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Shorter contribution

Tropical cyclone track prediction using high resolution satellite data with a new methodology

Abstract

Tropical cyclone track forecasting remains a difficult problem. Here, we summarise eleven forecast cases, almost all in the Australian Region (AR), each of which was regarded as a difficult forecast case. There are three new aspects in these forecasts. First, the modelling and data assimilation have been performed at very high (15 km) resolution. Second, a newly developed data source, namely, high spatial and temporal resolution cloud-drift winds (CDWs), has been used to augment the often quite poor observational database upon which operational forecasts currently are based. Finally, a range of continuous assimilation schemes, including recently developed four-dimensional (4-D) variational assimilation and hourly nudging have been tested. In these cases, conventional forecast guidance and CLIPER (a statistical model (Neumann 1972) based on CLImatology and PERsistance) usually were poor. In contrast, the continuous assimilation procedures, namely, one-hourly nudging and 4-D variational assimilation, took advantage of the high spatial and temporal resolution wind data and provided much improved forecasts, especially beyond 12 hours. Overall, the initialisation provided by continuous assimilation, combined with a substantial high spatial and temporal resolution database and high resolution modelling, has shown a capacity to improve greatly the accuracy of tropical cyclone track forecasts over the data-sparse oceans.

Introduction

Tropical cyclone track forecasting is, to a significant degree, an initial value problem, and, as such, is dependent on two key elements: First a well-parametrised, high resolution forecast model is required for use with data assimilation and for accurate forecasting. Second, a high spatial and temporal resolution observational database is also necessary if the correct initial conditions are to be established over the data-sparse areas usually associated with tropical cyclones. The importance of high resolution models in tropical cyclone forecasting is well known. The ability of high temporal and spatial resolution satellite data over the tropical oceans to improve forecasts is also well established (Velden 1996; Velden et al. 1997; Le Marshall et al. 1996a; Le Marshall et al. 1997). Some earlier higher resolution studies have been performed by Kurihara et al. (1995). These studies have been initialised by the use of an environmental field and a storm-related model compatible vortex rather than the use of continuous assimilation of observed data.

In these studies, an improved methodology for numerical tropical cyclone track forecasting has been tested. To determine a well-described initial state for tropical cyclone forecasts, we have used the high resolution numerical model of Leslie and Purser (1995), with a new data source, namely, hourly satellite-based cloud-drift winds (CDWs) (Le Marshall et al. 1996a). We have also tested a variety of data assimilation techniques, including six-hourly nudging, three-dimensional (3-D) variational assimilation (Bennett et al. 1993), one-hourly nudging and one-hourly 4-D variational assimilation (Bennett et al. 1996). In all, eleven sets of tropical cyclone track forecasts, the majority of which were deemed independently to be difficult forecast tasks on the basis of irregular tracks, have been studied in detail (See Tables 2 to 4).

Data assimilation and forecasts

The data: high spatial and temporal resolution winds.GMS Stretched-VISSR images are received hourly (and four times per day, half-hourly) and stored on cyclic datasets in the Australian Region McIDAS system (Le Marshall et al. 1987). Suitable targets for tracking are selected from these images. These targets are tracked automatically, using a forecast model first guess to initiate the search for the selected targets on subsequent images. A lag correlation technique is used to estimate the vector displacement.

Cloud height determination is similar to that in Le Marshall et al. (1994) with some modification to allow for changes in spectral response and calibration for the new GMS-5 VISSR. Real-time test systems have several enhancements such as the correction of poorly height-assigned transmissive cirrus using brightness temperature differences between IR1, IR2 and IR3 and use of a velocity test to check the level of best fit. For visible winds, height assignment uses the infrared imagery associated with the central time of the image triplet under consideration. After automatic velocity estimation and height assignment, quality control results in expected errors being assigned to the winds, based on several objective criteria (Le Marshall et al. 1994).

