8B.1

The Impact of Recently Implemented and Planned Changes to the Met Office Global Model on Tropical Cyclone Performance

Julian T. Heming * and Michael Vellinga
Met Office, Exeter, UK

1. MODEL UPGRADE AND NEW INITIALIZATION TECHNIQUE

In 2014 and 2015 two changes were made to the Met Office Global Model (MOGM) which had a significant impact on tropical cyclone (TC) predictions. Global Atmosphere 6 (GA6) (Walters *et al*., 2017), implemented in July 2014 included changes to the MOGM dynamical core, physics and horizontal resolution and improved satellite data usage. In February 2015 a new technique for initialization of TCs was introduced using TC warning centre estimates of central pressure. The combined impact of these changes resulted in significant improvement in the MOGM's predictions of both TC track and intensity (Heming, 2016).

During the northern hemisphere season in 2016 the MOGM continued to perform well. Track forecast errors were at their lowest ever (in verification dating back to 1988) at most lead times. There was a small weak bias in the analysis and short lead times (as measured by central pressure) reducing to near zero by the end of the forecast (168 hours).

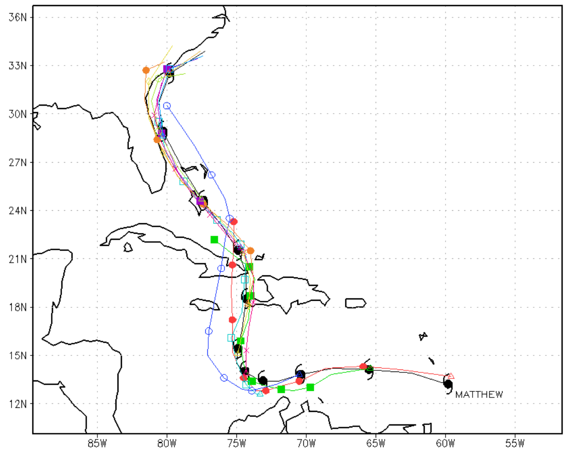

Figure 1.
MOGM forecast tracks for Hurricane Matthew. Forecasts starting from 1200 UTC only shown. Symbols 24 hours apart.

The most noteworthy TC of the season was Hurricane Matthew which caused many deaths and damage to buildings across the Greater Antilles, the Bahamas and south-eastern USA (Stewart, 2017). From a track forecasting perspective, the critical periods were the sharp turn northwards whilst Matthew was located in the Caribbean Sea and the bend towards the north-west after crossing Haiti and Cuba. The MOGM did particularly well at predicting the latter turn of Matthew and thus signalled the potential threat to the south-eastern USA at an earlier stage than some other models. Figure 1 shows all MOGM forecast tracks out to 168 hours ahead from start time 1200 UTC. Most forecasts show tracks close to that observed. Data produced by the National Hurricane Center (personal communication) indicated that the MOGM was the best performing guidance for Hurricane Matthew from lead time 48 hours and longer as shown in Figure 2.

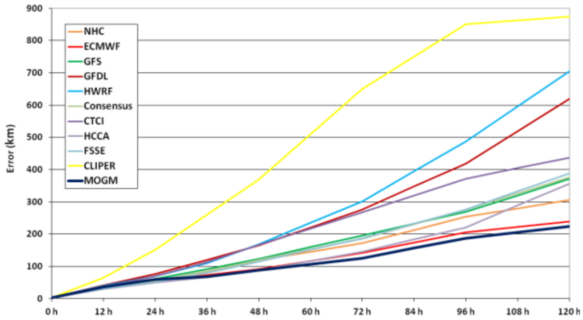

Figure 2.
Track forecast errors for Hurricane Matthew. Produced by the National Hurricane Center.

2. INCREASED HORIZONTAL RESOLUTION

The MOGM horizontal resolution was increased as part of the GA6 package of changes implemented in 2014. The grid spacing was set to approximately 26 km × 17 km at the equator (known as N768). In 2017, another increase in horizontal resolution was put under trial and assessed against the N768 resolution model. The new grid spacing was approximately 16 km × 10 km at the equator (known as N1280).

2.1 Trial Results

Hindcast trials were conducted for the periods January-March 2016 and July-October 2016. The results showed a reduction of 3.0% in track forecast errors. However, the largest impact was seen in intensity. The N768 MOGM had a weak bias in central pressure of 6 hPa in the analysis which rose to 8 hPa in the forecast before dropping back to 6 hPa at longer lead times. The N1280 MOGM had a much smaller weak bias in the analysis, which reduced in the forecast and reversed to became a strong bias from 60 hours into the forecast onwards, reaching over 4 hPa by 168 hours. This is shown in Figure 3. The over-deepening bias at longer lead times is illustrated in the time series of central pressure predictions for Typhoon Lionrock shown in Figure 4. One N1280 MOGM forecast achieved a central pressure of 884 hPa when the verifying observation (from the Japan Meteorological Agency real-time analysis) was about 60 hPa higher. This occurred during the period when the typhoon was very slow moving and would have produced upwelling of cooler waters beneath the ocean surface. It is likely that the lack of ocean coupling in the MOGM in this case resulted in too strong a heat flux and over-deepening

