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TROPICAL CYCLONE PREDICTIONS FROM THE MET OFFICE AND ECMWF MODELS – RELATIVE PERFORMANCE AND ERROR DIAGNOSIS

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1. RELATIVE PERFORMANCE OF MET OFFICE AND ECMWF MODELS

Homogeneous comparisons of the Met Office Global Model (MOGM) and ECMWF Model tropical cyclone (TC) track forecasts have been made since 1994 (Figures 1 and 2). For the period 1994 to 2003 these comparisons showed that MOGM errors were lower at short lead times (up to 48 hours). At longer lead times (72 to 120 hours) there was usually a crossover point where ECMWF errors became lower than MOGM. In some years (e.g. 1998) this crossover point was at a shorter lead time, but in other years (e.g. 1999) MOGM errors were lower than ECMWF as far as 120 hours into the forecast.

However, from 2004 ECMWF track forecast errors started to drop at longer lead times (72-120 hours) and in 2007 short lead time errors also started to drop (see Figures 1 and 2). This meant that by 2008, ECMWF track forecast errors were lower than MOGM at all lead times from 24 hours onwards. In 2008 ECMWF's 96-hour errors were lower than MOGM's 72-hour errors. From 2009 to 2011, this gap which had opened up between the ECMWF and MOGM TC track forecast errors did not widen further and at some lead times in some years narrowed slightly. However, ECMWF's performance for TC track forecasts is still superior to MOGM to the current time.

What is clear from these verification data is that the gap between ECMWF and MOGM has come about through a period of rapid error reduction by ECMWF rather than any worsening of performance in the MOGM. Indeed, MOGM track forecast errors at all lead times in 2011 were lower than in the years 2004-7 when the rapid reduction of ECMWF errors was taking place.

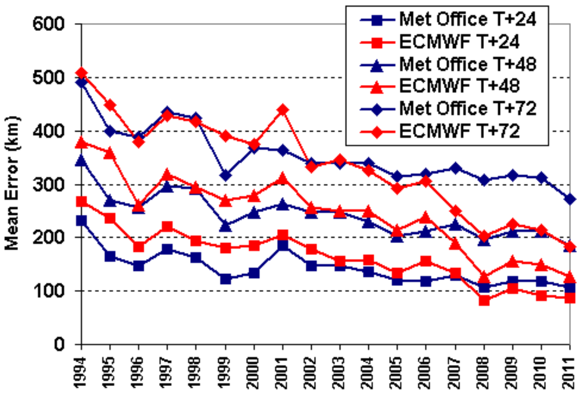

Figure 1. Met Office Global Model (blue) and ECMWF (red) tropical cyclone track forecast errors (global) for 24 to 72 hours

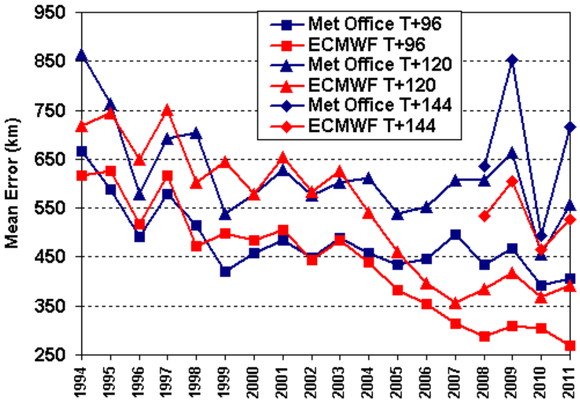

Figure 2. As Figure 1, but for 96 to 144 hours.

ECMWF made a number of changes to their model during the period 2003-7 which may account for much of the improvement in the model performance:

October 2003: Introduction of many new satellite data streams (e.g. AIRS, AMSU).
September 2004: Revised convection scheme. Further changes to satellite data usage.
June 2005: Changes to convection scheme and assimilation of satellite data.
February 2006: Horizontal resolution increased to T799 (~25 km) with 91 vertical levels.
September 2006: Revised cloud scheme and explicit convective transports.
June 2007: Revised 4D-Var scheme.
November 2007: Changes to convective entrainment and assimilation of satellite data.

