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THE IMPACT OF RESOLUTION ON MET OFFICE MODEL PREDICTIONS OF TROPICAL CYCLONE TRACK AND INTENSITY

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1. HISTORICAL BACKGROUND

Increases in the horizontal and vertical resolution of the various configurations of the Met Office Unified Model (MetUM) have been made at regular intervals over the years as greater computing power has become available. At the beginning of 2009 the global configuration of the MetUM was running at a horizontal resolution of approximately 40 km at mid-latitudes and with 50 vertical levels. By comparison, 20 years earlier the resolution was 150 km and 15 levels. By Spring 2010 the global MetUM was running at a resolution of 25 km and with 70 levels. A timeline of resolution changes to the global MetUM can be found in Table 1.

Date	Descriptor	Approximate horizontal resolution	Number of vertical levels
Pre June 1991	N96	150 km	15
June 1991	N144	90 km	20
October 1992	N144	90 km	19
January 1998	N216	60 km	30
August 2002	N216	60 km	38
December 2005	N320	40 km	50
November 2009	N320	40 km	70
March 2010	N512	25 km	70

Table 1.
Changes to horizontal and vertical resolution of the global configuration of the MetUM

In recent years various regional configurations of the MetUM have also been set up and run over areas that experience tropical cyclones – some on an ad hoc basis and some running regularly in real time. These models have been run at a resolution of 17 km in the horizontal with 38 vertical levels. By Spring 2010, one such model (covering most of the North Indian Ocean) was running at 12 km resolution and with 70 levels.

With each increase in model resolution, assessments have been made as to how it impacts both forecast track and intensity of tropical cyclones. Even at resolutions as high as 12 km numerical models are unable to represent the true intensity of strong tropical cyclones in particular. Hence, whilst each change has the potential to nudge the model closer to reality in terms of absolute values of tropical cyclone strength, this has been tempered by the requirement to forecast tropical cyclones with a realistic size and structure given the constraints of model resolution.

This paper will review the impact of resolution on forecasts of the track and intensity of tropical cyclones and severe tropical rainfall events in both the global and regional configurations of the MetUM. It will also explore how changes to data assimilation techniques and physics tunings have combined with resolution changes to impact on the forecast performance.

2. PAST CASES OF RESOLUTION IMPACT

2.1 Hurricane Katrina

At the time of Hurricane Katrina in 2005, the Met Office had a 17 km resolution regional configuration of the MetUM set up to run on an ad hoc basis over North America and the Gulf of Mexico. It was run after the event from a reconfigured global analysis to assess the impact of resolution on the model's representation of the hurricane. Figure 1 shows the 12-hour forecast of 10m wind from data time 0000 UTC 29 August for the 60 km global model (as it was then) and the 17 km regional model. This indicates that the regional model was able to represent the eye of the hurricane and the wind structure just outside the eye with much more detail. The 60 km global model central pressure and peak 10m wind were 976 hPa and 46 knots at this time. The 17 km regional model predicted 958 hPa and 62 knots, but this was still well short of the observed values of 923 hPa and 110 knots at this time.

Figure 2 shows the 3-hour rainfall accumulation forecasts valid at the same time as Figure 1. Figure 3 shows the actual radar rainfall image valid at this time. This indicates that the 17 km regional model was better able to represent some of the rainfall structure such as the intense band to the north of the eye and the dry slot to the west.

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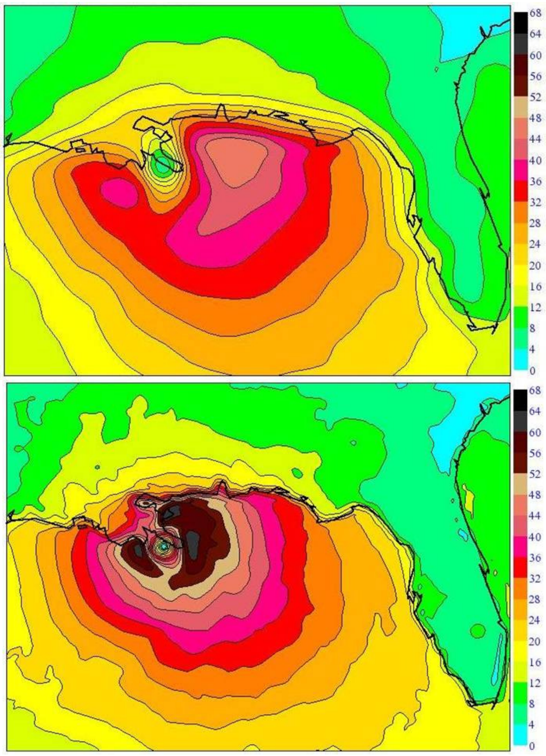