The current operational system runs four times per day, using three sequential infrared images, separated by half an hour. Winds are also produced hourly in real-time research mode, using both infrared and visible

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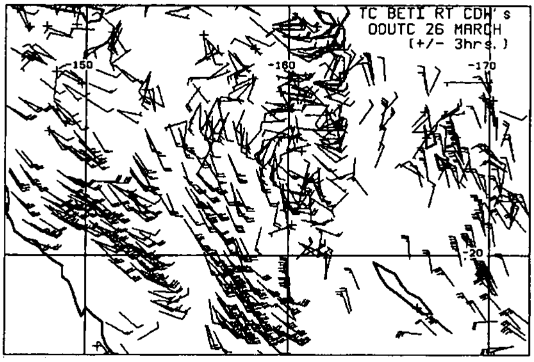
Table 1. Cloud-drift wind types generated in the Bureau of Meteorology. The table indicates type, image resolution, frequency of wind extraction, time of wind extraction and the separation of the image triplets used for wind generation (DT).

Wind type	*Image res.*	*Freq.*	*Time (UTC)*	*Wind triplet (DT)*
Op. IR	5 km	6 h.	05, 11, 17, 23	30 min.
Low-res. VIS	5 km	6 h.	05, 23	30 min.
High-res. VIS	1.25 km	6 h.	05, 23	30 min.
IR	5 km	1 h.	00, 01, ... 23	1 hour
Low-res. VIS	5 km	1 h.	23, 00, 01 ..., 08, ...	1 hour
High-res. VIS	1.25 km	1 h.	23, 00, 01 ..., 08, ...	1 hour

imagery. The infrared images are used to produce hourly winds throughout the day while the visible images are used to produce hourly and six-hourly wind sets during daylight hours, based on images of 5 km and 1.25 km subsatellite resolution. The CDW types generated in the Bureau of Meteorology are summarised in Table 1 and the typical vector numbers and accuracy are recorded in Le Marshall et al. (1996a).

Figure 1 provides an example of low error category visible and infrared (11 µm) winds, generated in real time around tropical cyclone (TC) *Beti* within three hours of 0000 UTC on 26 March 1996. The density of these winds may be contrasted with those shown in Fig. 2 which is the upper-level wind coverage available without local CDW data and was representative of the wind field available to the Tropical Analysis and Prediction System (TAPS) (Puri et al. 1992) within the National Meteorological Operations Centre (NMOC).

Fig. 1 **Visible and IR image-based cloud-drift winds around TC *Beti* within three hours of 0000 UTC on 26 March 1996. Vectors represent upper and lower level winds.**

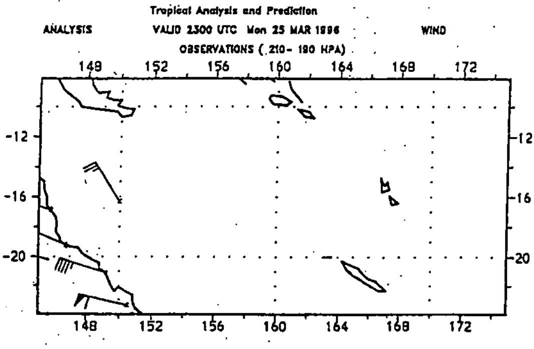


The data assimilation methodology. The data assimilation methodology was as follows. The control forecast used the forecast component of the 4-D variational assimilation system initialised with the Bureau of Meteorology's Tropical Analysis (Davidson and McAvaney 1981). Six-hourly nudging also used these Tropical Analyses (TAs) for the 24-hour period leading up to the commencement of the forecast. In this case, six-hourly CDWs were assimilated every six hours for 24 hours before forecast commencement. The analyses produced were then used for 24 hours of six-hourly nudging preceding the forecast. The forecasts were nested in the Bureau of Meteorology's TAPS. The nudging procedure is widely used to initialise NWP fields and, for a given variable, u, can be written simply as:

$$\frac{\partial u}{\partial t} = \ldots -G\nabla^2(u - u_a)$$

where G is the nudging coefficient and u_a is the analysis u field. This nudging coefficient is a function of resolution in particular and the 'optimal' choice of G (0.8 x

Fig. 2 **Upper-level winds available to TAPS in NMOC around TC *Beti* at 2300 UTC on 25 March 1996.**



10^7 m^2 s^{-1}) has been determined empirically over a number of forecasts preceding these studies.