Further details are available at http://www.ecmwf.int/products/data/technical/model_id/index.html.

The aim of this study is to investigate whether the superior performance of the ECMWF model is due to the formulation of the forecast model itself or due to the analysis of the TC or the wider environment around the TC.

2. METHOD FOR ERROR DIAGNOSIS

A series of cases were chosen where the operational MOGM and ECMWF forecast tracks of the TC diverged by a significant amount. In most cases the ECMWF track was better. In each case the analysis from the ECMWF model was transplanted into the MOGM and the forecast run forwards using the operational MOGM configuration. A set of 10 fields were transplanted, which enabled a fairly complete representation of the dynamics, thermodynamics and moisture within the analysis. The fields were as follows (all upper level fields were interpolated onto the 70 levels of the MOGM):

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u and v (zonal and meridional wind)
theta (potential temperature)
q, qcf and qcl (specific humidities of vapour, liquid and ice)
t* (screen level temperature)
w (vertical motion)
rho^2 (density squared)
exner pressure

As well as transplants of all fields and levels for a global domain, experiments were undertaken to restrict the number of fields, the levels and the geographical area - e.g. only transplanting fields encompassing the TC circulation as shown in Figure 3. In these cases there was no smoothing of the fields at the boundaries of the transplant area in the analysis, but the forecast model was allowed to smooth the fields as it ran forwards in time.

All cases were run with a version of the MOGM operational in 2011. Some cases were from 2009 when an earlier model configuration was in operation. Hence in all cases a Control run was made with the MOGM analysis and a Trial with the transplanted ECMWF analysis.

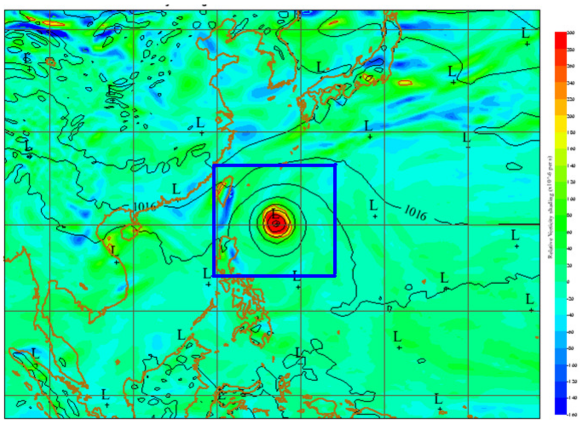

Figure 3. An example of the restricted domain used for transplant of ECMWF analysis in some cases.

3. TYPHOON LUPIT – A CASE STUDY OF ERROR DIAGNOSIS

Typhoon Lupit occurred in October 2009. It tracked westwards towards the northern Philippines before making an abrupt turn north-eastwards and accelerating into the mid-latitudes. Two days prior to this turn (00 UTC 21 October) the ECMWF model correctly predicted the turn, although did not accelerate the typhoon quickly enough. However, the MOGM continued with a slow westward track across the northern Philippines. Figure 4 shows the observed track of the typhoon along with four forecast tracks – the operational MOGM and ECMWF tracks and the Control and Trial. In this case the Trial included a global transplant of all ECMWF analysis fields listed in the previous section.

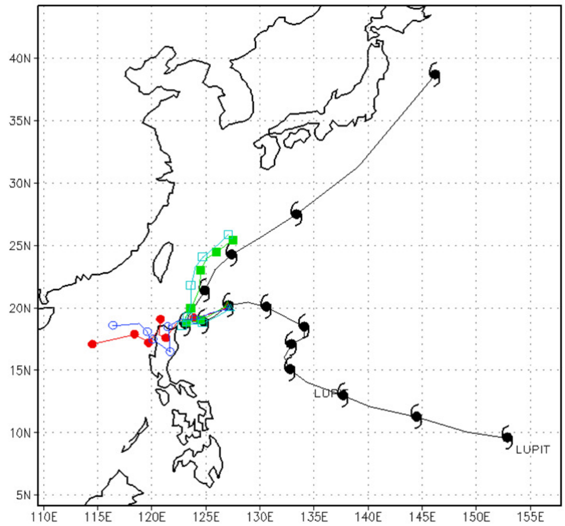

Figure 4. Typhoon Lupit observed and forecast tracks from data time 00 UTC 21 October 2009. Black – observed track. Red – operational MOGM. Green – operational ECMWF. Dark blue – Control. Light blue – Trial. All symbols 24 hours apart.

