level air approaching the often smaller area of maximum wind speed around the tropical cyclone vortex.

The use of cloud and water vapour motion vectors, particularly at the upper outflow level, also yields much improved intensity forecasts, a result suggested almost two decades ago in simulations using synthetic data. Overall, the results in these cases show that very high resolution modelling with cloud and water vapour wind data and continuous assimilation have the capability of significantly improving the analysis and forecasting of TC storm intensity and structure.

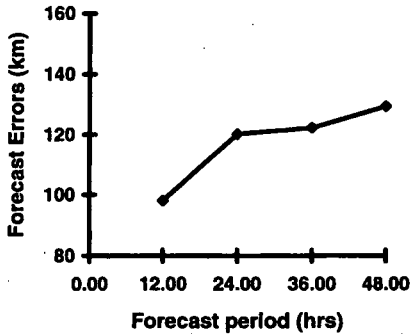
Background

Notable improvements in TC track forecasting have been made recently through use of high resolution modelling, an enhanced database and modern data assimilation techniques. For example, Le Marshall et al. (1996), Leslie et al. (1998) and Le Marshall and Leslie (1998a) have shown that high-resolution (15 km) modelling and the use of high spatial and temporal resolution cloud and water vapour motion vector data with continuous assimilation methods, in particular four-dimensional (4-D) variational assimilation (Bennett et al. 1996, 1997) and one-hourly nudging, have the ability to significantly improve TC track forecasting. The accuracy of eight southern hemisphere track forecasts using high-resolution data and 4-D variational assimilation is shown in Fig. 1. This approach to the forecasting problem has allowed the benefits of high resolution modelling to be realised both in the assimilation and forecast processes. Four-dimensional variational assimilation with the new high spatial and temporal resolution data source has also 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 also produced 48-hour track forecast errors considerably below those now associated with operational forecasts (Gordon et al. 1998).

Although the experiments above are representative of recent increases in the accuracy of forecasting TC tracks, the prediction of TC 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 TC has been depicted by several thousand wind observations over a 24-hour period prior to forecast start. These winds generally in the 200 - 2000 km range from the cyclone

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Fig. 1 Forecast position errors versus forecast period using 4-D variational assimilation for eight tropical cyclones in the Australian region (*Beti*, 26/03/1996; *Olivia*, 06, 09/04/1996; *Ethel*, 12/03/1997; *Justin*, 8, 10, 16/03/1997; *Katrina*, 03/01/1998).



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 four-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.

Much has been written on the problems of TC intensity prediction. The importance of the various physical processes is discussed in Elsberry et al. 1992 which provides a record of a panel discussion on the prediction of TC intensity. Most of the processes discussed, including the interaction with the storm's environment (e.g. passing weather systems), moist convection, the internal dynamics, upper-level momentum flux convergence and air-sea interaction, should be adequately represented in a NWP forecast model at 5 km resolution. Preliminary experimentation by the authors has revealed that simply increasing model resolution to 10 km or below resulted in a dramatic reduction of the forecast TC's central pressure. Others have since found similar results (Mailhot, personal communication 1998).

Finally, we note a much earlier sensitivity study on the impact of synthetic satellite-sensed winds on inten-

sity forecasts of tropical cyclones by Chang (1981), and remark the remotely sensed wind data source we have used in these studies provide a valuable measure of wind speed and direction at lower and mid-levels and, importantly, at the upper tropospheric outflow level where they may be expected to help determine cyclone intensity and subsequent development.

