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TROPICAL CYCLONE INITIALISATION IN THE MET OFFICE GLOBAL MODEL: IS IT STILL NECESSARY AND CAN IT BE IMPROVED?

Julian T. Heming *
Met Office, Exeter, UK

1. HISTORICAL BACKGROUND

The performance of the Met Office global model in the prediction of tropical cyclone tracks was first evaluated in 1988. At that time the representation of most tropical cyclones in the model was fairly poor due to the low model resolution (about 150 km in the horizontal at mid-latitudes) and the sparsity of data over the tropical oceans. Hence, a simple scheme was introduced to help initialise tropical cyclones in the global model. The system was used at the discretion of the forecaster and was based on information available from tropical cyclone advisory messages. The forecaster entered a value of mean sea-level pressure and wind speed at 850 hPa. The system then inserted these values at four points around the tropical cyclone at radius 2.5 degrees. At 850 hPa the system produced wind directions backed by 20 degrees from the tangent. It also inserted tangential and symmetric wind values at 700 hPa (5 knots less than at 850 hPa) and 500 hPa (10 knots less than at 850 hPa). These 'bogus' observations were then assimilated into the model alongside genuine observations. Despite the crude nature of this system it was found to reduce forecast track errors by up to 30% at short lead times (up to 48 hours), but had little impact at longer lead times. It also helped retain tropical cyclone circulations longer into the forecast (Heming, 1993).

Despite the fact that the simple tropical cyclone initialisation scheme improved forecast tracks, it was perceived as having a number of weaknesses: it assumed a symmetric wind structure, it was limited in its horizontal extent and its usage was dependent on whether the forecaster had time to attend to tropical cyclone initialisation prior to the data cut-off of the model. It was also found during the course of forecast verification that the model had a persistent bias towards excessive recurvature of tropical cyclones.

A new initialisation scheme was developed which dealt with each of these issues and was implemented into the global model in late 1994 (Heming et al., 1995). At this time, the global model had a horizontal resolution of approximately 90 km at mid-latitudes. In trials the new scheme was found to reduce tropical cyclone track forecast errors by 30% on average and, importantly, by up to 46% at 120 hours lead time when trialled against the old initialisation scheme. This was as a result of eliminating the poleward bias in forecast tracks. Once in operations, the new scheme continued the marked improvement first seen in trials. In 1995 the Met Office global model produced better track forecast guidance than any model available to the National Hurricane Center for the active Atlantic hurricane season of that year (Gross, 1996, Heming and Radford, 1998).

The only change made to the initialisation scheme since its introduction in 1994 was the addition of another ring of bogus data near the centre of each tropical cyclone. i.e. the 2 degree radius ring containing four points in the original configuration was replaced by two rings of radius 1.25 degrees and 2.5 degrees each containing four points (Heming, 1998). This was introduced in 1998, shortly after the global model horizontal resolution was increased to approximately 60 km at mid-latitudes. The change resulted in a better representation of tropical cyclone intensity in the model.

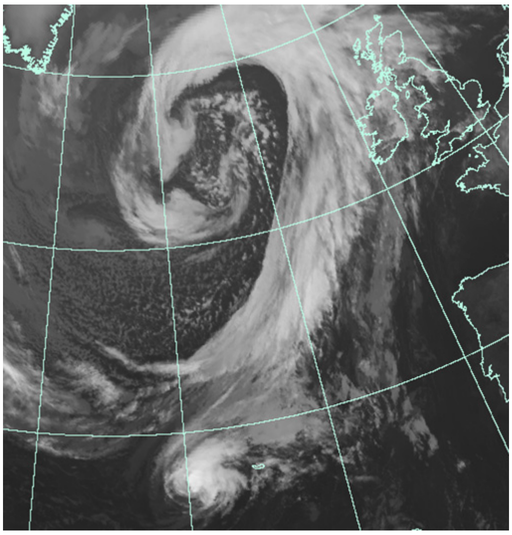

Figure 1. Infrared satellite image for 0000 UTC 20 September 2006.

