2A.6

KATRINA, RITA AND WILMA: MET OFFICE MODEL FORECASTS

Julian T. Heming * and Glenn Greed
Met Office, Exeter, UK

1. INTRODUCTION

The 2005 Atlantic hurricane season broke numerous records including the most tropical storms in a season (27), the most hurricanes (15), the most Category 5 hurricanes (3) and the most US insured damage in a season (Lea & Saunders, 2006). This paper will focus on the three Category 5 hurricanes (Katrina, Rita and Wilma), all of which struck the US coast as 'major' hurricanes (at least Category 3). In the case of Hurricane Katrina in particular, the impact of landfall was immense as large parts of New Orleans were flooded and other parts of Louisiana and Mississippi suffered severe flood and wind damage (McCallum and Heming, 2006). An evaluation of the Met Office global model forecasts of the tracks of these hurricanes will be made and set against the performance of the model in the whole of the 2005 season. In addition, an assessment will be made of the experimental Met Office North American model.

2. MET OFFICE GLOBAL AND NORTH AMERICAN MODELS

The Met Office global model (WMO, 2005) is used to provide operational tropical cyclone forecasts worldwide. It produces a 6-day forecast every 12 hours (5 days used and verified operationally). During the 2005 hurricane season, the model resolution was 0.83°x 0.55°x 38 levels, although the horizontal and vertical resolutions have subsequently been increased (Met Office, 2005). The global model uses 4D-Var data assimilation which was introduced in October 2004 (Rawlins, 2004) and uses a tropical cyclone initialisation system (Heming et. al., 1995).

Prior to the start of the 2005 Atlantic hurricane season, a North American (NA) regional model was built to investigate the impact of resolution on severe weather events such as hurricanes. The NA model has a domain covering North America and the Gulf of Mexico and operates with a resolution of 0.15°x 0.15°x 38 levels (approximately 17km in the horizontal). Boundary conditions are taken from the Met Office global model and the NA model uses 3D-Var data assimilation (which was used in the global model between 1999 and 2004). The NA model also uses a tropical cyclone initialisation system and produces a 36-hour forecast every 12 hours. The model was not run continuously during the 2005 Atlantic season, but was operative during Hurricanes Katrina and Rita.

3. HURRICANE KATRINA

3.1 Global Model

3.1.1 Cyclogenesis

The first National Hurricane Center (NHC) advisory for Katrina was issued at 1800 UTC 23 August with the designation Tropical Depression Twelve. The depression had a complex genesis as it formed over the Bahamas from the remnants of the previous Tropical Depression Ten, a tropical upper tropospheric trough and another tropical wave (Knabb et. al., 2005). It became a tropical storm at 1200 UTC 24 August and a hurricane at 2100 UTC 25 August, just two hours prior to landfall over southern Florida. The track of Hurricane Katrina can be seen in Fig. 1.

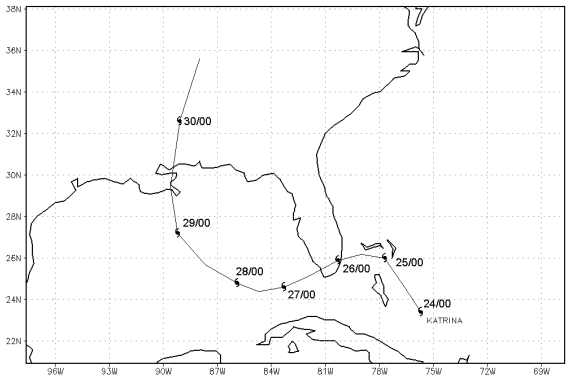

Figure 1. The track of Hurricane Katrina, 24-30 August 2005

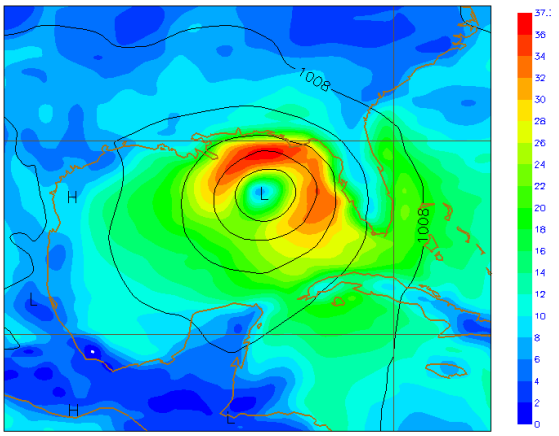

Figure 2. Met Office Global Model 144-hour forecast valid 0000 UTC 29 August 2005 (isobars and 10m wind speed shading)

