

# Shorter contributions

## Tropical cyclone *Beti* – an example of the benefits of assimilating hourly satellite wind data

Although the accuracy of tropical cyclone track forecasts from barotropic and baroclinic numerical weather prediction models has improved over recent years, forecast track errors still remain unacceptably high, and on occasion can be very large, for example when cyclone recurvature is not accurately captured by the prediction model.

This study examines one such case (tropical cyclone *Beti*) and compares forecast tracks using conventional six-hourly assimilation, six-hourly nudging, one-hourly nudging and three or four-dimensional variational assimilation of hourly cloud-drift wind observations. It was found that hourly nudging, and three or four-dimensional variational assimilation greatly reduce the tropical cyclone track forecast errors.

Whereas previous studies have also indicated the utility of using an enhanced cloud-drift wind database (available every six hours), combined with three and four-dimensional variational assimilation techniques, this study shows that significant benefits can be gained over six-hourly data assimilation by using much higher temporal resolution data through both hourly nudging or three and four-dimensional variational assimilation. The synoptic data contained in this 24-hour assimilation period, during which the cyclone commenced recurving, has a beneficial impact on subsequent trajectory forecasts. The result is also notable in that one-hourly nudging is shown to be almost as beneficial as one-hourly four-dimensional variational assimilation, so that the hourly data can be incorporated advantageously with moderate computing power.

An accompanying paper in this issue describes the application of the enhanced cloud-drift wind data base to Australian region numerical prediction using six-hourly intermittent assimilation.

### Introduction

Since the early 1980s, enhanced cloud and water vapour drift winds have been used to improve numerical forecasting of tropical cyclone tracks (Le Marshall et al. 1985; Mills et al. 1986). The utility of these winds in tropical cyclone track forecasting has also been demonstrated, using a barotropic forecast model by Velden et al. (1991). Higher spatial density cloud-drift winds, generated as part of the TCM-90 experiment (Elsberry

1990), have been shown to improve the accuracy of numerical cyclone track forecasting in the northwest Pacific when used with a three-dimensional variational assimilation procedure (Bennett et al. 1993). These gains were significantly diminished if the variational assimilation did not include an enhanced cloud-drift wind database, but used only cloud-drift winds (SATOBS) from the Global Telecommunications System (GTS) (Le Marshall et al. 1996a).

In recent experiments, it was shown that the use of hourly Geostationary Meteorological Satellite (GMS) winds through the three-dimensional variational technique of Bennett et al. (1993) led to an improvement in the accuracy of tropical cyclone track forecasting in a case study, examining tropical cyclone *Rewa*, in the Coral Sea (Le Marshall et al. 1996a). In that case, the gains from the use of hourly winds with variational assimilation were greater than those from the use of the Bureau of Meteorology (BoM) tropical analyses (Davidson and McAvaney 1981) with six-hourly nudging. In addition, Bennett et al. (1996) have recently shown the impact of the TCM-90 high resolution cloud-drift winds in a limited four-dimensional variational assimilation experiment using a baroclinic primitive equation (PE) model.

In principle, there are two broad assimilation procedures; intermittent and continuous. Intermittent data assimilation is used in the BoM's operational global and regional forecast systems and involves a six-hourly analysis-forecast cycle. Continuous data assimilation is the alternative approach and is used here for the data assimilation forecasts. It is further subdivided into nudging and variational data assimilation. The nudging procedure forces the model towards the analysis at  $t = 0$  by the use of an empirically derived 'nudging' term on the right-hand side of the prognostic equations (Haltiner and Williams 1980). It therefore is suboptimal but very inexpensive per timestep. The variational procedure is a least squares best fit of the model state to the data, boundary conditions, initial conditions and model formulation and is formally optimal. In practice, it too is suboptimal because the various weights (error covariances) in the least squares representation are not yet fully known (Bennett et al. 1996).

In this case study, we have used hourly cloud-drift winds, generated in real time at the BoM, and the BoM's tropical analyses to contrast forecasts from a baroclinic PE model, initiated using a BoM tropical analysis (the control), six-hourly nudging, hourly nudging using hourly data and four-dimensional variational assimila-

tion of hourly data. For comparison, forecasts produced using three-dimensional variational assimilation of hourly data with a barotropic model have also been generated.

In an accompanying paper in this issue (Le Marshall et al. 1996b), we describe the application of the hourly cloud-drift wind database to Australian region numerical prediction, using six-hourly intermittent assimilation.