The winds

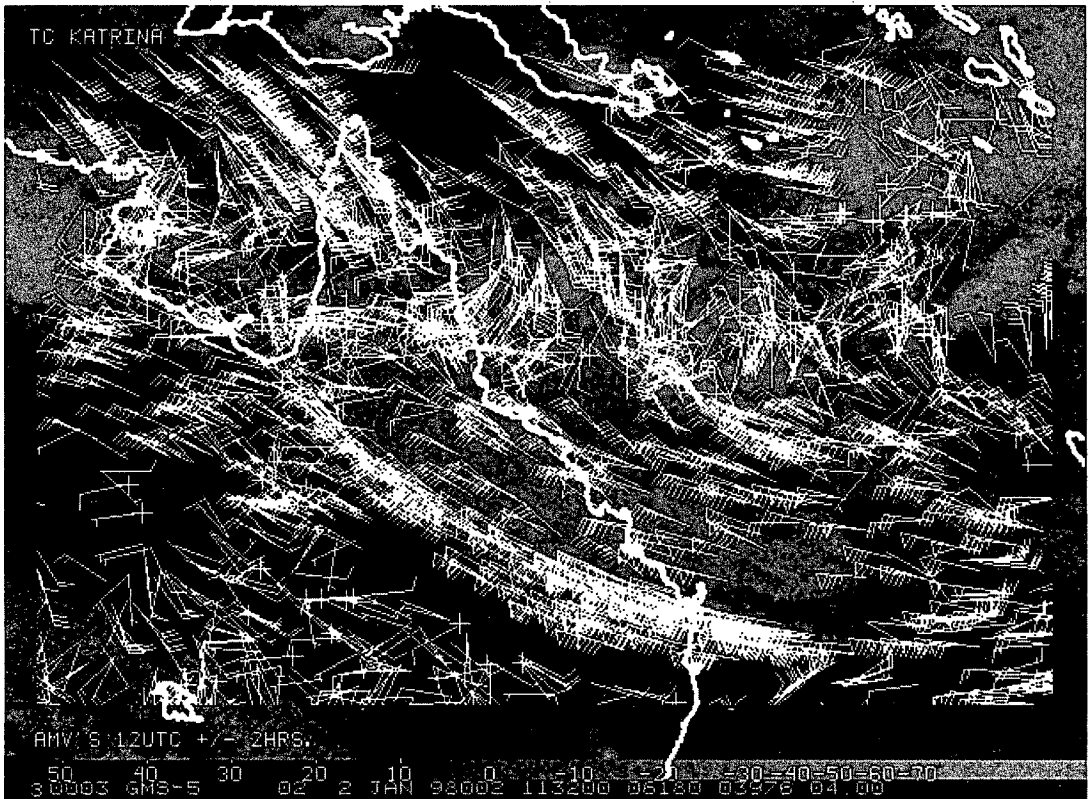
Hourly and half-hourly (four times per day), GMS S-VISSR infrared (IR), water vapour (WV) and visible (VIS) images are received in Melbourne and stored in cyclically navigated and calibrated datasets in the Australian Region McIDAS (Le Marshall et al. 1987). Targets are selected and tracked automatically using a model forecast to initiate the search for the selected targets on subsequent images. A lag correlation technique is used to estimate the vector displacement. Altitude assignment is similar to that in Le Marshall et al. (1994, 1998c) with refinements to allow for the changes in spectral response functions and calibration for the new GMS-5 VISSR. As a result, the winds reflect the benefit of dynamic calibration and use of the split window channels (IR1, IR2) for water vapour correction and height assignment (see, for example, Le Marshall et al. 1998b).

At the Australian Bureau of Meteorology (BoM), the current operational system generates winds from sets of three 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.

The assimilation methodology

In these studies, the control forecast (CN) used the forecast model component (Leslie and Purser 1995) of the 4-D variational assimilation system initialised with the Bureau of Meteorology's Limited Area Prediction System (LAPS, Puri et al. 1998) analysis. Details of the 4-D variational assimilation system used in these experiments are given in Bennett et al. (1996, 1997). It uses six-hourly LAPS analyses from $T = -24$ to $T = 0$. Forecast boundary conditions were derived from the Global Assimilation and Prediction System (GASP) in the case of tropical cyclone *Olivia* and the LAPS in the case of TC *Katrina*. Twenty-four

Fig. 2 Cloud and water vapour motion vectors around 11 UTC on 2 January 1998.



hours of hourly visible and infrared winds were incorporated asynchronously during the 4-D variational model initialisation. 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 experiments and results

The early stages of two TCs are studied in detail in these experiments. The first was TC *Olivia* which developed explosively off the NW coast of Western Australia during the forecast period. High spatial and temporal resolution cloud and water vapour motion vectors were assimilated for 24 hours between 1200 UTC on the 5th and 6th 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 1200 UTC on 6 April 1996 for the control and 4-D variational forecasts out to 72 hours is seen in Fig. 3 for each resolution. The control was a forecast from the LAPS analysis at 1200 UTC on the 6th April 1996, generated using diabatic initialisation. The clear benefit of increasing resolution is evident in these results, with the move from 25 km resolution through 15 to 5 km resolution showing significant improvement in the modelling of intensity. This result is not unexpected given that resolutions around 5 km or lower are required to be able to appropriately model both the dynamic and thermodynamic structure of these mesoscale tropical storms.