This case shows that the Control track closely follows the operational MOGM indicating just a small impact from using the more recent model configuration. However, the Trial closely follows the operational ECMWF track. This shows that the ECMWF analysis was the main factor in producing a better forecast track in this case.

The Met Office runs a variety of ensemble configurations of its Unified Model. TC predictions are obtained from the 24-member 15-day global configuration known as MOGREPS-15 (Bowler et al., 2008). In the case of Typhoon Lupit there was considerable bifurcation in the forecast tracks to reflect a possible continued westward track or a turn north-eastwards. For this particular data time the majority of ensemble members favoured the north-eastwards turn and the actual track was captured within the ensemble spread as shown in Figure 5.

In order to establish how much of the improvement in the Trial forecast track has come about through the ECMWF analysis of the typhoon itself and how much from the wider environment a second trial was undertaken transplanting the analysis in a rectangular area similar to that shown in Figure 3 (known as TrialTConly). The MOGM analysis was used outside of this area. Figure 6 shows an overlay of the 120-hour forecast charts for the Control, the Trial and TrialTConly. This shows that the Trial and TrialTConly positions (and intensities) are very similar. Whilst still showing a considerable error compared to the verifying position, they are much better than the Control. This indicates that virtually all the improvement seen in the forecast with the transplanted analysis is obtained by the analysis of the TC itself rather than the wider environment.

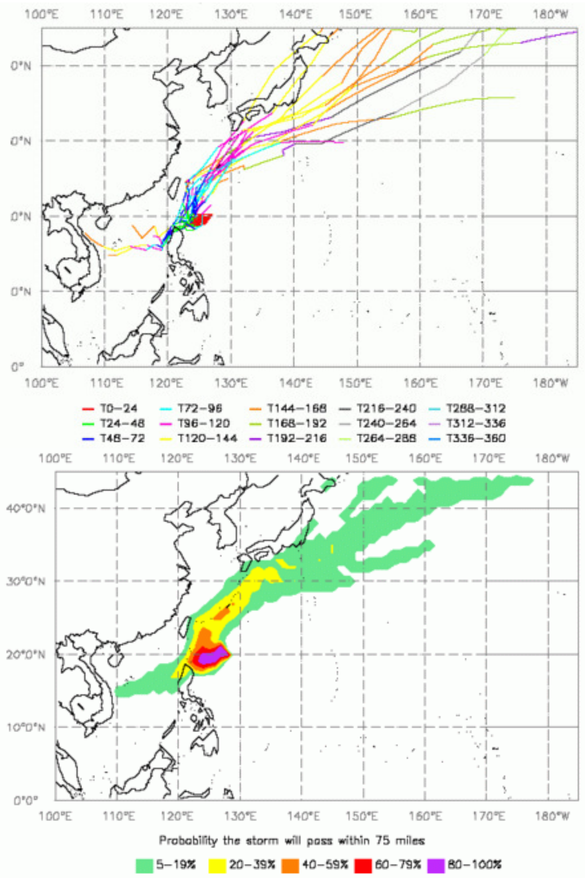

Figure 5. Typhoon Lupit MOGREPS-15 forecast from data time 00 UTC 21 October 2009.
Top – individual ensemble tracks. Bottom – probablility of storm passing within 75 miles.