2. BACKGROUND TO EXPERIMENTS

2.1 Modifications to Initialisation Scheme

In September 2006 Hurricane Gordon developed in the North Atlantic Ocean. It underwent recurvature in mid-Atlantic and tracked eastwards at subtropical latitudes for several days before undergoing extra-tropical transition and accelerating north-eastwards, briefly bringing stormy conditions to western parts of the UK. During the latter stages of Gordon's 'tropical' life, some forecasts from the Met Office global model were poor in terms of the depth of the storm and its speed of movement as it underwent extra-tropical transition. Investigation showed that the use of the tropical cyclone initialisation scheme in these cases made the forecast worse. At this time, Gordon was a small hurricane embedded at the base of a trough associated with a larger mid-latitude cyclone to the north (see Figure 1). Whilst the model's analyses correctly represented Gordon as a distinct feature, examination of the model's wind fields showed that the

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

circulation was too broad for a small compact hurricane and impinged on the westerly flow which was present just to the north of the hurricane (Heming, 2006).

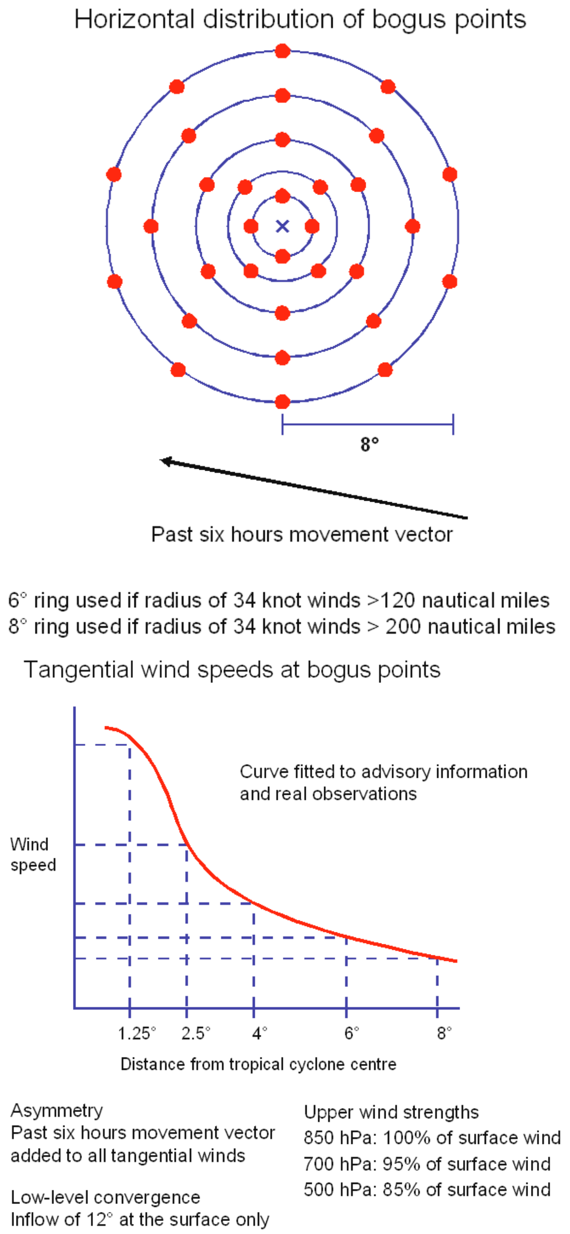

Figure 2. Revised formulation of the tropical cyclone initialisation scheme

This case highlighted a deficiency in the formulation of the tropical cyclone initialisation scheme. It always produced bogus observations on rings of radius 1.25, 2.5 and 4 degrees of latitude. A ring of 6 degrees was added for tropical cyclones of strength 35 knots or more and a ring of 8 degrees if the strength was 45 knots or more. Hence, the radial spread of the bogus data was dependent on the storm's intensity rather than its size. A new formulation was derived whereby the use of 6 and 8 degree winds was dependent on the radius of 34 knot winds rather than the maximum sustained wind. After some initial trials with different values it was decided that the 6 degree ring would be added if the radius of 34 knot winds was 120 nautical miles or more and the 8 degree ring added if the radius of 34 knot winds was 200 nautical miles or more. Although radius of 34 knot winds may not be the best measure of storm size, it is the most readily available measure contained in advisories used in real time by the initialisation scheme. The revised formulation is shown in Figure 2.

2.2 Value of Initialisation Scheme

Tropical cyclone track forecast errors in the Met Office global model have continued to show a modest downward trend in the years since the initialisation scheme was first introduced. For example, see the trend in the 5-year running mean of northern hemisphere track forecast errors in Figure 3. However, there has been a considerable increase in satellite data available to numerical models during this period, which provides a large amount of data in the previously data sparse tropical oceans. This raises the question of whether usage of the initialisation scheme is still necessary to produce a good analysis and forecast of tropical cyclones.