The beneficial impact of the high resolution wind data used during initialisation is also evident. While there is little difference between the control and 4-D assimilation forecasts at the lowest resolution, the differences progressively increase with higher model resolution. At high resolution, the atmospheric motion

vectors have clearly aided the estimation and forecasting of intensity. In particular in the 5 km resolution 4-D assimilation forecasts, the use of the atmospheric motion vectors has reduced the initial pressure of the TC *Olivia* from 1001 hPa to 994 hPa (see Fig. 3 (a) at 0 h.) compared to the official National Climate Centre (NCC) estimate of 985 hPa and provided improved intensity forecasts compared to the control. Intensification is a complex process depending on many parameters including sea-surface temperature, vertical shear and upper-level divergence. Here the depiction of the background environment and the upper wind structure over the cyclone has been achieved using primary (wind) observations which are fitted during initialisation and result in an improved prognosis. In particular the upper divergence fields which these winds can represent in the outflow layer of the cyclone (Chang 1981; Bosart 1998) appear to be an important component in the 4-D analysis and the subsequent prognosis. This was graphically seen in cases of TC *Olivia* and TC *Katrina* for the 150 to 300 hPa, mean layer streamlines and divergence (not shown). While no claim can be made concerning the detail and exact accuracy of the divergences (given they are calculated from an uneven four-dimensional distribution through the outflow layer over four hours) the relative magnitude of the divergence appears significant. Very high values were found for TC *Olivia* corresponding to a situation midway through the forecast period when it was intensifying rapidly from 960 hPa to 925 hPa over twenty-four hours, while for the initialisation period for TC *Katrina* where little change was recorded even in the subsequent 24 hours (995 hPa to 990 hPa), values were significantly reduced.

The winds associated with TC *Olivia* at 0000 UTC on 9 April 1996 (Fig. 4(a)) are shown in Fig. 4(b). This is a southwest to northeast cross-section of the winds at 900 hPa. The winds are a 15-minute average. As expected, with the vortex moving away from the coast (to the West) the wind maximum is on the southwest side of the cross-section which corresponds to the highest wind speeds. 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. This fraction of the maximum wind speed seen near the surface is a widely accepted value. (see e.g. Simpson and Riehl 1981).

The second cyclone examined in this study was TC *Katrina*. The time for the start of the forecasts was 0000 UTC on the 3 January 1998. This cyclone formed very slowly in the Coral Sea. The intensities forecast in this case are summarised in Fig. 3(b). Here again the benefits of very high resolution 4-D

Fig. 3 (a) Forecast intensities for TC *Olivia* from 1200 UTC on 6 April 1996 with varying grid resolution, for the control and 4-D variational assimilation cases.

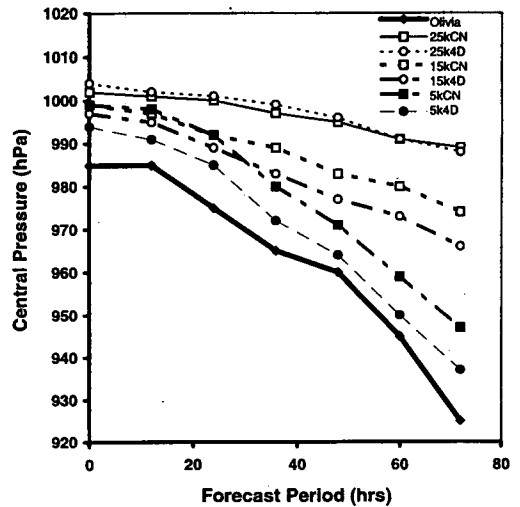
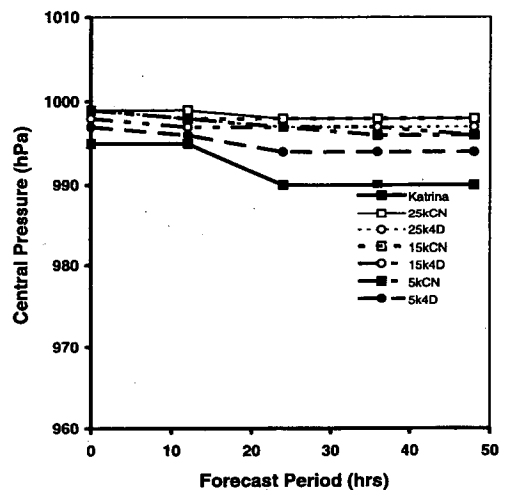