The Met Office global model gave some mixed signals prior to the genesis of Katrina. Forecasts from 18 and 19 August featured a shallow wave, but did not develop it at all during the forecast. Forecasts on 20 August developed the wave during the forecast, but accelerated it into the Gulf of Mexico too quickly. Forecasts the following day (21 August) backtracked somewhat, featuring no development of the wave (0000 UTC) or development of a broad area of low pressure in the Gulf of Mexico (1200 UTC). On the 22 August the model again developed the wave modestly, but did not feature anything which could be interpreted as a hurricane by late on 25 August as actually occurred. The 0000 UTC 23 August run of the model

* Corresponding author address: Julian T. Heming, Numerical Weather Prediction, Met Office, FitzRoy Road, Exeter, Devon, UK; email: julian.heming@metoffice.gov.uk

was the first to predict the strengthening, landfall over southern Florida and further strengthening and recurvature once in the Gulf with some degree of success (Fig. 2). However, following this successful forecast, the next run of the model (1200 UTC 23 August), which was the last prior to advisory initiation, predicted far more modest strengthening and a straight-running system heading west into the western Gulf by late in the forecast.

3.1.2 Track Forecasts

Following the development of Tropical Depression Twelve at 1800 UTC on 23 August, Met Office global model forecasts showed some variation in predicted track. Figs. 3 and 4 show the 0000 UTC and 1200 UTC forecast tracks of Hurricane Katrina at 24-hourly intervals. The 0000 UTC 24 August forecast was good, although the speed of movement was a little slow. It predicted correctly the south of westward dip of Katrina just prior to its Florida landfall and showed a mature cyclone heading for the Louisiana/Mississippi area by the end of the forecast. However, the following two runs (1200 UTC 24 August and 0000 UTC 25 August) predicted a track which made landfall over Florida too far north and then recurved Katrina very sharply almost as soon as it emerged over the Gulf, so making landfall a second time on the Florida Gulf coast. The 1200 UTC 25 August run (about 9 hours prior to Florida landfall) again predicted the south of westward movement well and again predicted recurvature of a strong cyclone with landfall just east of New Orleans. However, once again the next run (0000 UTC 26 August) turned Katrina too quickly and had landfall over the Florida panhandle. Finally, the forecast from 1200 UTC 26 August gave a near perfect (within one grid length) prediction of the location and timing of landfall 72 hours later near New Orleans. Subsequent forecasts showed subtle variations, but all gave a consistent prediction of landfall of a strong hurricane over or near New Orleans on 29 August.

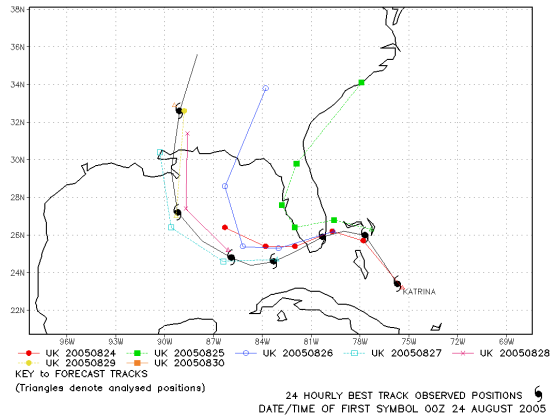

Figure 3. 0000 UTC forecast tracks from the Met Office global model of Hurricane Katrina (including tropical depression positions). All symbols plotted 24-hourly.

Other numerical models showed as much if not more variation in the forecast tracks of Katrina during its lifetime. This provided a challenge for the NHC who use a variety of dynamical and statistical models to produce their official forecast tracks. However, from 60 hours prior to the landfall of Katrina over Louisiana, all NHC forecasts gave excellent guidance. The Met Office global model forecasts were all very accurate from 72 hours before Gulf coast landfall and some earlier forecasts were also good. The NHC found the Met Office global model to provide the best guidance of all numerical models for Hurricane Katrina up to 72 hours ahead and had lower errors than NHC forecasts at lead times of up to 96 hours (Knabb et. al., 2005).

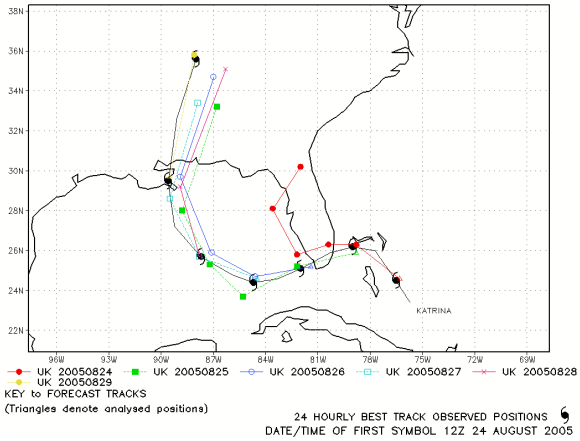

Figure 4. 1200 UTC forecast tracks from the Met Office global model of Hurricane Katrina (including tropical depression positions). All symbols plotted 24-hourly.