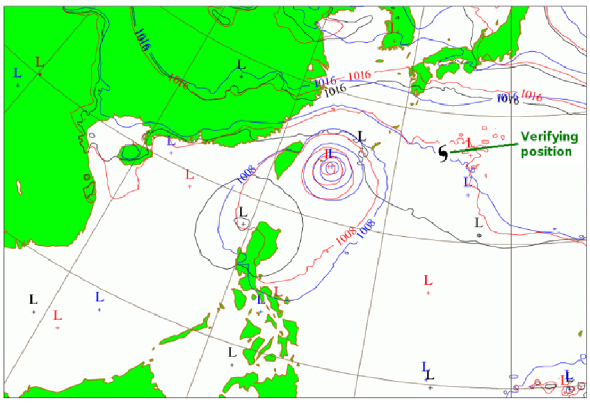

Figure 6. Typhoon Lupit 120-hour forecast from data time 00 UTC 21 October 2009.
Black – Control. Blue – Trial. Red – TrialTConly.

Further experiments were conducted which involved transplanting just the u and v fields around the TC (TrialTConlyuv) and transplanting all the fields around the TC *except* u and v (TrialTConlyNOuv). The 120-hour forecasts for these configurations are shown in Figure 7. This shows that the improved forecast seen in the previous trials was achieved by transplanting the u and v fields only. Without the ECMWF u and v fields, the forecast is as poor as the Control. A cross section of the v-wind profile (Figure 8) indicates that the ECMWF analysis has a more compact vortex with stronger winds at all levels. Having isolated the improvement in forecast track to the wind fields around the TC itself, further experiments were conducted in an attempt to isolate the cause of the improvement further.

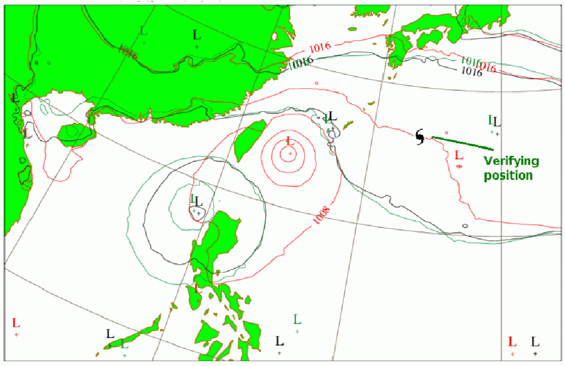

Figure 7. Typhoon Lupit 120-hour forecast from data time 00 UTC 21 October 2009.
Black – Control. Red – TrialTConlyuv.
Green – TrialTConlyNOuv.

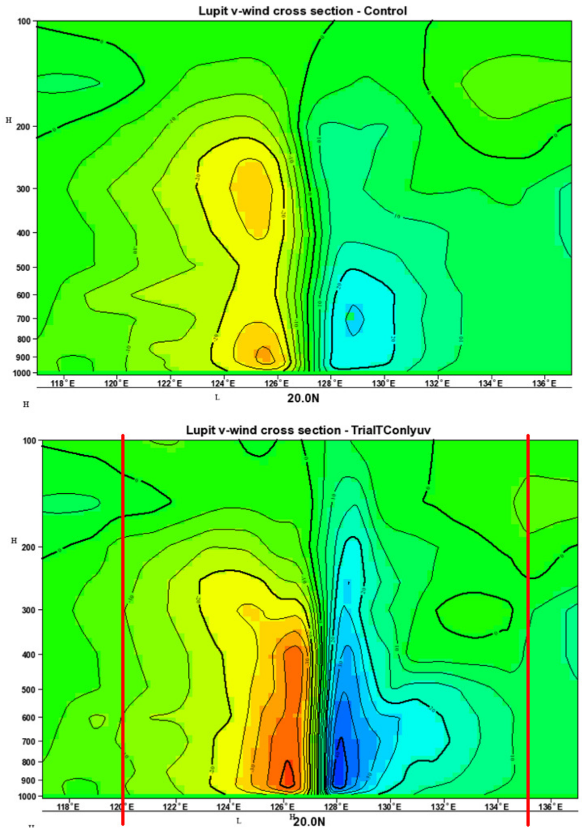

Figure 8. Typhoon Lupit analysis at 00 UTC 21 October 2009. v-wind field cross section.
Top – Control. Bottom – TrialTConlyuv showing the boundary of the transplanted fields.