The three-dimensional variational assimilation used the Bureau of Meteorology's TAs to provide an 850 - 200 hPa deep layer mean field with the variational assimilation being used to incorporate the deep layer mean winds into the system, while the model and its generalised inverse are used to find the appropriate starting point for the barotropic forecast. Details of this forecast system are in Bennett et al. (1993). The idea is quite simple although the procedure is not. In variational data assimilation, a quantity called the 'penalty function' is minimised in a least squares manner. This provides a best fit between the model, data, initial conditions and boundary conditions.

Hourly nudging was first performed by using the six-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 the spurious generation of gravity waves before production of the 48-hour forecast, based on the evolved state at T = 0. The forecasts were nested in TAPS. Divergence damping was very simple to introduce, requiring the addition of one term to each of the prediction equations for the horizontal wind components U and V, namely $K\ \nabla D$ where D is the divergence. Care must be taken in choosing the size of K (here,1.1 x 10^8 m^2 sec^{-1}) so that damping of gravity waves is achieved without suppressing vertical velocities too greatly.

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. The 4-D variational procedure is simply an extension of the 3-D procedure but is far more computationally expensive.

The model configuration (except for the 3-D variational assimilation barotropic forecasts) used in these studies was 25 levels, 15 km resolution and 180 x 180 grid-points. For TC *Beti*, for example, the domain covered approximately 5°S to 35°S, 145°E to 175°E. The model is described in Leslie and Purser (1995).

Experiments and results

The first experiment using real-time high temporal and spatial resolution cloud-drift winds with continuous assimilation methods was with TC *Rewa* which approached the Queensland coast in January 1994 (Le Marshall et al. 1996a). Forecasts were initiated, contrasting the control, six-hourly nudging and hourly 3-D variational assimilation as this cyclone approached the coast and then veered away. The control forecast was quite poor and located the cyclone ashore while the six-hourly nudging and three-dimensional variational assimilation forecasts kept the cyclone at sea in accordance with observations. A summary of the position errors is given in Table 2.

This barotropic study, which pointed to the advantage of using one-hourly CDWs with continuous assimilation, was followed by five studies examining tropical cyclones *Beti, Olivia, Ethel* (Le Marshall et al. 1996b, 1997) and *Justin* (Le Marshall 1998) for which two sets of forecasts were performed. These contrasted a control run (high resolution forecast using the operational tropical analysis), six-hourly nudging, one-hourly three-dimensional variational assimilation, one-hourly nudging and full four-dimensional variational assimilation, using the model of Leslie and Purser (1995) and the initialisation method of Bennett et al. (1996). Results for TC *Justin* as it approached the Queensland coast are shown in Fig. 3 (a). Forecasts started at 0000 UTC on 10 March, after 24 hours of hourly data assimilation indicated that the storm would stall, in contrast to much conventional forecast guidance material and the climatology and persistence based forecast, CLIPER (Morison 1993).

All forecasts are summarised in Table 3, which gives the relative accuracy of control run (M), CLIPER (CL), one-hourly nudging (1HN), and 4-D variational (1H4D) assimilation. 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 two orders of magnitude in resources, it shows a far less significant increase in forecast accuracy.

As a result of the clear practical advantages of one-hourly nudging, three further experiments were run for TCs *Justin*, *Drena* and *Rachel* and used to contrast the control forecast, CLIPER and one-hourly nudging (Table 3). Again, the control and CLIPER forecasts were clearly inferior to the one-hourly nudging forecasts. (It should be noted that the good results obtained from CLIPER at T = +12 h are due to the fact that the Australian CLIPER has used non real-time best track

Table 2. TC *Rewa* forecast position errors (km) for the nudging and variational assimilation methods for forecasts from 1200 UTC on 17 January 1994.