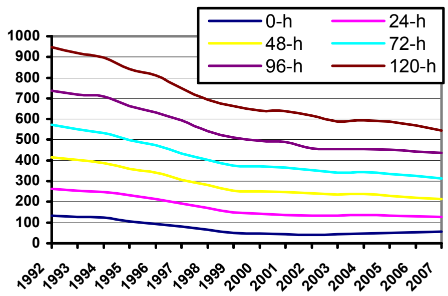

Figure 3. 5-year running mean of Met Office global model tropical cyclone track forecasting errors (kilometres) for the northern hemisphere

Having decided to test a new configuration of the initialisation scheme, the opportunity was taken to firstly establish the value of the initialisation scheme as a whole by running an experiment with it switched off. Such an experiment had not been undertaken for more than a decade.

Results of a trial of the new configuration of the initialisation scheme against model runs with the scheme switched off are presented in section 3. This is followed by results of the trial of the modified initialisation scheme against the operational scheme in section 4.

3. TRIAL WITHOUT TROPICAL CYCLONE INITIALISATION

3.1 Configuration

The Met Office global model was rerun with a continuous assimilation cycle from 20 August to 20 September 2006. During this period there were 14 tropical cyclones of tropical storm strength or greater in the North Pacific and North Atlantic regions. A run was made with the new configuration of the tropical cyclone bogus scheme (Trial) and a run was made with no tropical cyclone initialisation (NoTCI).

3.2 Detection Percentage

Tropical cyclones are tracked in the Met Office global model using 850 hPa relative vorticity (Heming, 1994). This method uses an empirically derived threshold value of relative vorticity to define whether a tropical cyclone circulation can still be tracked in the model forecast or should be considered as dissipated. During the trial period it was found that a great many more forecasts fell below this threshold in the NoTCI run than the Trial. This was due to much poorer initialisation of many tropical cyclones and subsequent premature dissipation in the NoTCI run. Figure 4 shows the detection percentage for all forecasts from the two runs. Detection percentage is defined as the percentage of tropical cyclones which were successfully tracked in the model forecast when an observed position (of tropical storm strength or greater) was available for verification. This indicates that by 120 hours into the forecast only 75% of tropical cyclones which should have been tracked by the model could actually be identified in the NoTCI forecasts. This compares with a value of 96% for the Trial run. In 2% of cases a tropical cyclone could not even be identified in the NoTCI analysis.

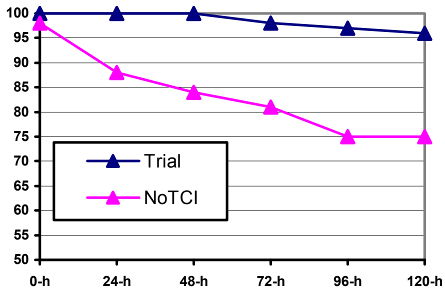

Figure 4. Detection percentage for Trial and NoTCI runs

The failure to detect tropical cyclones in the forecast in the NoTCI runs was particularly prevalent in the Pacific Ocean. For example, Typhoon Shanshan, which attained peak wind speeds of 120 knots, was barely analysed for the first few days of its life in the NoTCI runs. Only when it became a full blown typhoon did these runs start to produce an identifiable feature. Figures 5 and 6 show the analysis and 120-hour forecasts for Typhoon Shanshan from data time 1200 UTC 11 September 2006. The poor representation of the typhoon in the NoTCI run is apparent when compared to Figure 7, the verifying analysis for the 120-hour forecast.

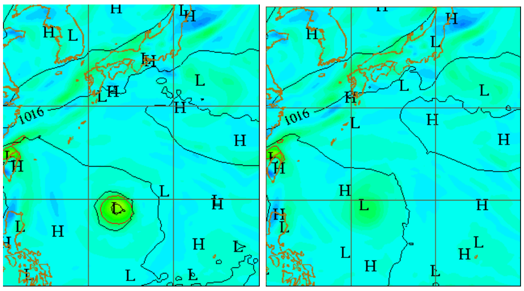

Figure 5. MSLP and 850 hPa relative vorticity shading analysis for Typhoon Shanshan valid at 1200 UTC 11 September 2006: Trial (left) NoTCI (right)