Figure 1. Data Time 0000 UTC 29 August 2005, 12-hour forecast of 10m wind (knots).
Top: 60 km global model. Bottom: 17 km regional model

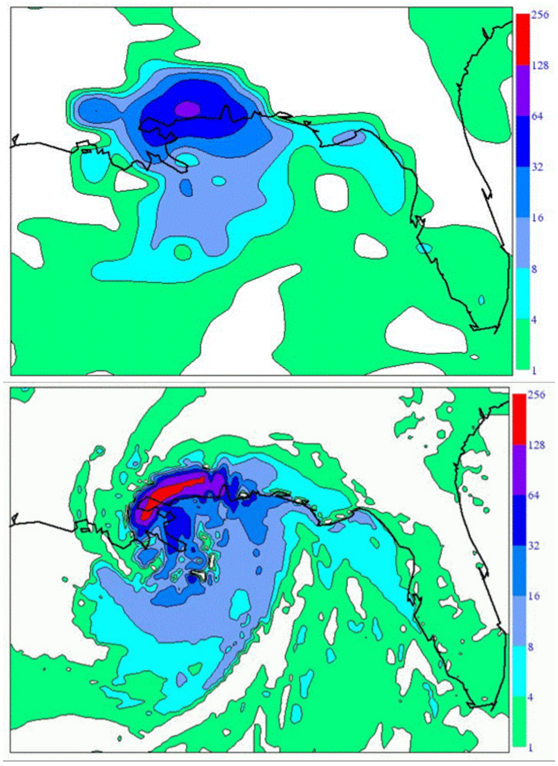

Figure 2. Data Time 0000 UTC 29 August 2005, 12-hour forecast of 3-hour precipitation accumulation.
Top: 60 km global model. Bottom: 17 km regional model

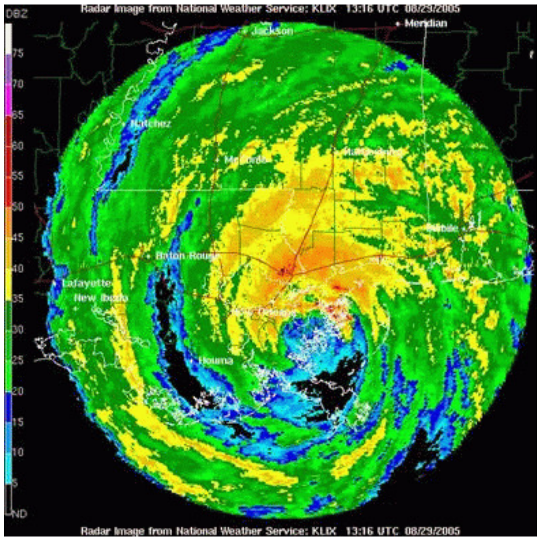

Figure 3. Data Time 1200 UTC 29 August 2005, radar rainfall rate.

2.2 Mumbai Floods

Earlier in 2005 Mumbai in India suffered an extreme flooding event with over 900mm rainfall measured on 25-26 July at one site. In the two days prior to the event the 60 km global model operational at the time performed fairly well in predicting the location of the heaviest rain. Figure 4 shows the rainfall accumulations from the first 24 hours of the forecast from 0000 UTC 26 July. The highest totals of about 350 mm in the 60 km global model prediction were lower than actually recorded, but this peak value was correctly located over Mumbai. The Met Office runs a regional model with its own 3D-Var assimilation cycle in this region (known as the South Asia model), which produces a 48-hour forecast every 12 hours and had a resolution of 17 km and 38 levels in 2005. This model shows more detail and higher totals (over 500mm), but the peak values were incorrectly located some distance south of Mumbai. It was speculated that the poorer performance may be due to the fact that the South Asia model runs on its own 3D-Var assimilation cycle whereas the 60 km global model uses 4D-Var, which is known to be a superior data assimilation method (Lorenc and Rawlins, 2005). To evaluate the impact of the data assimilation scheme, the same case was rerun on the 17 km regional model, but with a reconfigured 4D-Var generated global model analysis. The result (Figure 5) shows a much improved location for the highest rainfall totals, which peaked at more than 500mm.