The transplanted region was split further into sub-regions as shown in Figure 9. Experiments were conducted to transplant u and v fields only above 500 hPa (area 1), only below 500 hPa (areas 2 + 3 + 4) and only in a narrow region (six degrees square) below 500 hPa (area 3). The only configuration to show an improvement in forecast track was the transplant of areas 2 + 3 + 4. This suggests it is the wind fields below 500 hPa around the periphery of the TC's circulation that is producing the improvement. A closer look at the wind field cross section reveals a lobe of strong winds (southerlies) in area 4 not present in the Control (Figure 8 – top). Although it is not possible to verify whether this lobe of stronger winds is realistic it seems likely that this is the cause of the difference in forecast track.

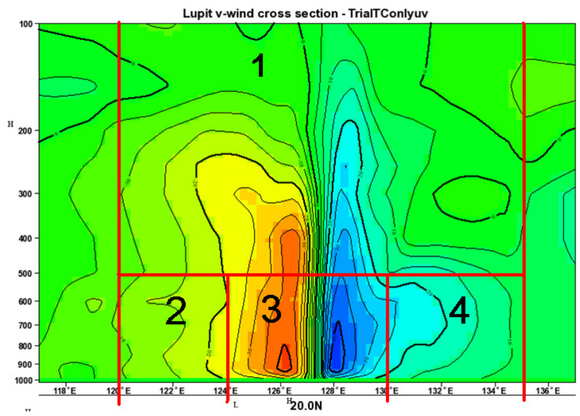

Figure 9. Typhoon Lupit analysis at 00 UTC 21 October 2009.
v-wind field cross section for TrialTConlyuv.
Transplanted areas indicated by numbers 1 to 4.

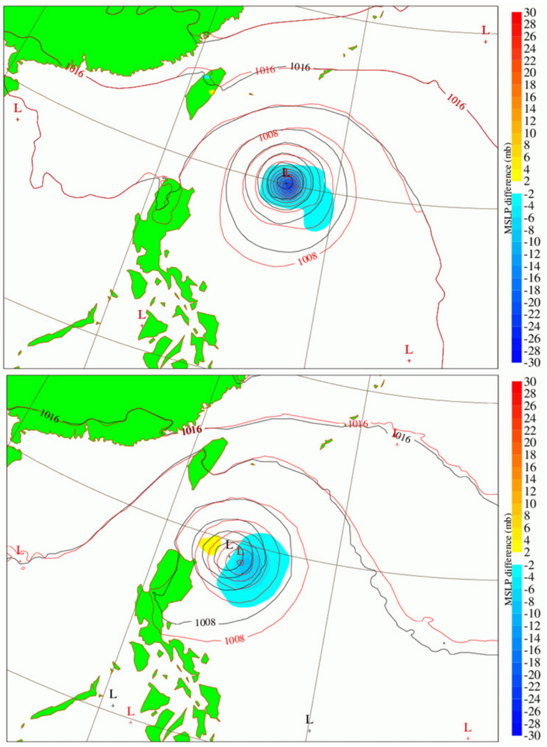

Figure 10. Typhoon Lupit data time 00 UTC 21 October 2009.
Analysis (top) and 24-hour forecast (bottom).
Black – Control. Red – Trial TConly.

The prime focus of these experiments has been the TC track forecasts. However, as a secondary point of interest it is worth mentioning the TC intensity forecasts in the experiments. For many years the ECMWF model has been able to represent the depth of strong TCs much better than other global models including the MOGM. Hence it is no surprise that the transplanted analysis in these experiments has a much deeper TC. However, it is of note that as the forecast is run forward in the various trials, the additional depth seen in the analysis is lost very quickly. For example, Figure 10 shows that the TrialTConly analysis for Typhoon Lupit was 22 hPa deeper than the Control (969 hPa v. 991 hPa). However, by 24 hours into the forecast the difference between the two was just 4 hPa (988 hPa v. 992 hPa). The estimated central pressure at that time was 965 hPa. Hence, the MOGM was unable to retain the additional strength of the TC transplanted from the ECMWF analysis. Despite this rapid spin down in TC intensity, there was no detrimental impact on forecast track which, as shown above, was much better with the transplanted analysis.