### Background

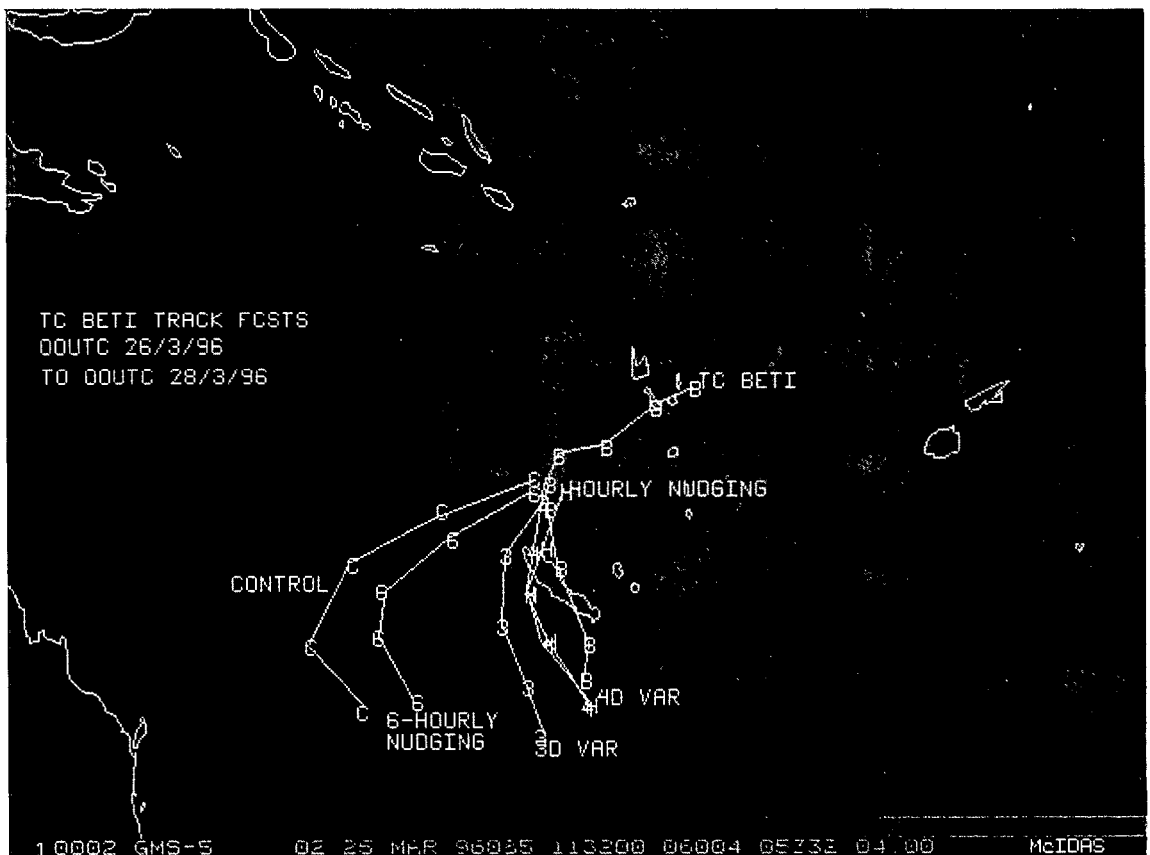
Tropical cyclone *Beti* started near 16°S, 168°E on 24 March 1996. It tracked southwest during most of 24 and 25 March, being near 18°S, 164°E on 26 March. From there, it tracked almost due south, across New Caledonia and from 28 March, headed to the southeast. The track of cyclone *Beti* can be seen in Fig. 1, displayed over the 1200 UTC GMS-5 IR-1 image for 25 March. Recurrence of the cyclone had commenced during the data assimilation period, 24 hours prior to 0000 UTC on 26

March. The cyclone was, in general, poorly forecast by operational numerical weather prediction systems which generally relied upon six-hourly intermittent assimilation and had no access to high temporal and spatial resolution wind data.

### The hourly cloud-drift winds

GMS Stretched VISSR (visible and infrared spin scan radiometer) images from GMS-5 are received hourly (and four times per day, half-hourly), at the BoM and are calibrated, navigated and stored on cyclic datasets in the Australian region McIDAS system (Le Marshall et al. 1987). Images are automatically scanned to determine suitable cloud fields for automatic tracking, using forecast winds from the operational regional assimilation and prediction system to provide a first-guess displacement. Selected targets are tracked automatically, then a lagged correlation technique is used to estimate vector displacement.

Fig. 1 Tropical cyclone *Beti* track (B) with forecast tracks from 0000 UTC on 26 March to 0000 UTC on 27 March 1996. Labelled tracks for the control (C), six-hourly nudging (6), one-hourly nudging (H) and three and four-dimensional variational assimilation runs (3D and 4D) are shown.



Winds are produced hourly, in real-time research mode, using both infrared and visible imagery (Le Marshall et al. 1996a). 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 resolution. The 24 one-hourly wind datasets provided more than 2000 wind vectors over the assimilation period for both the nudging and variational assimilation schemes.