These results indicate that the regional model would benefit from using 4D-Var. This is something which, whilst desirable, could not be implemented before now since 4D-Var is computationally far more expensive than 3D-Var and constraints on computer resources did not permit implementation. However, 4D-Var will be implemented in the South Asia regional model in 2010.

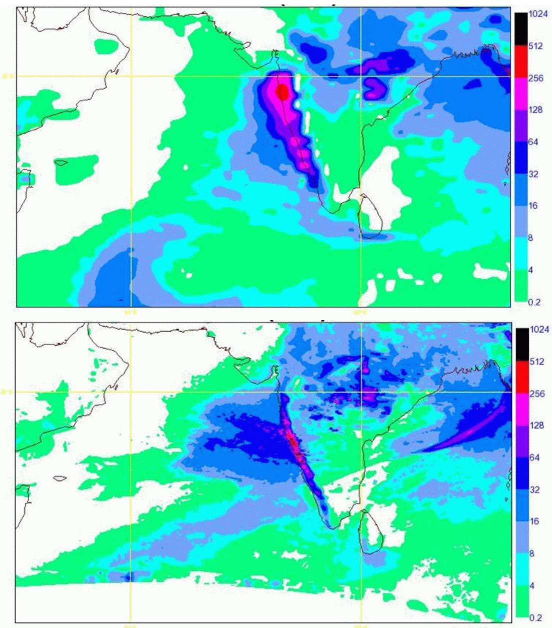

Figure 4. Data Time 0000 UTC 26 July 2005, 0-24 hour rainfall accumulations (mm).
Top: 60 km global model. Bottom: 17 km regional model.

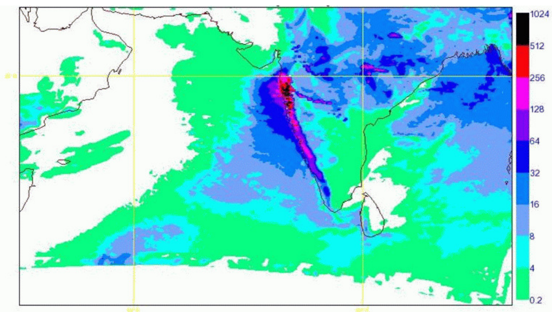

Figure 5. Data Time 0000 UTC 26 July 2005, 0-24 hour rainfall accumulations (mm).
17 km regional model reconfigured from global analysis.

2.3 North Indian Ocean Tropical Cyclones

More recently, case studies have shown that the South Asia model can give better representations of tropical cyclones than the 40 km global model. For example, Figure 6 shows a 48-hour forecast for Tropical Storm Bijli in April 2009. The global model shows a barely discernable storm centre (as diagnosed from the 850 hPa relative vorticity contour). However, the South Asia model shows a well marked low centre close to the observed position of the storm (black dot). At this time Bijli was a 50 knot tropical storm.