4. RESULTS FROM OTHER CASES

Clearly more cases needed to be examined to determine whether the result seen in the case of Typhoon Lupit was systematic or otherwise. Similar transplant experiments were run on seven other cases. In two of the cases there were two TCs active simultaneously. In the majority of cases the results were very similar – transplanting the ECMWF analysis of lower tropospheric winds around the TC were primarily responsible for a forecast track close to the operational ECMWF track. In two of the cases the ECMWF analysis was not the major factor (i.e. accounted for less than half of the improvement), but still contributed to a better forecast track. In the cases where the ECMWF analysis was not the major factor in the forecast improvement the MOGREPS-15 ensemble did not capture the correct track.

Hurricane Igor was one of the strongest Atlantic hurricanes in 2010. Several forecasts from the MOGM started the recurvature process, but then cut-off the circulation in the subtropics thus not completing extratropical transition. The ECMWF forecast fully engaged Igor with the mid-latitude westerlies and completed its extratropical transition, which was a more accurate forecast. The MOGM and ECMWF forecast tracks for one of these cases is shown in Figure 11. This shows how the MOGM track has a slight westwards bias, then slows and ends near 35°N. In reality Igor completed extratropical transition near 45°N and continued on a north-easterly track. A few members of the MOGREPS-15 ensemble capture this more rapid movement into the mid-latitudes (not shown).

The 132-hour Control and TrialTConly forecast charts for the Hurricane Igor case are shown in Figure 12. These show that when the ECMWF analysis around the TC only is transplanted into the MOGM, the forecast track is far superior. In this case further transplants of just the u and v fields below 500 hPa were made as for Typhoon Lupit. The results were similar in that most of the improvement in forecast track was as a result of the lower tropospheric winds around the TC.

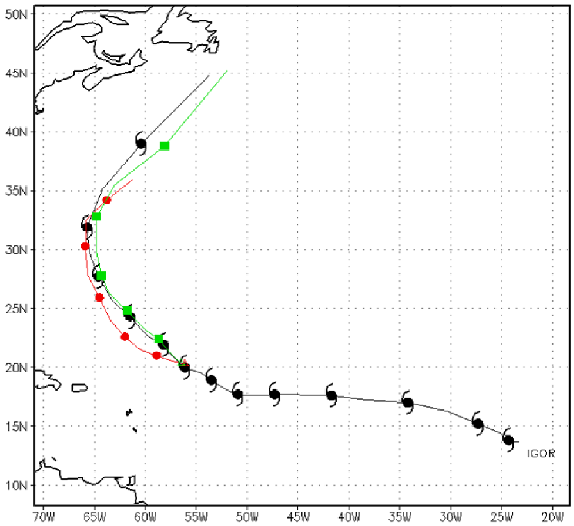

Figure 11. Hurricane Igor observed and forecast tracks from data time 00 UTC 16 September 2010.
Black – observed track. Red – operational MOGM.
Green – operational ECMWF.
All symbols 24 hours apart.

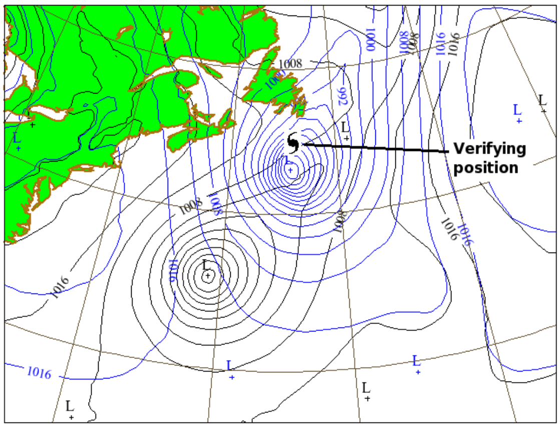

Figure 12. Hurricane Igor 132-hour forecast from data time 00 UTC 16 September 2010.
Black – Control. Blue - TrialTConly.