3.2 North American Model

Table 1 shows the mean track forecast errors for the global and NA models for 10 consecutive forecasts. These indicate that there was little overall difference in the track errors for the two models. Figs. 5 and 6 show the 0000 UTC and 1200 UTC forecast tracks of Hurricane Katrina at 12-hourly intervals for the two models. These indicate that the global model tended to turn Katrina to the right a little more than the NA model. In some cases (e.g. 0000 UTC 26 August) this produced a better track in the NA model, but in others (e.g. 1200 UTC 27 August), the NA model track was worse.

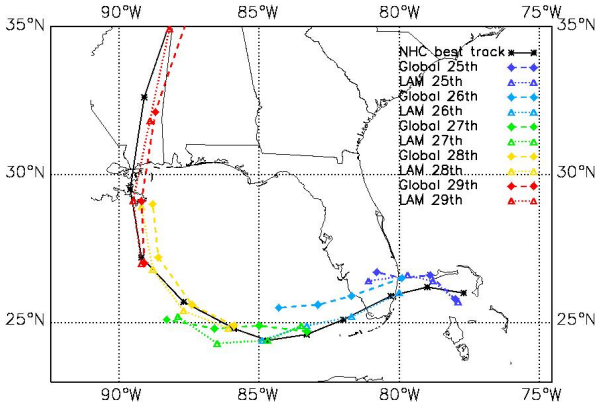

Figure 5. 0000 UTC forecast tracks from the Met Office global and NA models of Hurricane Katrina. All symbols plotted 12-hourly.

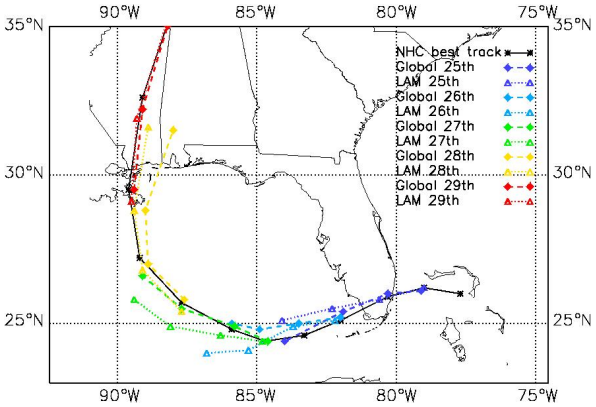

Figure 6. 1200 UTC forecast tracks from the Met Office global and NA models of Hurricane Katrina. All symbols plotted 12-hourly.

	0-h	12-h	24-h	36-h
Global model	23	45	66	95
NA model	26	40	71	98

Table 1. Mean track forecast errors (in kilometres) for Hurricane Katrina; global and NA models (homogeneous sample)

Although the greater resolution of the NA model produced little overall positive impact on the track forecast, it did produce improvements in both intensity and precipitation.

Figs. 7 and 8 show the 12-hour forecast of 10m wind speed from 0000 UTC 29 August for the global and NA models, verifying at the time of landfall. The global model peak wind and central pressure was 979 hPa and 46 knots. The NA model had 958 hPa and 62 knots. This compared to observed values of 923 hPa and 110 knots. This equates to the NA model forecast being 37% and 25% closer to the observed values of central pressure and wind speed respectively. Of particular note is the NA model's much better eye structure as seen in the wind field. The peak winds are much closer to the eye than the global model. Also, the NA model shows the finer detail in the strong winds wrapping round the northern flank of the hurricane into the Breton Sound, which would have contributed to the massive storm surge.

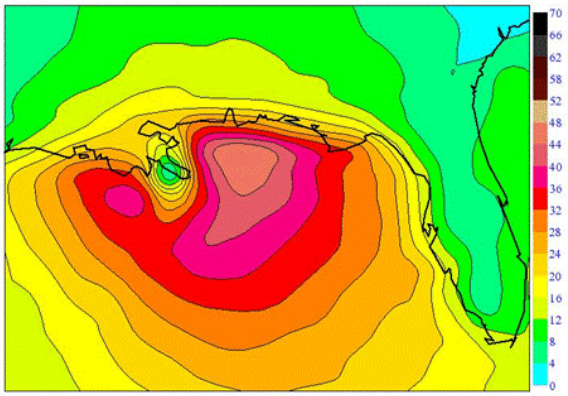

Figure 7. 0000 UTC 29 August 12-hour forecast of 10m wind speed (knots), global model.

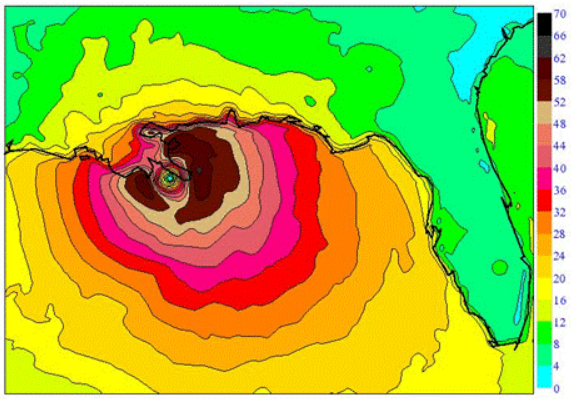

Figure 8. 0000 UTC 29 August 12-hour forecast of 10m wind speed (knots), NA model.