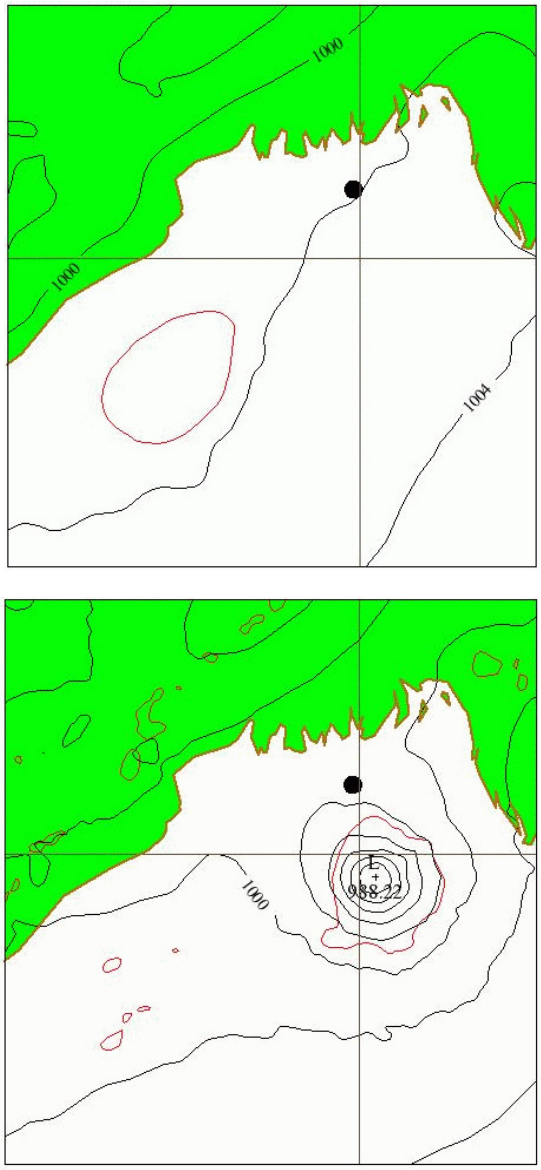

Figure 6. Data Time 1200 UTC 15 April 2009, 48-hour mean sea-level pressure (black)
and critical 850 hPa relative vorticity contour (red).
Top: 40 km global model. Bottom: 17 km regional model.

However, cases such as Bijli should not disguise the fact that track and intensity forecasts from the higher resolution regional model are still in need of improvement. Firstly, in a homogeneous evaluation of all forecasts from 2007-9 from the global model and South Asia model, the global model track forecast errors were in fact 19% lower than the South Asia model and track skill scores 5% higher on average as shown in Figure 7. This poorer performance by the higher resolution regional model may be due to its usage of 3D-Var rather than 4D-Var as the latter is known to improve tropical cyclone predictions (Lorenc and Rawlins, 2005 and Rawlins et al., 2007). As discussed above, 4D-Var will be introduced to the South Asia model later in 2010.

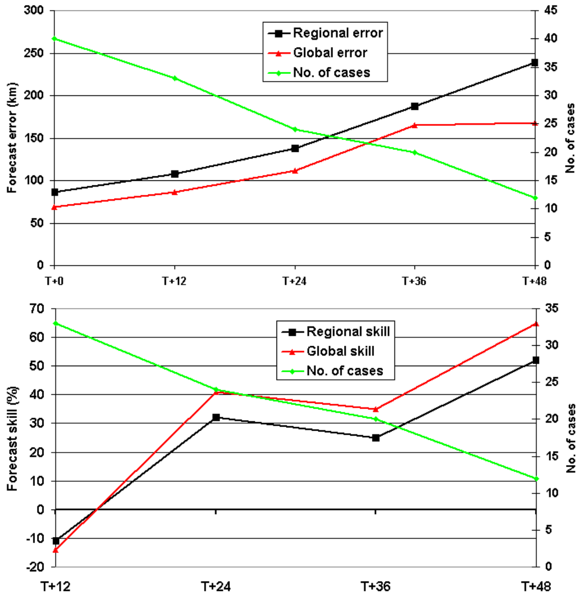

Figure 7. Comparison of performance between global and regional models for all North Indian Ocean tropical cyclones in 2007-9. Top: track error. Bottom: track skill score against CLIPER

Although the South Asia model is better able to represent the intensity of tropical cyclones than its lower resolution global counterpart, the same study of forecasts from 2007-9 in the North Indian Ocean discussed above has shown that there is an erroneous spin up of tropical cyclones in the regional model. Figure 8 show the mean value of peak 850 hPa relative vorticity near the storm centres for the two models. Clearly this shows much higher absolute values in the regional model as one would expect, but it also shows a spin up relative to the global model which persists throughout the length of the 48-hour prediction.