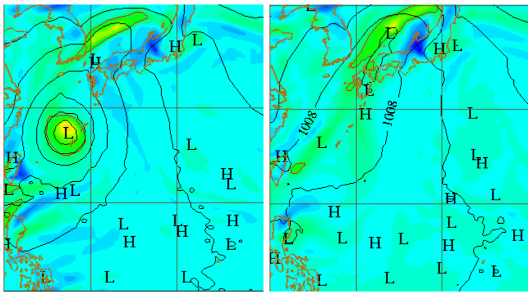

Figure 6. MSLP and 850 hPa relative vorticity shading 120-hour forecast for Typhoon Shanshan valid at 1200 UTC 16 September 2006: Trial (left) NoTCI (right)

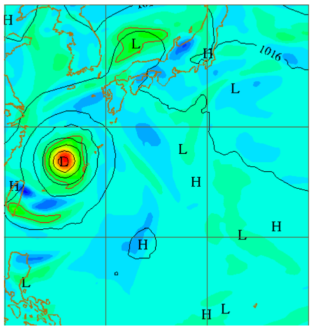

Figure 7. MSLP and 850 hPa relative vorticity shading (Trial) analysis for Typhoon Shanshan valid at 1200 UTC 16 September 2006

Failure to analyse and forecast tropical cyclones adequately in the NoTCI run was not restricted to Pacific cases. Early in the life of Hurricane Ernesto in the Caribbean and Gulf of Mexico, the NoTCI run barely analysed and forecast a discernable feature. Figure 8 shows the 96-hour forecast from data time 1200 UTC 26 August 2006. Figure 9 is the verifying analysis. Whilst the Trial forecast position of Ernesto was poor, it at least showed a marked circulation, whereas the NoTCI run showed a weak wave with an even poorer forecast position.

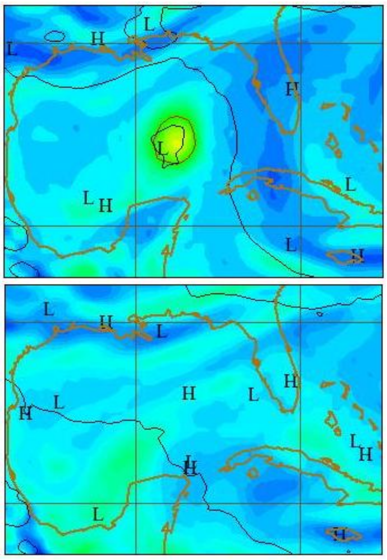

Figure 8. MSLP and 850 hPa relative vorticity shading 96-hour forecast for Hurricane Ernesto valid at 1200 UTC 30 August 2006: Trial (top) NoTCI (bottom)

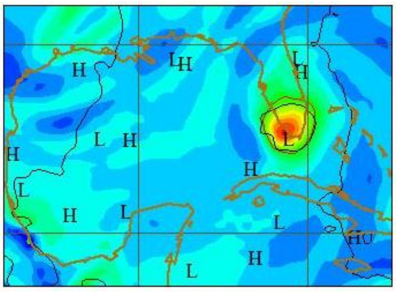

Figure 9. MSLP and 850 hPa relative vorticity shading (Trial) analysis for Hurricane Ernesto 1200 UTC 30 August 2006

As might be expected given the detection percentage results, the NoTCI run persistently featured weaker tropical cyclones in its analyses and forecasts, even in the forecasts which contained tropical cyclone circulations which could be successfully tracked. Figure 10 shows the mean intensities of all forecasts as measured by 850 hPa relative vorticity for the trial period for cases only where a tropical cyclone was identified in both the Trial and NoTCI runs. This indicates that for forecasts only (24-hour to 120-hour) the mean intensity was 20.6% higher in the Trial than for NoTCI.

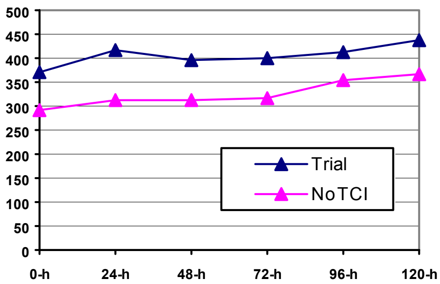

Figure 10. Mean tropical cyclone intensity (850 hPa relative vorticity x10^6 s^{-1}) for Trial and NoTCI runs

3.3 Track and Intensity Forecast Verification

Table 1 contains the following verification measures:

- Track forecast errors
- Track skill score (percentage improvement of model forecast over equivalent CLIPER forecast)
- Intensity tendency skill score (percentage improvement of model forecast of the intensity tendency over chance).

These figures only include cases where a tropical cyclone was identified in both the Trial and NoTCI runs.