Figs. 9 and 10 show the 3-hour precipitation totals from the models starting at 1200 UTC 29 August. The accumulation exceeds 128mm in the NA model which is greater than any observations recorded at the time, but when compared with radar data (Fig. 11), the NA model clearly gave a much better representation of rain bands around the hurricane at landfall than does the global model.

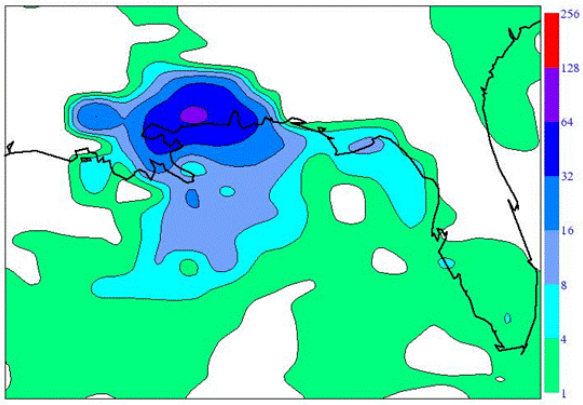

Figure 9. 1200 UTC 29 August 3-hour rainfall accumulation (millimetres), global model.

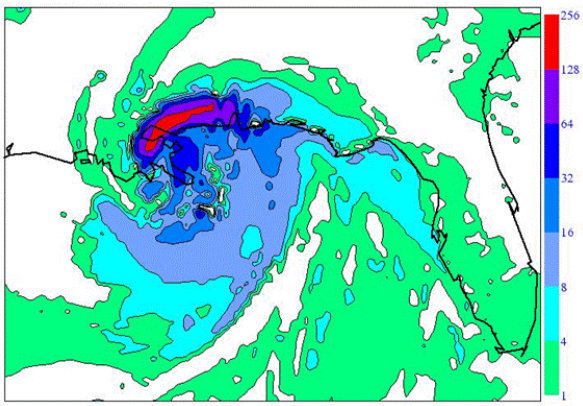

Figure 10. 1200 UTC 29 August 3-hour rainfall accumulation (millimetres), NA model.

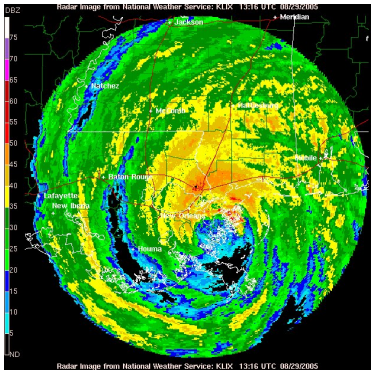

Figure 11. 1300 UTC 29 August New Orleans rainfall radar.

4. HURRICANE RITA

4.1 Global Model Forecasts

4.1.1 Cyclogenesis

The first NHC advisory for Tropical Depression Eighteen was issued at 0000 UTC 18 September when the system was located just north of the Dominican Republic. The depression was upgraded to Tropical Storm Rita at 1800 UTC 18 September and became a hurricane at 1200 UTC 20 September. The track of Hurricane Rita can be seen in Fig. 12.

Met Office global model forecasts did not predict the formation of Tropical Depression Eighteen with a great deal of success. Forecasts from 13 and 14 September all featured a wave, but did not strengthen it. However, the model was quite vigorous in developing the next wave further east which eventually became Hurricane Philippe. On 15 September, the model showed some strengthening of Rita upon entering the Gulf of Mexico, but still favoured Philippe for the greater deepening. Forecasts on 16 September were very poor for Rita, showing virtually no strengthening to the wave as it travelled westwards. By 17 September, the model was showing some strengthening again, but raced the developing storm on a fast due westwards track across the Gulf of Mexico, making landfall over Mexico.

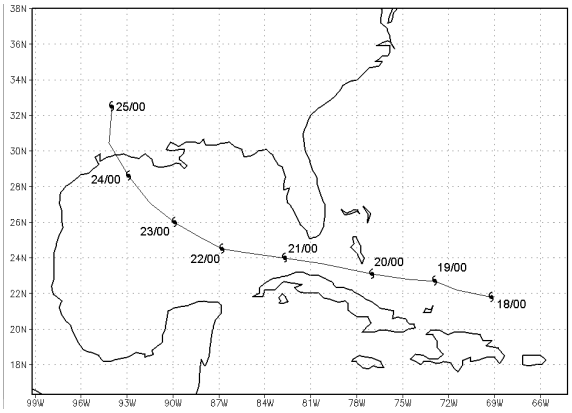

Figure 12. The track of Hurricane Rita, 18-25 September 2005.