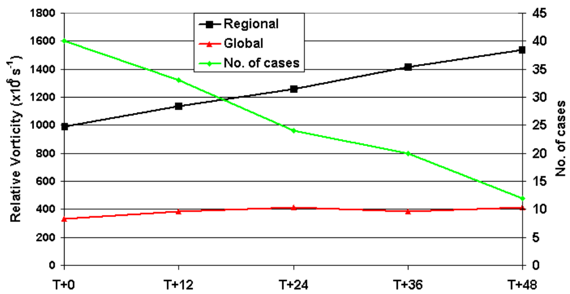

Figure 8. Peak 850 hPa relative vorticity for all North Indian tropical cyclones in 2007-9

This spin up is illustrated in a forecast for Cyclone Gonu from 1200 UTC 04 June 2007. At the analysis time Gonu's intensity was 914 hPa and 145 knots, which was near its peak. 36 hours later Gonu had weakened to 956 hPa and 90 knots. Figure 9 shows the South Asia model analysis and 36-hour forecast of mean sea-level pressure and 10m wind. The analysed values of central pressure and peak 10m wind were 983 hPa and 44 knots. However, by 36 hours into the forecast the cyclone had intensified to 955 hPa and 74 knots. The forecast values were far closer to reality than the analysed values, but the spin up required to obtain these forecast values was unrealistic as the cyclone was actually going through weakening during this period.

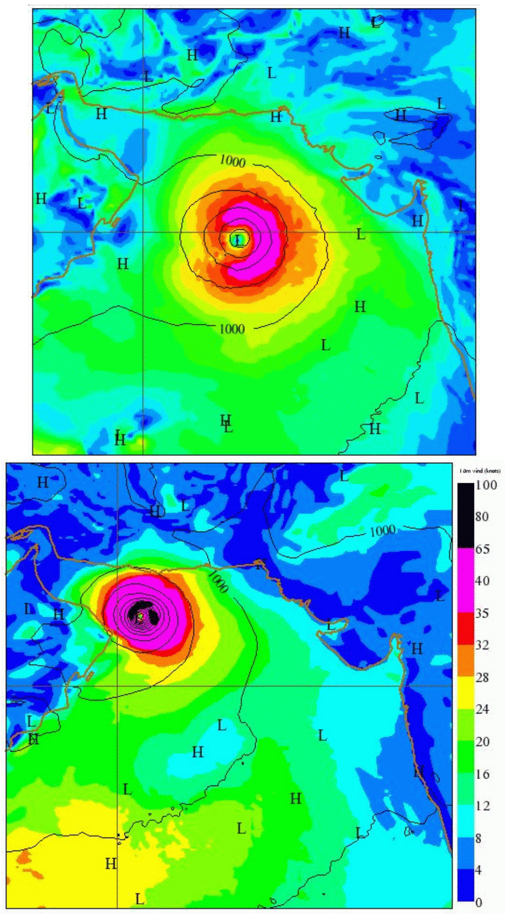

Figure 9. Tropical Cyclone Gonu South Asia model analysis (top) and 36-hour forecast (bottom) of mean sea-level pressure (hPa) and 10m wind speed (knots). Data time 1200 UTC 04 June 2007

2.4 Typhoon Ketsana

In 2009, Tropical Storm Ketsana developed to the east of the Philippines and caused extensive flooding in Manila as it tracked westwards across the country. Having developed into a typhoon it later made landfall over Vietnam and tracked across Cambodia, Laos and Thailand as a weakening feature. Rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) satellite indicated that the highest accumulations were generally along the central part of the track of the typhoon. However, global model predictions of rainfall accumulations at landfall both in the Philippines and Vietnam tended to show the highest totals on the windward facing coastal regions to the north of the typhoon centre's path. For example, Figure 10 shows the global model 24-hour rainfall accumulation from 1200 UTC 29 September 2009 to 1200 UTC 30 September 2009 (top image). This shows a peak in the coastal region near the Gulf of Tonkin. However, the TRMM analysis for the same period (bottom image) shows the peak in western Cambodia. This model behaviour is currently under investigation. For the purpose of this paper, it is interesting to see the results from a 12 km and a 4 km resolution regional model simulation of this period (Figure 11). These forecasts were run from reconfiguration of the global analysis – i.e. no data assimilation of their own. A comparison with the global model forecasts suggests that they exhibit the same error in the positioning of the rainfall accumulations, but are simply upscaled as a result of the higher resolution. This suggests that whilst a higher resolution model gives more fine detail, it does little to mitigate the impact of systematic model errors that are present in all configurations of the MetUM.