	0h	24h	48h	72h	96h	120h
Number of cases	176	135	112	90	68	54
Trial track error (km)	**45**	**99**	**183**	**264**	**337**	**448**
NoTCI track error (km)	100	129	192	289	361	514
Trial track skill score (%)		**39**	**54**	**58**		
NoTCI track skill score (%)		21	52	54		
Trial intensity tendency skill score (%)		**44**	**49**	**17**	-4	**21**
NoTCI intensity tendency skill score (%)		20	36	15	**1**	2

Table 1. Mean track forecast errors (kilometres), track and intensity tendency skill scores (%) for the whole trial (homogeneous sample). **Bold** indicates the better score.

These figures indicate that for the trial period as a whole, tropical cyclone initialisation had a positive impact on forecasts by reducing track forecast error (by 12.2%) and increasing track forecast skill (by 8.9%) averaged over all forecasts. Intensity tendency skill scores were better in the Trial run by an average of 12.1%, although the value for 96-hour NoTCI forecasts was slightly better than the Trial.

3.4 Regional Breakdown

The results shown in 3.3 above indicate an overwhelmingly positive result for the Trial configuration over NoTCI for the whole trial period. During this trial period there were five tropical cyclones in the North-West Pacific, seven in the North-East Pacific and five in the North Atlantic. When broken down into these three basins, the figures indicate a regional split. The Trial was much better than NoTCI in both Pacific regions at all forecast lead times, but in the Atlantic the results were more variable – NoTCI was actually better than the Trial at 24-, 48- and 72-hour lead times.

This raises the question of whether the negative results for short lead times seen in the North Atlantic are systematic or whether they are case specific or can be attributed to certain situations - e.g. tropical cyclones above a certain strength, in a certain locality etc. To help answer this question an evaluation was made of all forecasts for the five TCs which were in the North Atlantic region during the trial period.

3.4.1 Tropical Storm Debby

This was a short-lived storm and only a few 24- and 48-hour forecasts verified. However, the Trial track errors were lower than NoTCI in all cases. Hence, tropical cyclone initialisation had a positive impact in this case.

3.4.2 Hurricane Ernesto

Early in Ernesto's life, the NoTCI run was barely able to analyse the storm and degenerated it into a shallow wave in the forecast. The bogus data used in the Trial run enabled the model to analyse and forecast the circulation of Ernesto well, although track errors were large (see Figures 8 and 9). For the runs where forecast circulations were present in both runs, the Trial track errors were consistently lower than NoTCI. These results indicate that tropical cyclone initialisation had a positive impact in this case.

3.4.3 Hurricane Florence

For this hurricane the Trial track errors were larger than NoTCI at 48, 72 and 96 hours. From examining individual runs, there were in fact some where the Trial was better and some where NoTCI was better. However, it is notable that there was a block of three consecutive forecasts where NoTCI was consistently much better than the Trial by predicting a much slower recurvature and northward acceleration. These were 0000 UTC and 1200 UTC 8 September and 0000 UTC 9 September 2006. Figure 11 shows the Trial and NoTCI forecast tracks to 72 hours plotted against the best track observed track from the last of these three dates.

An examination of the National Hurricane Center advisories during the period when NoTCI forecasts were better than the Trial indicates that the analysts were having trouble locating the storm's true centre:

"Satellite images indicate that Florence remains poorly organized with an elongated shapeless cloud pattern which is not very typical of a tropical cyclone."

"As depicted in infrared satellite imagery...Florence has a very large circulation but continues to struggle in organization...the low-level center is difficult to find...but there must be one given the large and well defined circulation of the storm."

"The cloud pattern became a little more symmetric a couple of hours ago but it has deteriorated a little bit since."

"The initial motion is 305/13...though this is somewhat uncertain given the difficulty in determining the exact center with infrared imagery."

However, just prior to the 0600 UTC 9 September advisory a reconnaissance aircraft reached the vicinity of the storm and found that earlier centre fixes had been too far north (later confirmed in post-season reanalysis):

"An Air Force reserve hurricane hunter aircraft reached the center of Florence about 04Z...with a second fix about 0630Z....the aircraft found the center south of the previous forecast track...and a review of earlier satellite data suggests that Florence has been moving west-northwestward for the past 12 hr or so."