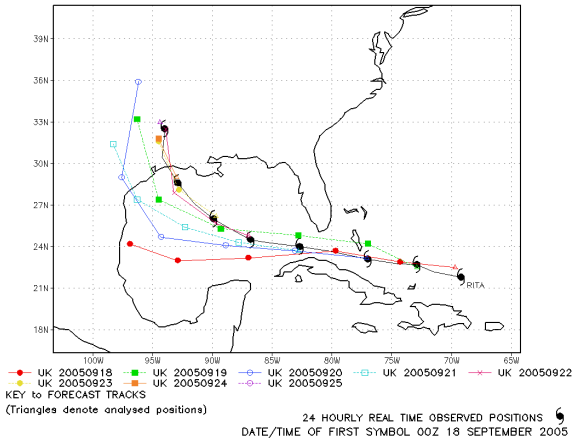

Figure 13. 0000 UTC forecast tracks from the Met Office global model of Hurricane Rita (including tropical depression positions).

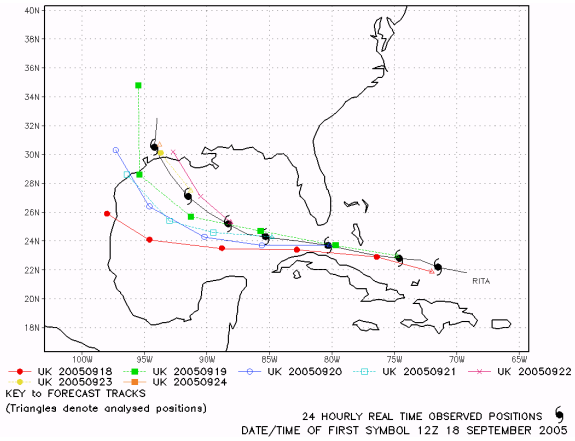

Figure 14. 1200 UTC forecast tracks from the Met Office global model of Hurricane Rita (including tropical depression positions).

4.1.2 Track Forecasts

Figs. 13 and 14 show the 0000 UTC and 1200 UTC forecast tracks of Hurricane Rita at 24-hourly intervals. At the time that Tropical Depression Eighteen formed (0000 UTC 18 September) the model predicted good strengthening of the system, but still had a track which was too straight and too fast. The following run of the model was similar. The first significant change in forecast track came at 0000 UTC 19 September. There was a marked northwards turn in the predicted track and whilst the speed of movement later in the forecast was still too fast, the location of landfall was shifted a long way up the coast to near Galveston. Again, this was supported by the following run of the global model. However, on 20 and 21 September there was a shift back to a more southerly track with landfall locations predicted to be near or just to the north of Corpus Christi. These four successive forecasts giving the same story may have built confidence in this as the likely correct solution, but this all changed in the 0000 UTC 22 September run which slowed the pace of the storm and turned it more sharply making landfall near Port Arthur on the Texas-Louisiana border. This forecast, which was produced 56 hours before the actual landfall at around 0800

UTC 24 September, turned out to be highly accurate in terms of landfall location and timing. Whilst the next forecast shifted the landfall a little too far to the east, the remaining model predictions gave excellent guidance of the track of Hurricane Rita and supported the idea that Houston and Galveston would be spared the worst effects of the hurricane.

A detailed breakdown of the performance of forecast guidance available to the NHC was not available at the time of writing. Examination of real time track charts indicates that most numerical guidance made the shift in landfall from the Houston-Galveston area to the Texas-Louisiana border in the 12 hours or so following 0000 UTC 22 September. On this basis it appears that the Met Office global model was one of the first to make this shift to a correct landfall location some 56 hours before landfall occurred.

4.2 North American Model Forecasts

Table 2 shows the mean track forecast errors for the global and NA models from 7 consecutive forecasts. These indicate that there was again little overall difference in the tracks of the two models. Figs. 15 and 16 show the 0000 UTC and 1200 UTC forecast tracks of Hurricane Rita at 12-hourly intervals for the two models. These indicate that the results were again mixed. The NA model gave an improved forecast on the poor 1200 UTC 21 September global forecast track, but was poorer than the global model in the forecast issued 12 hours later.

	0-h	12-h	24-h	36-h
Global model	26	59	111	154
NA model	25	53	117	158

Table 2. Mean track forecast errors (kilometres) for Hurricane Rita; global and NA models (homogeneous sample).