As with the case of Typhoon Lupit, it was interesting to note that the much deeper analysis of Hurricane Igor (963 hPa in TrialTConly against 991 hPa in the Control) was mostly lost by 24 hours into the forecast. A 28 hPa difference had reduced to just 4 hPa (979 hPa v. 983 hPa). This is shown in Figure 13. The estimated central pressure at the analysis time was 942 hPa and at the validity time of the 24-hour forecast was 935 hPa.

Another case examined was Typhoon Nida on 00 UTC 25 November 2009. In this case the operational ECMWF track forecast was as poor as MOGM, but in the opposite direction. MOGM turned Nida sharply westwards or south-westwards whilst ECMWF turned Nida north then north-east. In reality Nida took a track between the two, slowly drifting north-west. The Control track was fairly close to the operational MOGM and the Trial (global transplant of ECMWF analysis) accelerated Nida to the north-east even quicker than the operational ECMWF forecast. These tracks are shown in Figure 14. The majority of members of the MOGREPS-15 ensemble followed the operational MOGM track, but a few members showed a north or north-eastwards track (not shown).

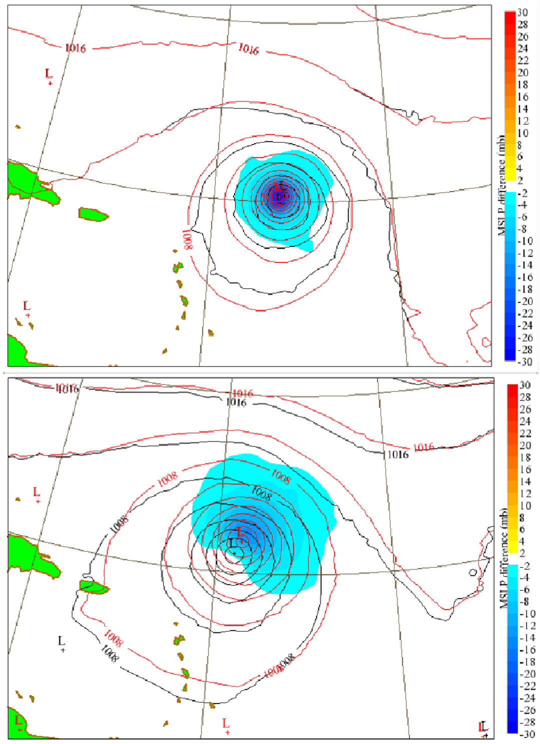

Figure 13. Hurricane Igor data time 00 UTC 16 September 2010.
Analysis (top) and 24-hour forecast (bottom).
Black – Control. Red – Trial TConly.

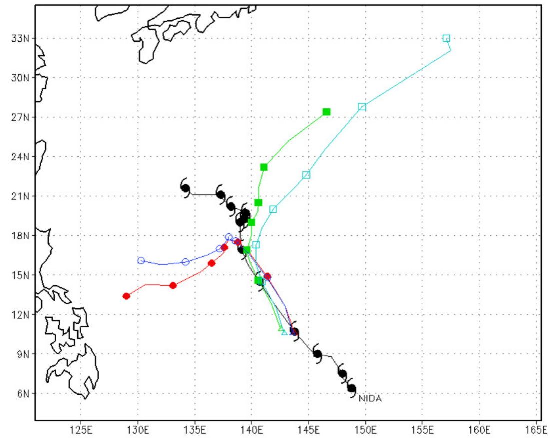

Figure 14. Typhoon Nida observed and forecast tracks from data time 00 UTC 25 November 2009.
Black – observed track. Red – operational MOGM.
Green – operational ECMWF. Dark blue – Control.
Light blue – Trial. All symbols 24 hours apart.