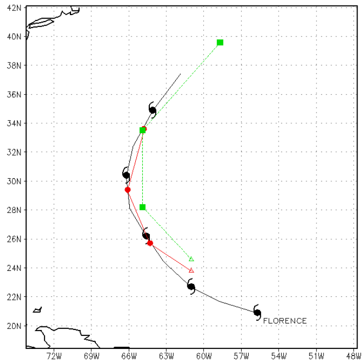

Figure 11. Trial (green) and NoTCI (red) forecast tracks (24-hour steps) for 0000 UTC 9 September 2006 plotted against best track observed positions for Hurricane Florence.

Figure 11 clearly shows that the initial position of Florence in the Trial is too far north when plotted against the best track data. The subsequent forecast accelerates Florence northwards too quickly and produced a 72-hour track error of 703 km. In fact the real time position used in the initialisation was 1.4 degrees further north than the best track position. Following the much better centre fixes from 0600 UTC onwards, the 1200 UTC 9 September Trial forecast was much improved; the 72-hour track error was reduced to 126 km and the forecast track was better than NoTCI throughout.

This case suggests that one of the main reasons for forecasts with tropical cyclone initialisation being worse was the fact that these forecasts were being initialised with the tropical cyclone in the incorrect location and with the incorrect recent movement vector due to real time storm fixes being incorrect. As soon as the correct fix was made, the forecast improved. Unfortunately the capability to replace bogus data derived operationally with those derived using best track data and perform a rerun is not available, so this theory cannot be verified.

3.4.4 Hurricane Gordon

The overall track forecast errors for Gordon indicate that NoTCI was better at 24-, 48- and 72-hours, but the Trial was better at longer lead times. From examining the sequence of forecasts, there is no clear pattern as to when one is better than the other. For example at 0000 UTC 12 September NoTCI was the better forecast throughout. However, by 0000 UTC 13 September the Trial was better throughout. The 1200 UTC 13 September forecast then reverted to being better for NoTCI. The best track fixes from this period are not significantly different to the real time fixes, so this is unlikely to have caused the difference. However, comments in the advisories from 0600 UTC and 1200 UTC 12 September suggested that the storm was difficult to locate and the steering motion in earlier advisories may have been too far to the left. It is possible that incorrect steering motion vectors used to derive the tropical cyclone bogus data were responsible for the poorer forecast tracks from the Trial at 0000 UTC 12 September, although would not account for later cases where the Trial was worse than NoTCI.

3.4.5 Hurricane Helene

As for Gordon, the overall track forecast errors for Helene indicate that NoTCI was better at 24, 48 and 72 hours, but the Trial was better at longer lead times. During the early part of Helen's life, the NoTCI forecast tracks were generally to the right of the Trial. This motion was better on many occasions, but was also worse on some. During the latter part of the storm's life, NoTCI forecast tracks for Helene were slower than the Trial and thus recurved Helene and made it extra-tropical later. However, some of these NoTCI forecasts were better and some worse than the Trial. The alternation in the relative performance of the Trial and NoTCI forecasts in this case suggest that the initialisation of the tropical cyclone was not causing a systematic error, but was not beneficial in all cases.

4. TRIAL OF MODIFIED TROPICAL CYCLONE BOGUS SCHEME

4.1 Configuration

The Met Office global model was rerun for the same period as described in the earlier results (20 August to 20 September 2006). This time the new configuration of the tropical cyclone bogus scheme (Trial) was compared with the configuration in operation during the trial period (Control).

	0h	24h	48h	72h	96h	120h
Number of cases	179	155	133	111	92	73
Control track error (km)	**43**	102	188	281	383	461
Trial track error (km)	45	**101**	**179**	**262**	**346**	**447**
Control track skill score (%)		36	50	55		
Trial track skill score (%)		**38**	**54**	**58**		
Control intensity tendency skill score (%)		41	42	6	**15**	**25**
Trial intensity tendency skill score (%)		**45**	**47**	**15**	8	19

Table 2. Mean track forecast errors (kilometres), track and intensity tendency skill scores (%) for the whole trial (homogeneous sample). **Bold** indicates the better score.

4.2 Results

Table 2 contains the following verification measures:

- Track forecast errors
- Track skill score (percentage improvement of model forecast over equivalent CLIPER forecast)
- Intensity tendency skill score (percentage improvement of model forecast of the intensity tendency over chance).

These figures only include cases where a tropical cyclone was identified in both the Control and Trial runs.

These figures indicate that for the trial period as a whole, the revised tropical cyclone initialisation scheme gave better results than the operational version by reducing track forecast error (by 4.6%) and increasing track forecast skill (by 2.9%) averaged over all forecasts. Intensity tendency skill scores were better in the Trial run by an average of 2.1%, although the value for 96- and 120-hour Control forecasts was slightly better than the Trial.