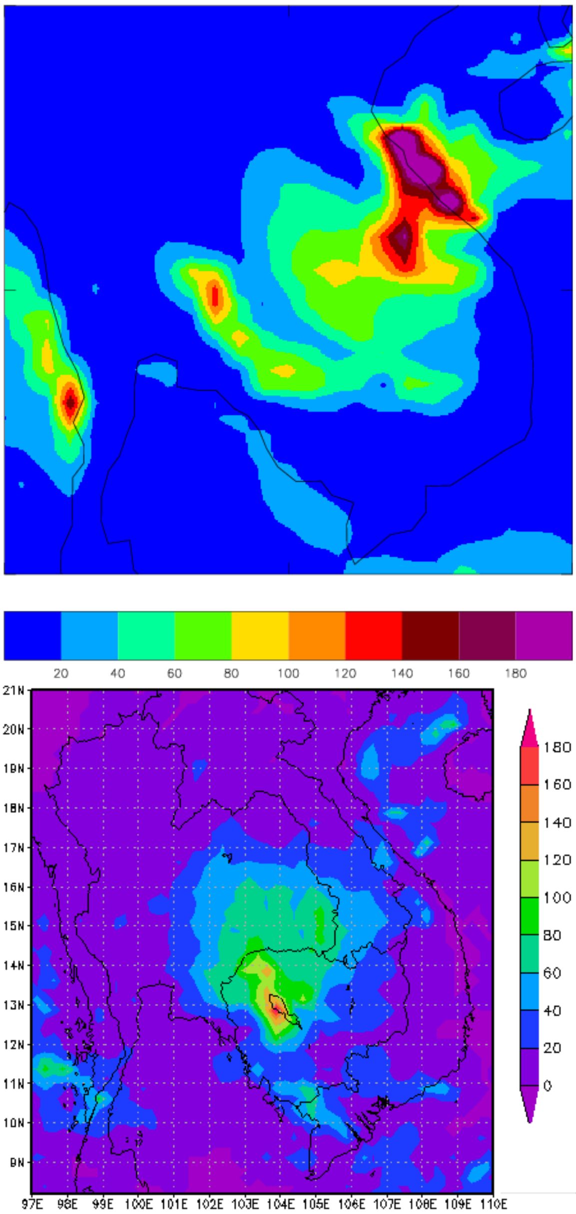

Figure 10. 24-hour rainfall accumulation 1200 UTC 29 September 2009 to 1200 UTC 30 September 2009. Global model prediction (top) and TRMM analysis (bottom)