Further transplant experiments were undertaken in this case and it is interesting to note that the transplant configuration which gave the best result was TrialTConlyuv as shown in Figure 15. This suggests that in this case the combination of the ECMWF u and v fields around the TC along with the MOGM analysis of the wider environment beyond the TC produced the best result.

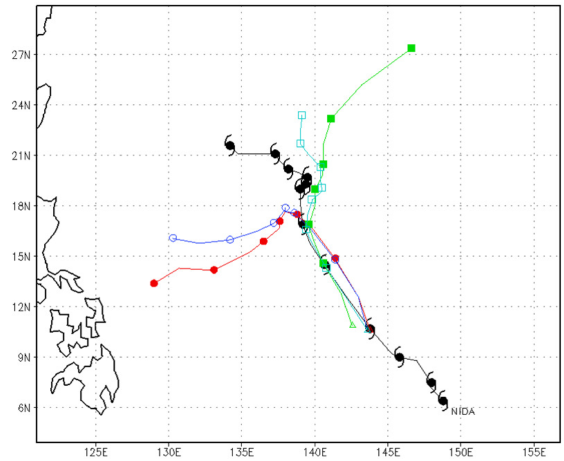

Figure 15. Typhoon Nida observed and forecast tracks from data time 00 UTC 25 November 2009. Black – observed track. Red – operational MOGM. Green – operational ECMWF. Dark blue – Control. Light blue – TrialTConlyuv.
All symbols 24 hours apart.

5. CONCLUSIONS

An investigation has been made into the superior performance of the ECWMF model compared to the MOGM for TC track prediction, which has been prevalent in the last few years. ECMWF analyses were transplanted into the MOGM in a series of cases. In the majority of cases it was found that using a transplanted analysis resulted in a superior track forecast which was much closer to the operational ECMWF forecast than the operational MOGM forecast. Further experiments established that the prime area of sensitivity was lower tropospheric winds in the analyses. In many cases a forecast track close to the operational ECMWF track was obtained by transplanting just the ECMWF analysis of u and v below 500 hPa around the TC only.

The MOGREPS-15 24-member ensemble predictions were examined for these cases and it was generally found that when the ECMWF analysis was a major factor in an improved track forecast by the MOGM, the ensemble captured the correct track. When the ECMWF analysis was not such a major factor in the improvement, the ensemble did not capture the observed track.

These results are similar to those found in Yamaguchi et al. (2012). In this study ECMWF analyses were transplanted into the Japanese Meteorological Agency (JMA) Global Spectral Model and in many cases resulted in a significant improvement in TC forecast track. In the cases of major improvement, the observed track was captured by the JMA typhoon ensemble prediction system.

Whilst focusing on track forecasts in this investigation it was also found that when the much deeper ECMWF analysis of the TC was transplanted into the MOGM, most of this depth was lost by 24 hours into the forecast. Despite this rapid spin down of TCs the forecast track was still much improved in most cases.

These results raise several issues and areas for further investigation. ECMWF analyses are clearly superior. Thus investigation needs to be made as to whether this is related to data assimilation, observations, cut-off time or other issues. The MOGM includes artificial initialisation of all TCs, which involves insertion of lower tropospheric wind observations (Heming et al., 1995; Heming, 2009). Given that results show the analysis of lower tropospheric wind around the TC is the area of greatest sensitivity with regard to track forecasts, further evaluation is being made of the scheme. The last time it was evaluated (Heming, 2009) it still produced a 10% reduction in track forecast errors. However, preliminary results from a new trial suggest that the scheme is now detrimental to TC forecast tracks in many cases. Hence, changes to the way TCs are initialised in the MOGM are likely in the near future.

The failure of the MOGM to retain the depth of TCs transplanted from the ECMWF analyses is an issue worthy of further investigation. The ECMWF model has a higher horizontal resolution than the MOGM, but how much of this loss in intensity is down to resolution, the model's physical processes, parametrizations or other factors?

This series of experiments have provided a useful insight into the importance of the analysis of TCs in numerical models and its impact on forecast track and indeed intensity. This has given focus to efforts to improve the way the MOGM represents and forecasts TCs.

6. REFERENCES

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