4.3 Hurricane Gordon

In many cases (e.g. tropical cyclones with large areal extent), the modification to the initialisation scheme would have no impact. Bogus data would be generated on concentric rings out to 8 degrees radius for both the Control and Trial configurations. However, in cases of small intense systems, such as Hurricane Gordon, the amount of bogus data used would be far less under the Trial configuration since the outer ring of bogus data would be at 4 degrees radius rather than 8 degrees.

Figures 12 and 13 show the Control and Trial analysis for 0000 UTC 20 September 2006 and Figure 1 the corresponding satellite image. At that time Hurricane Gordon was moving eastwards under the influence of a frontal system associated with a mature mid-latitude cyclone. A comparison of Figures 12 and 13 shows that the 700 hPa wind flow exhibited significant differences. In the Control run bogus data were inserted around the hurricane to a radius of 8 degrees, but were restricted to a maximum of 4 degrees in the Trial. This resulted in the Control run having a much broader flow of strong winds on the southern flank of the hurricane, whilst the winds were weak to the north of the hurricane due to impingement of the bogus easterly winds on the westerly flow on the southern flank of the mid-latitude low. The Trial analysis shows a much more compact circulation around the hurricane and less disruption to the westerly flow to the north of the hurricane. A similar effect was also seen in the 850 hPa and 500 hPa wind fields – the other levels where bogus data are inserted by the initialisation scheme.

The broader circulation of Hurricane Gordon in the Control analysis resulted in the development of a larger, deeper and slower moving feature in the forecast. Figures 14 and 15 show the 36-hour forecasts for this case from the Control and Trial runs. Figure 16 shows the analysis for this time. The Control forecast features a 973 hPa low just to the west of north-western Spain, whereas the Trial forecast features a 981 hPa low west of the Brest peninsula of France. The latter was closer to the verifying analysis both in terms of depth and position and resulted in a much better forecast for the passage of what was by then ex-Hurricane Gordon across the west of the UK and Ireland.

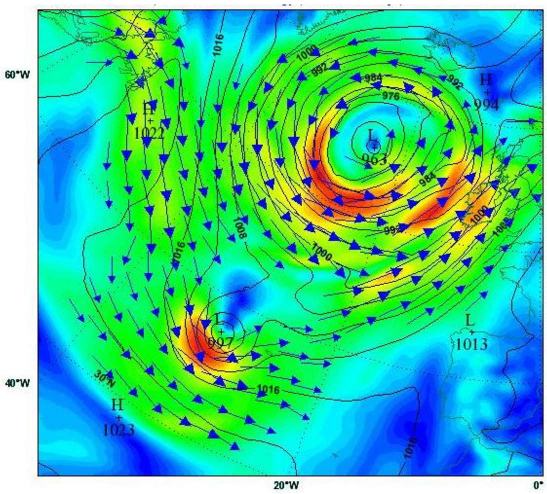

Figure 12. Control analysis for 0000 UTC 20 September 2006. MSLP, 700 hPa wind speed (shading) and 700 hPa wind arrows (25 knots and above)

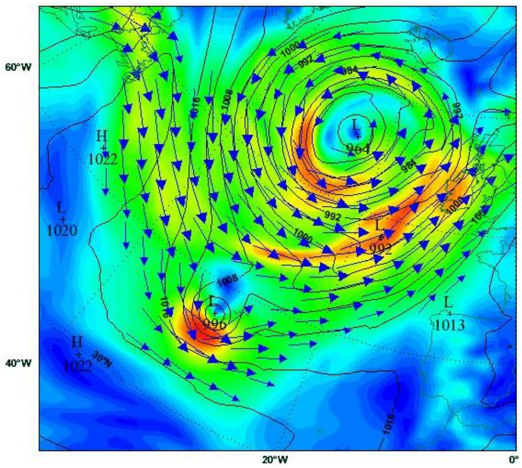

Figure 13. Trial analysis for 0000 UTC 20 September 2006.MSLP, 700 hPa wind speed (shading) and 700 hPa wind arrows (25 knots and above)

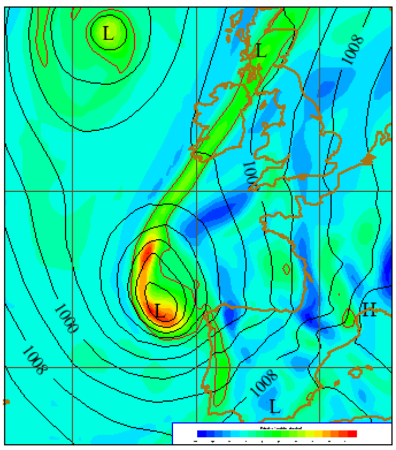

Figure 14. Control 36-hour forecast valid at 1200 UTC 21 September 2006. MSLP and 850 hPa relative vorticity (shading)