Assimilation Method	+24 h	+36 h	+48 h
6-h. Nudging	123	211	249
1-h. Variational	81	121	166

Fig. 3(a) **Tracks for TC *Justin*, starting at 0000 UTC on 10 March 1997, predicted by the Control (M), one-hourly nudging (N1) and hourly 4-D variational assimilation (4). The actual track is (J).**

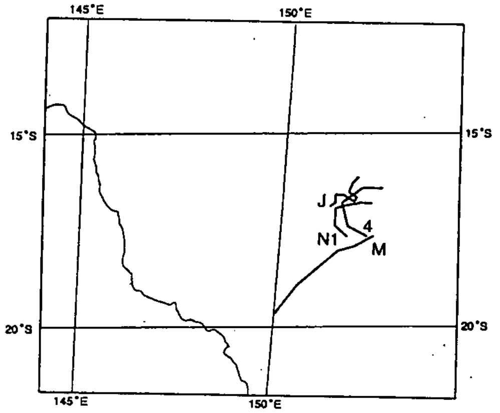
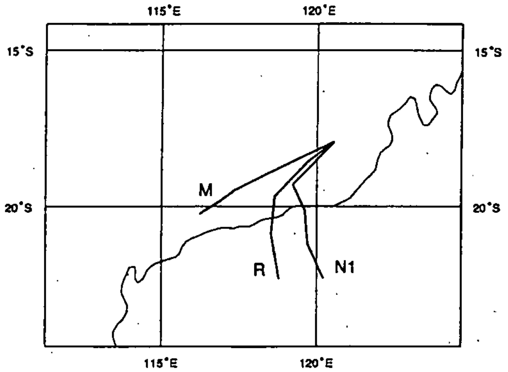


Fig. 3(b) **Tracks for TC *Rachel*, starting at 0000 UTC on 06 January 1997, predicted by the Control (M) and one-hourly nudging (N1). The actual track is (R).**



data, unlike the NWP models). An example of these forecasts can be seen in Fig. 3(b) where TC *Rachel* is seen to cross the WA coast after the assimilation of the high resolution CDWs, a considerable improvement on most available NWP guidance (Foley 1997).

An overview of the results presented here is seen for TCs *Beti, Olivia, Ethel* and *Justin* (2) in Fig. 4(a), where the mean forecast errors from +12 to +48 hours are presented for the different forecast methodologies (and database) used. There is an almost linear increase in error with time. There is also a distinct jump in forecast accuracy (reduction in error growth) as one goes from the control and CLIPER to hourly nudging and 4-D variational assimilation. A similar diagram for the eight sets of forecasts (*Beti, Olivia, Ethel, Justin* (3), *Drena* and *Rachel*) is shown in Fig. 4(b) where only the control, CLIPER and hourly nudging have been displayed for this larger dataset. Inspection of these cases shows the distinct advantage of hourly nudging over the control and CLIPER to be clearly evident.

After completion of the Australian studies, an examination of hurricane *Opal* in the Gulf of Mexico, was undertaken. Forecasts based on 0000 UTC and 1200 UTC, 12 October 1995 (Leslie et al. 1998), namely, the control, CLIPER (Neumann 1972), six-hourly nudging and six-hourly 3-D and 4-D variational assimilation were contrasted. Table 4 shows that mean errors for six-hourly nudging and 4-D variation-

Table 3. **Tropical cyclone track forecast errors for the control (M), CLIPER (CL), one-hourly nudging (1HN) and one-hourly 4-D variational (1H4D) forecast systems (ET denotes extratropical system).**

Cyclone	*Forecast Start*	*24 h forecast*				*48 h forecast*			
		M	CL	1HN	1H4D	M	CL	1HN	1H4D
Beti	00 UTC 26/03/96	652	190	110	110	712	522	105	57
Olivia	00 UTC 09/04/96	190	188	62	124	623	867	120	81
Ethel	00 UTC 12/03/97	362	111	136	181	405	499	89	161
Justin 1	00 UTC 08/03/97	89	178	85	84	268	407	143	107
Justin 2	00 UTC 10/03/97	164	226	148	76	383	693	274	151
Interim Average (5 cases)		291	179	108	115	478	598	146	111
Justin 3	00 UTC 20/03/97	167	136	46		272	290	120	
Drena	12 UTC 08/01/97	385	60	147		ET	ET	ET	
Rachel	00 UTC 06/01/97	141	188	118		360	208	143	
Mean forecast error (8 cases)		269	160	107		432	498	142	

Fig. 4(a) Tropical cyclone forecast position errors for the Control (M), one-hourly nudging (1HN), one-hourly 4-D variational (1H4DV) and CLIPER (CL) using best track data (5 cases).