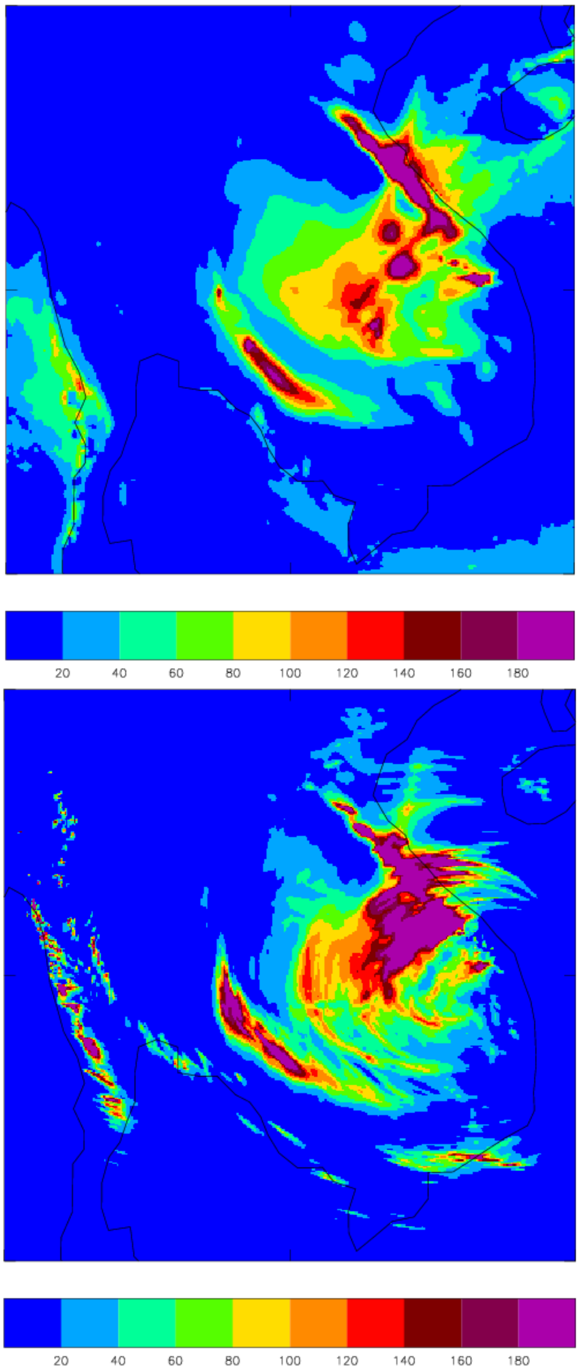

Figure 11. 24-hour rainfall accumulation 1200 UTC 29 September 2009 to 1200 UTC 30 September 2009. 12 km regional model prediction (top) and 4 km regional model prediction (bottom)

3. RECENT RESOLUTION CHANGES

3.1 70 Level 40 km Global Model

The first part of a resolution upgrade to the global configuration of the MetUM was to increase the number of vertical levels from 50 to 70 in November 2009. The majority of the extra levels were within the troposphere to enable better representation of weather features. However, the model lid was also raised from 63 km to 80 km to capture more of the stratosphere and mesosphere. Changes to the various configurations of Met Office models are normally carried out every three or four months. This inevitably means that changes developed from different areas of research are packaged together for implementation at the same time. On this occasion, the change to vertical resolution was packaged with a variety of other changes to the data assimilation and model physics and dynamics. The results of two month-long trials showed a positive impact on many area-based measures of forecast accuracy. This included a 5-10% reduction in RMS wind errors in the tropics. However, these trial periods did not include any significant periods of tropical cyclone activity. It was only once the package of changes was put under final trial in September 2009 that it became apparent that it was causing a systematic loss in intensity of tropical cyclones as well as having a negative impact on track forecasts.

The physics changes within this package included a reduction in convective entrainment, an increase in detrainment and an increase in convective momentum transport at upper levels. Investigation showed that these changes in particular were the biggest contributory factor in the weakening of tropical cyclones, although it was also found that they had a positive impact on tropical winds and precipitation. Adjustments to these aspects of the package to bring them closer to the operational MetUM configuration were made such that the reduction in tropical cyclone intensity was not so large, whilst the positive impact of the package on global verification scores was not reduced by an unacceptable amount.

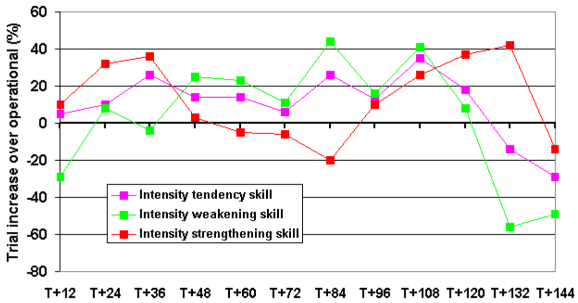

Figure 12. Difference in skill scores for tropical cyclone strengthening, weakening and tendency between the 70 level model trial and the operational model (October-November 2009). Positive values indicate the trial results were better than operational

In most cases, any loss in intensity of tropical cyclones in the model forecast would be considered as a negative impact since a model of 40 km resolution will only rarely be able to represent the true intensity of a tropical cyclone. However, it could be argued that some loss in absolute intensity is worth undergoing if it results in a more realistic representation of physical processes in the model as was intended with this package of changes. In this case, despite a systematic loss in absolute intensity as a result of the package of changes, the intensity tendency was actually improved at most lead times as can be seen in Figure 12. This suggests the revised model is better able to predict the strengthening and weakening phases of the tropical cyclone's evolution.