### Assimilation and forecast systems

In this study, forecasts from the control, six-hourly nudging, one-hourly nudging, hourly three-dimensional variational assimilation and hourly four-dimensional variational assimilation have been contrasted. Data assimilation and forecasts have been performed on a 15 km resolution 180 x 180 grid, covering approximately the domain 5°S to 35°S, 145°E to 175°E. The baroclinic PE model, used in this study for all but the three-dimensional variational assimilation, had 25 levels.

The control forecast was generated using the forecast component of the four-dimensional variational assimilation system (Bennett et al. 1996), initialised using the Bureau of Meteorology Research Centre (BMRC) tropical analysis (Davidson and McAvaney 1981) valid at 2300 UTC on 25 March. Six-hourly nudging was performed using the same baroclinic PE model and the BMRC tropical analyses for the period 2300 UTC on 24 March to 2300 UTC on 25 March. The six-hourly cloud-drift winds were assimilated at 2300 UTC on 24 March and at 0500, 1100, 1700 and 2300 UTC on 25 March, before nudging commenced. The forecasts were nested in the BoM's tropical analysis and prediction scheme (TAPS; Puri et al. 1992). The three-dimensional variational assimilation was run using the BoM's tropical analyses to provide a 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 were used to find the appropriate starting point for the barotropic forecast, commencing at 2300 UTC on 25 March 1996. Details of this forecast system are in Bennett et al. (1993).

Hourly nudging was also performed using the baroclinic model described in Bennett et al. (1996), by first using six-hourly nudging from 2300 UTC on 24 March to 2300 UTC on 25 March and then analysing the hourly winds into the hourly model output fields generated during this process. The model again was started at 2300 UTC on 24 March and the evolving forecast nudged towards these hourly analyses as it progressed through the 24-hour time period. Divergence damping (Haltiner and Williams 1981) was used during this process to suppress the spurious generation of gravity waves, before producing a 48-hour forecast based on the assimilation

at 2300 UTC on 25 March. The forecasts were nested in the TAPS.

The final forecast in this experiment was from an initial state generated by four-dimensional variational assimilation (Bennett et al. 1996). It used tropical analyses from 2300 UTC on 24 March 1996 and the 0500, 1100, 1700 and 2300 UTC tropical analyses on 25 March. Boundary conditions were derived from the TAPS forecasts and 24 hours of hourly visible and infrared cloud-drift winds were incorporated asynchronously during the four-dimensional assimilation.

### Results

The forecasts generated by the control run and the six-hourly nudging, using the operational tropical analyses and six-hourly winds, both show poor agreement with the operational track data for tropical cyclone *Beti*, obtained from the Fijian Meteorological Office and the Joint Typhoon Warning Centre at Guam. Both the control and the six-hourly nudging forecasts underestimate the cyclone's recurvature in the 24-hour period to 2300 UTC on 25 March.

The three forecasts using the hourly observations, and the BMRC tropical analyses, namely the hourly nudging, the three-dimensional variational assimilation and the four-dimensional variational assimilation, show much closer agreement with the observed storm track. All tracked south during the first 24 hours and passed over the western tip of New Caledonia in the case of the hourly nudging and four-dimensional variational assimilations. After 24 hours, the models all moved the storm to the south-southeast, with the one-hourly nudging and four-dimensional variational assimilation schemes using hourly winds providing better guidance at 48 hours. Figure 1 summarises the actual and forecast tracks of the storm, while Table 1 gives the forecast position errors from 12 to 48 hours.

### Summary and conclusions

Enhanced cloud-drift wind datasets, similar to those described above, have been used over the years for predicting tropical cyclone movement in several experiments. In the northwest Pacific, using a barotropic model with three-dimensional variational data assimilation at 12-hour intervals and an enhanced cloud-drift wind dataset, the forecasts from the variational system showed small but significant improvement over those produced using the nudging technique (Bennett et al. 1993). Both of these forecast techniques were superior to forecasts based on a single tropical analysis.

In a later study (Le Marshall et al. 1996a), it was found that the gains from the variational procedure were marginal if the procedure did not include an enhanced cloud-drift wind dataset, but rather GTS SATOBs, which were already contained in the tropical analysis. In the same study, but over the Australian region, six-

**Table 1. Tropical cyclone *Beti* forecast position errors (km) at 12, 24, 36 and 48 h.**

<i>Assim. type</i>	<i>Valid date/time</i>				<i>Mean error</i>
	26/12 UTC	27/00 UTC	27/12 UTC	28/00 UTC	
<i>Control</i>	318	652	901	712	646
<i>6 h nudging</i>	298	530	686	550	516
<i>1 h 3-D var.</i>	184	230	227	186	207
<i>1 h nudging</i>	158	110	122	105	124
<i>1 h 4-D var.</i>	167	110	144	57	119

hourly nudging, and variational assimilation using hourly winds were contrasted in a study of tropical cyclone *Rewa*, in the Coral Sea. In that case, the gains from the use of hourly winds with the variational assimilation were greater than those from the use of the BMRC tropical analyses through six-hourly nudging, and both were clearly superior to the use of conventional six-hourly assimilation.