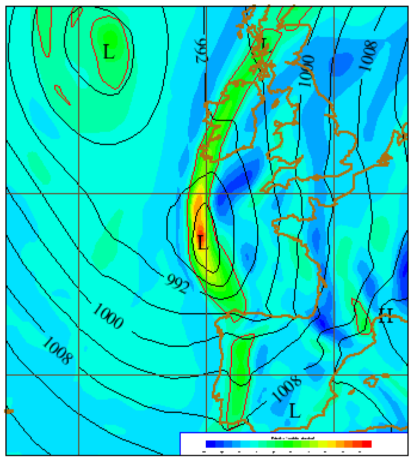

Figure 15. Trial 36-hour forecast valid at 1200 UTC 21 September 2006. MSLP and 850 hPa relative vorticity (shading)

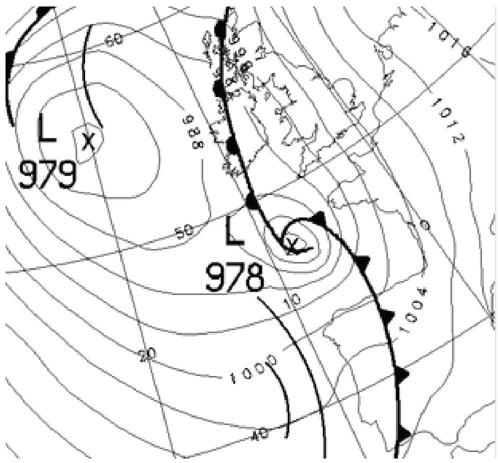

Figure 16. Analysis valid at 1200 UTC 21 September 2006.

5. CONCLUSIONS

5.1 Value of Initialisation Scheme

Tropical cyclone initialisation by assimilation of bogus data in the Met Office global model has been found to have a positive impact overall when compared to the model's performance with the initialisation scheme switched off. Forecast tracks errors were reduced by an average 12.2%, track skill scores were increased by an average 8.9% and intensity tendency skill scores were increased by an average 12.1%. The detection percentage was increased from 75% to 96% (at 120 hours) and forecast storms were 20.6% more intense when initialisation was used. The impact was greatest in the Pacific basins and least in the Atlantic. In fact, in three of the five Atlantic cases initialisation had a negative impact overall on track forecasts up to the 72-hour lead time. An evaluation of these cases revealed some where the fixes used to derive the bogus data were later found to be in error. However, overall no other systematic reason was identified as to why the initialisation should have a negative impact. In many cases, there was marked variation, sometimes from run to run, in whether the forecast was better or worse with initialisation included.

Given the higher density of observational data in some parts of the Atlantic than in other regions, it is not surprising that initialisation has less of an impact in this region. However, results for Hurricane Ernesto indicate that removing the initialisation from all Atlantic cases is not an option, since even in a comparatively data rich region, the model can fail to analyse and forecast a tropical cyclone correctly without initialisation. There currently seems to be no basis upon which to identify cases in real time where initialisation can be selectively suppressed when it is expected to have a negative impact.

5.2 Modifications to Initialisation Scheme

The tropical cyclone initialisation scheme was modified such that the areal extent of the bogus data inserted into the model was determined by the radius of 34 knot winds of the storm rather than the storm's maximum sustained wind speed. This resulted in fewer bogus observations being generated for strong, but small tropical cyclones. In a trial against the operational initialisation scheme, the new configuration was found to have a positive impact overall by reducing forecast tracks errors by an average 4.6%, increasing track skill scores by an average 2.9% and increasing intensity tendency skill scores by an average 2.1%.

The development of the modified initialisation scheme was prompted by some poor forecasts for Hurricane Gordon as it began interaction with a mid-latitude low and frontal system. Examination of one of these forecasts showed that the revised initialisation scheme gave a more realistic analysis of the hurricane and its broader environment and resulted in a better forecast of the eventual extra-tropical transition of the hurricane.

As a result of this trial it was decided to implement the modified configuration of the tropical cyclone initialisation scheme in the Met Office global and regional models from 27th November 2007.

6. REFERENCES

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