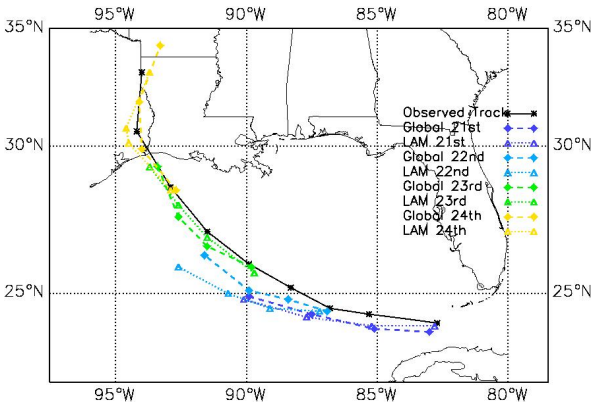

Figure 15. 0000 UTC forecast tracks from the Met Office global and NA models of Hurricane Rita. All symbols plotted 12-hourly.

The NA model again made improvements over the global model in terms of intensity and precipitation forecasts. The 12-hour forecast of 10m wind speeds from 1200 UTC 23 September for the global and NA models, verifying a few hours before the time of landfall, were examined. The global model peak wind and central pressure was 985 hPa and 41 knots. The NA model had 974 hPa and 51 knots. This compared to observed values of 931 hPa and 105 knots. This equates to the NA model forecast being 20% and 16% closer to the observed values of central pressure and wind speed. The NA model also showed improved detail in the structure of the eye and rain bands of the hurricane (not shown).

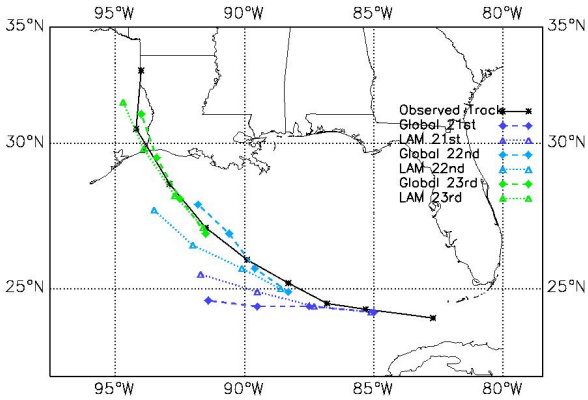

Figure 16. 1200 UTC forecast tracks from the Met Office global and NA models of Hurricane Rita. All symbols plotted 12-hourly.

5. HURRICANE WILMA

5.1 Global Model Forecasts

5.1.1 Cyclogenesis

The first NHC advisory for Tropical Depression Twenty-four was issued at 1800 UTC 15 October. The genesis of Wilma was complex as it evolved from a broad area of low pressure over the Caribbean Sea. Part of this low pressure moved north-eastwards and merged with a non-tropical low which raced northwards. The western part of the low pressure area consolidated into Tropical Depression Twenty-four (Pasch et. al., 2006). The depression was upgraded to Tropical Storm Wilma at 0600 UTC 17 October and to a hurricane at 1200 UTC 18 October. The track of Hurricane Wilma can be seen in Fig. 17.

Met Office global model forecasts prior to the formation of the tropical depression were generally very good. As early as 0000 UTC 11 October the model predicted the aforementioned splitting of the broad low, the rapid northward movement of the non-tropical low and the formation of a tropical depression in the Caribbean Sea. The 1200 UTC 12 October run was the first to predict the development of an intensifying system in the western Caribbean, although at that stage the system was moved westwards too quickly (see Fig.18). Forecasts on 13 and 14 October all continued to develop a strong system, but tended to track it too far westwards and at too fast a pace. However, both the 0000 UTC and 1200 UTC 15 October forecasts (the last before the depression formed) gave good prediction of the north-westward movement towards the Yucatan Peninsula and Yucatan Channel which actually occurred.

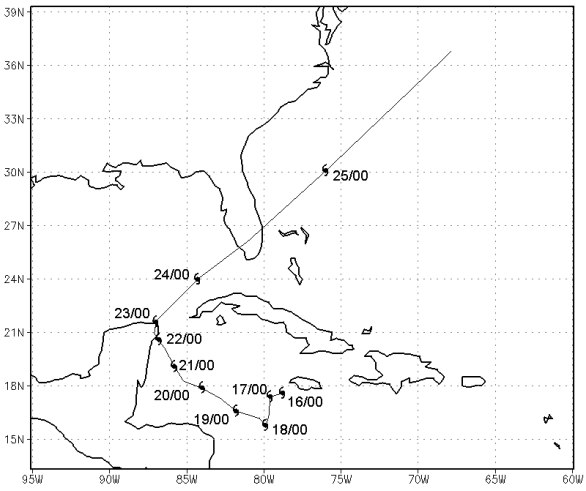

Figure 17. The track of Hurricane Wilma, 16-25 October 2005.