This study has extended the earlier studies to include four-dimensional variational assimilation and one-hourly nudging, using a multilevel primitive equation model (Bennett et al. 1996). Here, the control forecast, six-hourly nudging, one-hourly nudging, three-dimensional variational assimilation and four-dimensional variational assimilation have been contrasted. It was found that both one-hourly nudging and three and four-dimensional variational assimilation provide improved forecasts, using hourly observations. The results are also consistent with earlier findings that the variational assimilation is marginally better than nudging using a similar database.

It was also found that both the three and four-dimensional variational approaches and one-hourly nudging, provide a demonstrable improvement over the use of six-hourly nudging. This result is consistent with other studies and provides support for the testing of systems, in the short term, which incorporate one-hourly nudging with hourly winds as candidates for the next generation operational forecast systems.

At this point in time, hourly nudging only is tractable in operational practice, as there is a very large difference in the computing requirements for the nudging and variational assimilation techniques. The variational assimilation procedure requires approximately an order of magnitude more computing time than

nudging. Given that the time required for hourly nudging is about the same as that for the 48-hour forecast itself, at present, the variational procedure is not operationally practicable. However, considerable effort is being directed at improving the efficiency of the variational approach.

In summary, these results provide evidence of the utility of both high temporal frequency (hourly) observations and (hourly) four-dimensional assimilation of cloud-drift wind data in forecasting the position of tropical cyclones, especially recurving cyclones. This hypothesis will be further tested over the coming months when the database will be extended by the addition of water vapour vectors to depict steering level flow, and additional cases are examined.

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## Estimation and assimilation of hourly high spatial resolution wind vectors based on GMS-5 observations

To date, triplets of infrared images separated by half an hour have been used to produce winds, every six hours, for operational use in the Bureau of Meteorology. This paper describes the derivation of hourly estimates of wind over the Australian region, using observations in the visible and infrared spectral bands from the new stretched visible and infrared spin-scan radiometer (S-VISSR) instrument on the GMS-5 satellite. It discusses the accuracy of the derived wind fields and examines their application to numerical weather prediction over the Australian region. A quantification of the impact of six-hourly infrared (IR) cloud-drift wind datasets from GMS-5 is provided and, we believe, for the first time, the benefits of using hourly cloud-drift wind datasets for operational numerical weather prediction is documented. An accompanying paper in this issue presents a spe-

cific case study of the benefits of hourly winds for tropical cyclone track prediction.

### Introduction

Sequential geostationary meteorological satellite observations provide a unique opportunity to monitor atmospheric motion over the data-sparse regions of the southern hemisphere (Meteorological Satellite Centre 1989). Initial methods 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 and recent expansion of the number of channels and changes in their spectral content, there has been an increase in the observational power of GMS 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 routinely in real time for research and operational evaluation, at high spatial resolution using both visible (VIS) and infrared (IR) imagery (Le Marshall et al. 1996a). In the case of IR image-based cloud-drift winds (CDWs), the full-resolution 5 km imagery has been used, while for the VIS image-based CDWs, full-resolution 1.25 km and resampled 5 km subsatellite (IR) resolution imagery has been used. CDWs are generated hourly (and four times per day, half-hourly) from hourly (and half hourly) IR and, during daylight hours, VIS images. The generation of CDWs using differing spatial and temporal resolution imagery has been examined by several authors (Rodgers et al. 1979; Johnson and Suchman 1980; Hamada 1985; and Uchida 1991). These studies examined the generation and utility of winds as the time interval between images varied from two hours to three minutes and horizontal resolution varied from 8 km to 1 km. Generally, as times between images decreased and the spatial resolution of the imagery used for tracking and height assignment increased, the number of CDWs generated increased. The works of Johnson and Suchman (1980) and Rodgers (1979) demonstrate the utility of shorter interval images for generation of low-level winds while, for instance, Johnson and Suchman (1980) and Hamada and Mosher (personal communication) indicated that image separation of the order of fifteen minutes provides good density and quality for vectors from faster moving, upper-level cloud.

It is clear that improved pixel resolution will increase wind measurement accuracy and will allow shorter time interval imagery to be used. It is also clear that image granularity, navigation accuracy, cloud development and other factors limit wind accuracy. With these considerations in mind, and also noting recent demonstrations of the utility of hourly wind data for tropical cyclone track