Fig. 3 (b) Forecast intensities for TC *Katrina* from 0000 UTC 3 January 1998 with varying grid resolution, for the control and 4-D variational assimilation cases.



variational assimilation and modelling and high resolution data are evident. Once again the 5 km 4-D variational assimilation provides the best results, indicating only a slow development of the cyclone with the influence of the winds giving the best results for this case.

Fig. 4 (a) The forecast MSLP for TC *Olivia* at 00 UTC 9 April 1996.

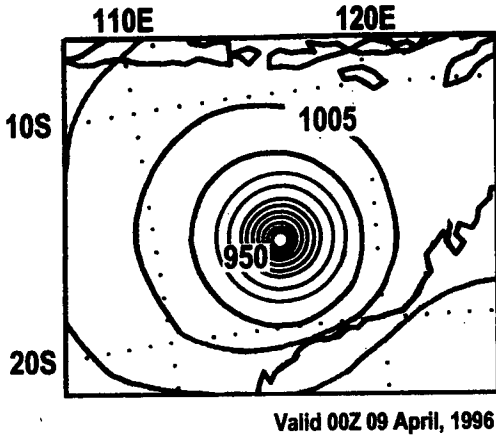
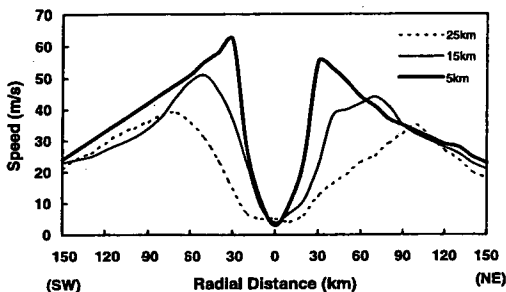


Fig. 4 (b) A SW to NE cross-section of winds through TC *Olivia* at 900 hPa at 00 UTC 9 April 1996.



Discussion and conclusions

We have studied two contrasting TCs, a developing and non-developing storm and examined the effects of high spatial and temporal resolution data, a 4-D variational assimilation scheme and very high resolution in the assimilation and forecast model, (ranging from 25 km down to 5 km). In the cases studied, horizontal resolution is revealed to be a key element in predicting storm intensity. It is required to represent the strong gradients in the wind fields associated with TCs, to depict the areas of highest (maximum) wind speeds, and to capture the thermodynamic structure of the storm. It is also required for realistic intensity

prognoses. In addition the modelled intensity was improved through use of high spatial and temporal resolution winds via 4-D assimilation. The winds used were mainly in the upper outflow region of the storm and had a major impact on the overall accuracy of both the initialised fields and the subsequent forecasts. While this study is not exhaustive it points to the importance of including upper tropospheric wind fields in the initialisation, to provide an indication of divergence in the outflow layer of the (incipient) TC.

Overall the results have shown that, modelling at an appropriately high resolution, the use of high-resolution wind data, and the use of modern assimilation techniques have the potential to significantly improve intensity forecasts. As a result, this approach warrants further study to determine its utility for operational forecasting. (Such work is well underway and yielding similar results). The practicality of the approach is likely, given the availability now or in the near future of satellite atmospheric motion vector and sounding data, scatterometer winds and even the possibility to determine cyclone central pressure by use of unmanned light planes. Currently, computing resources within the BoM, for instance, would support a 15 km resolution 4-D system and take two hours to produce a 48-hour forecast. Numerical experiments using now-available next-generation machines take a similar amount of CPU time for 5 km resolution 4-D assimilation forecasts.

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