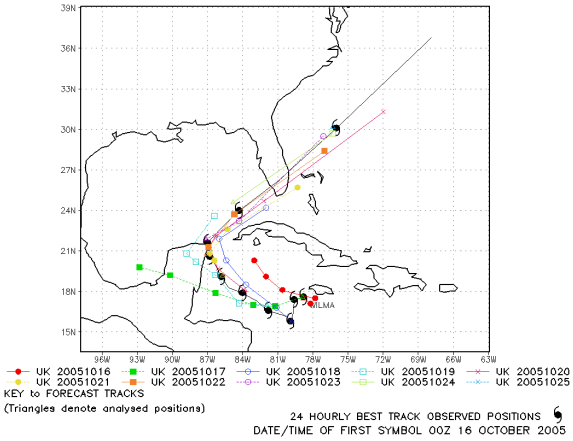

Figure 19. 0000 UTC forecast tracks from the Met Office global model of Hurricane Wilma (including tropical depression positions).

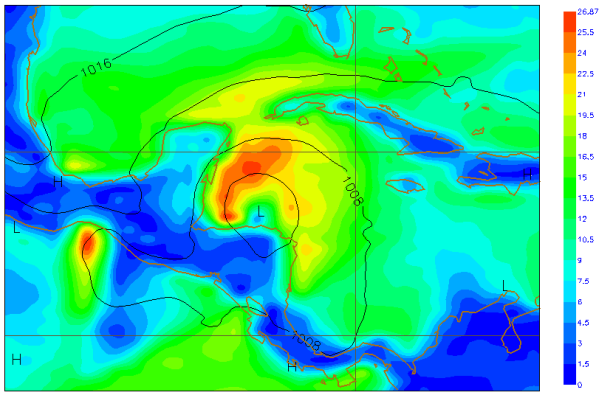

Figure 18. Met Office Global Model 144-hour forecast valid 1200 UTC 18 October 2005 (isobars and 10m wind speed shading).

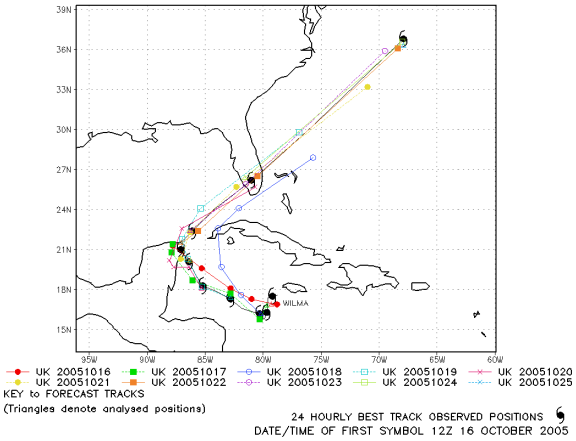

Figure 20. 1200 UTC forecast tracks from the Met Office global model of Hurricane Wilma (including tropical depression positions).

5.1.2 Track Forecasts

Figs. 19 and 20 show the 0000 UTC and 1200 UTC forecast tracks of Hurricane Wilma at 24-hourly intervals. Following the formation of Tropical Depression Twenty-four at 1800 UTC 15 October, the Met Office global model track forecast skill was variable for the next three days. The 0000 UTC 16 October forecast did not track the system westwards fast enough, whilst the 0000 UTC 17 October run predicted a westward track towards Belize. The 1200 UTC 16 October and 1200 UTC 17 October forecasts, however, predicted the north-westward turn and deceleration near the Yucatan Peninsula well. Forecasts on 18 October, particularly at 1200 UTC, were very poor. The latter turned Wilma across western Cuba and recurved it south of Florida at a rapid rate. From 0000 UTC 19 October onwards (incidentally the time of the peak and record intensity) all forecasts gave a very good prediction of the north-westward movement and stalling over the Yucatan peninsula as well as the recurvature and landfall over southern Florida. Just a couple of the forecasts (1200 UTC 20 October and 0000 UTC 21 October) were a little slow in taking Wilma across southern Florida.

Other numerical models showed some wild variations in the timing of the recurvature of Hurricane Wilma. Some predicted recurvature of the hurricane short of the Yucatan Peninsula and accelerated it rapidly across southern Florida, whilst others lingered the hurricane in the region of the Yucatan Channel for many days. There were also significant variations from run to run for the same model. For example, the 1200 UTC 19 October run of the GFDL model had a 120-hour forecast position over Maine in the far north-east of the USA. Just six hours later the next run of this model had a 120-hour forecast position just south of the western tip of Cuba! This kind of variation provided a considerable forecasting challenge for the NHC. Whilst there were some variations in early forecasts from the Met Office global model it gave some very consistent guidance from 19 October onwards, some 72 hours before landfall over the Yucatan Peninsula and more than 120 hours before landfall over southern Florida. Overall, the Met Office global model gave the best dynamical guidance for Hurricane Wilma, had track errors lower than the NHC at 36 hours and beyond and was only bettered by the Florida State

University superensemble (Krishnamurti et. al., 1999) at lead times up to 48 hours (Pasch et. al., 2006).