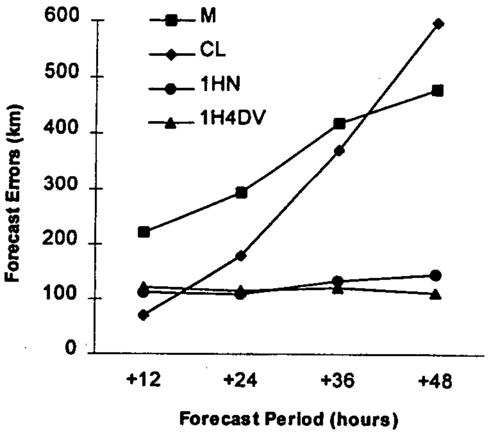
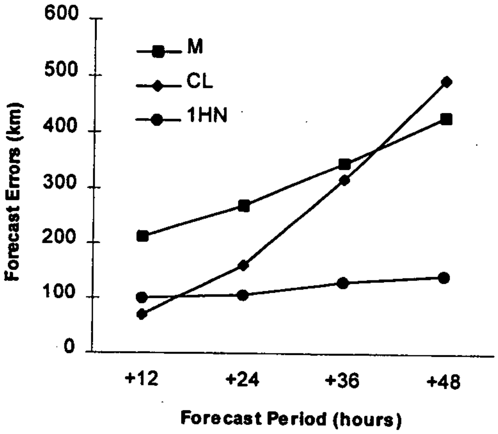


Fig. 4(b Forecast position errors as in 4(a) but for 8 cases (See Table 3).



al assimilation, which use the same enhanced database, are similar and clearly superior to the control, CLIPER and 3-D variational assimilation. It should be noted that, in this case, the GOES operational program did not provide hourly data so neither hourly nudging nor hourly 4-D variational assimilation were undertaken.

Conclusions

While it is well established that high resolution numerical modelling and an enhanced database are important to accurate tropical cyclone forecasts, here, for the first time, high resolution modelling, high spatial and temporal resolution data and continuous data assimilation have been combined and applied to the 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.

Table 4. Hurricane Opal mean forecast position errors at 12, 24, 36 and 48 hours for forecasts commenced at 0000 UTC and 1200 UTC on 2 October 1995.

Assim type	*Forecast period*				*Mean err.*
	+12	*+24*	*+36*	*+48*	
Control	126	200	339	569	308
CLIPER	64	173	366	669	318
Baro. var.	93	171	259	435	240
Nudging	63	116	157	233	142
4-D var.	76	108	152	182	129

It is interesting to note the US cases show that when similar data were incorporated by the six-hourly nudging and six-hourly 4-D variational schemes, the forecast accuracies were not greatly different from each other, a result found in the 3-D variational cases reported in Le Marshall et al. (1996a). In the Australian studies, however, use of continuous assimilation has allowed incorporation of additional data for these cases at non-synoptic times with quantifiable benefit. Additional benefit may be expected by further increasing data coverage at synoptic and asynoptic times, for example, by addition of water vapour winds, an option now available with GMS-5.

In summary, it would appear that one-hourly nudging is a practicable forecast approach. However, in the longer term, 4-D var. which is more flexible and mathematically sound may prevail. Initial position errors are still major contributors to forecast errors, although this problem should be ameliorated by the future availability of both Advanced Microwave Sounder Unit (AMSU) observations from the NOAA satellites and scatterometer surface-wind observations.

Overall, the results obtained indicate that the wind data base and assimilation methodology adopted here appear to 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.

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