3.2 70 Level 12 km South Asia Model

In March 2010, the South Asia model resolution was increased from 17 km 38 levels to 12 km 70 levels. In addition to the resolution changes, the same physics changes were implemented as in the global model and described in the section above. It was only possible to evaluate the performance in one weak tropical storm during trials and this showed a consistently weaker storm – a similar result to that seen in global trials of the same package.

Although little can be concluded from one case, it was noted that the peak rainfall rates in the trial were lower and closer to TRMM values and the trial showed a much reduced spin up in intensity than the operational run in the first 24 hours of the forecast. If this change was systematic then it would address the known problem of model spin up described in section 2.3 above, despite the fact that absolute values of intensity were reduced as a result of the change. Further evaluations will be undertaken during periods of cyclonic activity in 2010.

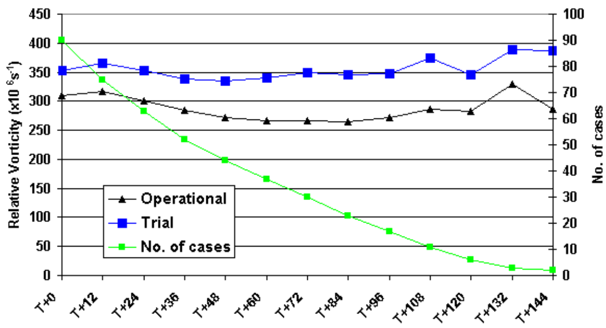

Figure 13. Mean tropical cyclone intensity (as measured by 850 hPa relative vorticity); December 2009 to February 2010. Black: operational 40 km resolution global model. Blue: trial 25 km resolution global model.

3.3 70 Level 25 km Global Model

The second part of the global model resolution upgrade was completed in March 2010 with the increase in horizontal resolution from approximately 40 km to 25 km. As with the change to 70 levels, other changes were included in this package, such as the use of AMSU-A and IASI satellite data in cloudy areas. Trials of the change indicated a small positive impact overall on tropical cyclone track forecasts and a systematic modest increase in tropical cyclone strength as shown in Figure 13. In fact at short lead times the increase in strength effectively recovers the loss of strength seen following the introduction of the previous package of changes described in 3.1 above. At longer lead times the strength of tropical cyclones was actually greater than seen prior to the implementation of this previous package of changes. From an examination of a number of cases from the trial, this manifests itself in a reduction in central pressure of tropical cyclones of up to 3 hPa and an increase in 10m wind strength of up to 3 knots. These are modest changes and show that, as illustrated in section 2.1 above, a much higher model resolution is required to represent the true intensity of most tropical cyclones.

4. FUTURE PLANS

A further increase in computing power at the Met Office is expected to become available by 2012 at which time the global MetUM resolution may be increased further – possibly to 20 km or 17 km. Furthermore, the Met Office is currently collaborating with several other meteorological services around the world that are running their own versions of the MetUM. Some of these (such as the Bureau of Meteorology, Australia) have a particular interest in regional modelling in the tropics and will be developing versions of the MetUM to run at resolutions as high as 5 km. This will provide a useful insight into the capabilities of the MetUM to represent some of the smaller scale processes within tropical cyclones.

5. CONCLUSIONS

An evaluation has been made of the impact of model resolution on tropical cyclone prediction from various configurations of the MetUM. The main (unsurprising) conclusion is that a higher model horizontal resolution results in tropical cyclones that are systematically stronger. However, results from a 17 km resolution regional model show that a more realistic representation of absolute intensity is achieved through an unrealistic spin up of tropical cyclones through the forecast. In the few cases where changing model resolution alone was evaluated the results indicated that any model deficiencies at the lower resolution are simply upscaled at the higher resolution. Most experiments evaluated here were not ‘clean’, in the sense that only the impact of resolution was tested. Whilst resolution is clearly an important factor in the prediction of tropical cyclone intensity in particular, other aspects of the model such as data assimilation techniques and the modelling of physical processes are equally important where the processes are still parametrized. The impact of resolution on MetUM predictions of tropical cyclones will continue to be evaluated through planned model upgrades and collaborative projects in the coming years.

6. ACKNOWLEDGEMENTS

Some of the regional model configurations of the MetUM referred to in this paper were set up and run by Glenn Greed and Mark Weeks. Thanks to Sean Milton for comments on a first draft of this paper.

7. REFERENCES

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