6. GLOBAL MODEL PERFORMANCE: ATLANTIC 2005

Table 3 shows tropical cyclone track forecast errors for Katrina, Rita and Wilma along with some mean errors, for the Met Office global model and the NHC official forecasts. These statistics are shown graphically in Figs. 21 and 22. The results firstly indicate that Met Office global model forecast errors for the three hurricanes considered in this paper were lower than the errors for the season as a whole up to 72 hours. At 96 hours only Wilma's errors were lower than the season's average and at 120 hours all three hurricanes had errors larger than the season's average. The errors for the season as a whole were lower than the average for the previous five seasons at all lead times.

Fig. 22 shows that the combined track forecast errors for Katrina, Rita and Wilma were lower in the Met Office global model than in the NHC official forecasts at all lead times. Over the whole season Met Office global model errors were lower than the NHC at 48, 96 and 120 hours, but not 24 and 72 hours. Note that these figures are for homogeneous samples of forecasts, so do not include 0600 UTC and 1800 UTC NHC forecasts. It should also be pointed out that the Met Office global model forecasts which are verified here are produced after the NHC guidance for the same time is issued and so do not directly contribute to the NHC guidance at this time. The NHC has to interpolate guidance from previous runs of models such as the Met Office global model for use in its forecasting process.

	24-h	48-h	72-h	96-h	120-h
Katrina – Met Office	51	131	245	488	896
Rita – Met Office	81	157	288	415	511
Wilma – Met Office	70	111	174	354	597
Atlantic 2000-4 – Met Office	133	231	319	412	577
Atlantic 2005 – Met Office*	111	187	294	399	465
Atlantic 2005 – NHC*	102	192	279	422	507
K, R and W combined – Met Office#	64	122	224	412	678
K, R and W combined – NHC#	70	157	282	456	683

Table 3. Track forecast errors (kilometres), tropical storms and hurricanes. * # Homogeneous samples.

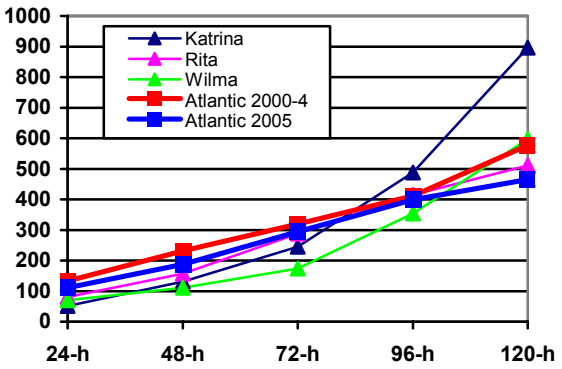

Figure 21. Track forecast errors (kilometres) – Met Office global model.

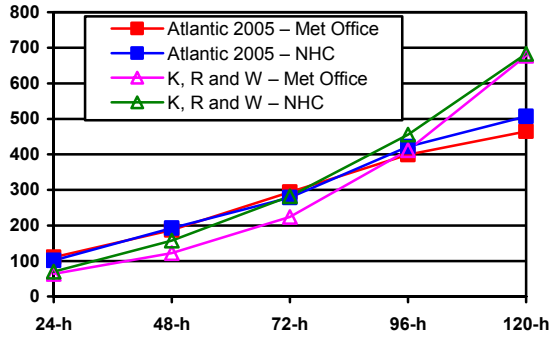

Figure 22. Track forecast errors (kilometres) – Met Office global model and NHC (homogeneous samples).

7. CONCLUSIONS

An evaluation of Met Office global model forecasts for the three most noteworthy hurricanes of the 2005 Atlantic season has shown that the forecast guidance was excellent for Hurricane Katrina up to 72 hours before landfall on the Gulf coast, was excellent for Hurricane Rita up to 56 hours before landfall and for Hurricane Wilma was excellent up to 72 hours before landfall over the Yucatan Peninsula and 120 hours before landfall over Florida. At longer lead times the model tended to recurve Hurricane Katrina too soon, keep Hurricane Rita on too straight a track and show variations in the timing of recurvature and forward speed of Hurricane Wilma. However, these errors were not peculiar to this model alone. On the whole, the model was one of the first to arrive at the correct forecast track in all of these cases.

The Met Office global model performed better in these three hurricanes than for the season as a whole at lead times up to 72 hours, but performed worse at longer lead times due to errors in the prediction of recurvature. Errors for the season as a whole were lower than for the previous five seasons' average and is part of a continuing long term downward trend in track forecast errors. Along with the GFDL model, the Met Office global model was one of the best performers during the Atlantic hurricane season of 2005 (Franklin, personal communication).

An experimental 17km resolution North American model did not produce better forecasts of the tracks of Hurricanes Katrina and Rita than those from the global model. It should be noted that despite a higher resolution than the global model, it uses an inferior data assimilation system (3D-Var). However, the greater resolution has contributed to a better representation of peak wind speed, central pressure and eye and rain band structure in these hurricanes.

8. REFERENCES

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