* Corresponding author address: Julian T. Heming, Met Office, FitzRoy Road, Exeter, Devon, EX1 3PB, UK; email: julian.heming@metoffice.gov.uk

of the TC. In similar cases to this in the past a weak bias due to the relatively low resolution of the model would have offset this over-deepening due to lack of ocean coupling, but at N1280 resolution this is no longer the case. The impact of coupling the model to the ocean is discussed further in Section 3.

It should be noted that whilst there was an over-deepening bias in the N1280 MOGM as measured by central pressure, forecast 10m winds were still too low at high wind speeds as shown in the wind-pressure scatter plot for the trial period in Figure 5. The weak bias in winds is discussed further in Section 4.

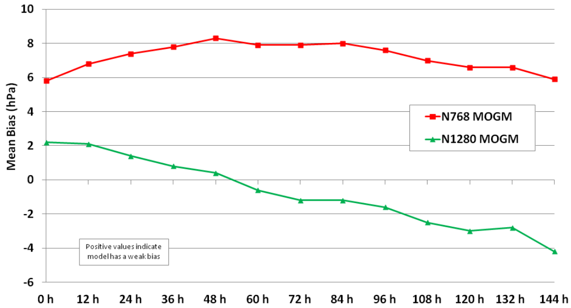

Figure 3.
TC central pressure bias. N768 MOGM (red), N1280 MOGM (green).

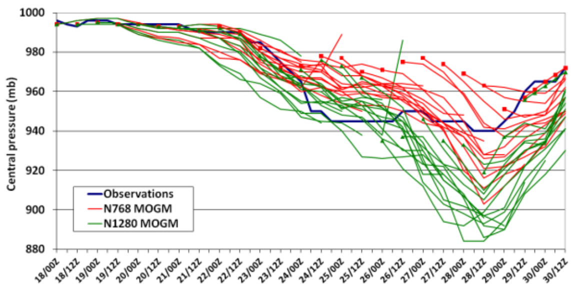

Figure 4.
TC central pressure predictions for Typhoon Lionrock (August 2016).
N768 MOGM (red), N1280 MOGM (green), observations (blue).

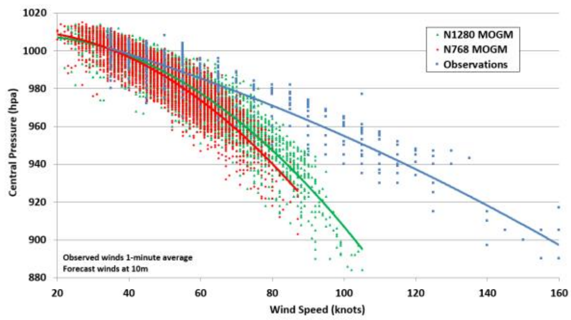

Figure 5.
TC wind-pressure scatter plot.
N768 MOGM (red), N1280 MOGM (green), observations (blue).

2.2 Performance since implementation

The N1280 MOGM was implemented in July 2017. Thus it was operational during the peak of the active Atlantic hurricane season including the three most notorious hurricanes of the season Harvey, Irma and Maria.

Having degenerated into a tropical wave in the Caribbean Sea, Harvey made a dramatic comeback in the Gulf of Mexico, strengthening from a tropical depression to a category 4 hurricane within 60 hours. Although in general the MOGM is not good at predicting rapid intensification of TCs, in the case of Harvey the rapid intensification was well signalled, if at a slightly slower rate and not quite to the intensity that actually occurred. For example, between 1200 UTC 23 August and 0000 UTC 26 August (60 hours) Harvey deepened from 1006 hPa to 941 hPa. Starting from the same time the MOGM predicted a deepening from 1007 hPa to 950 hPa in the slightly longer time of 72 hours. A time series of forecast central pressure from the MOGM can be seen in Figure 6.

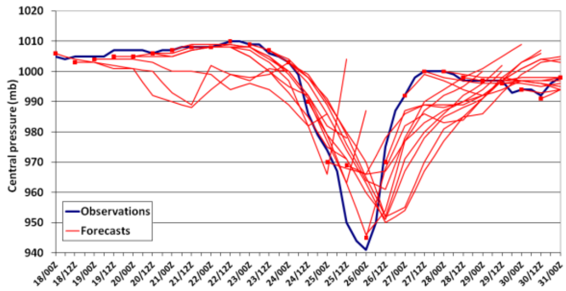

Figure 6.
TC central pressure predictions for Hurricane Harvey (August 2017).
MOGM forecasts (red), observations (blue).

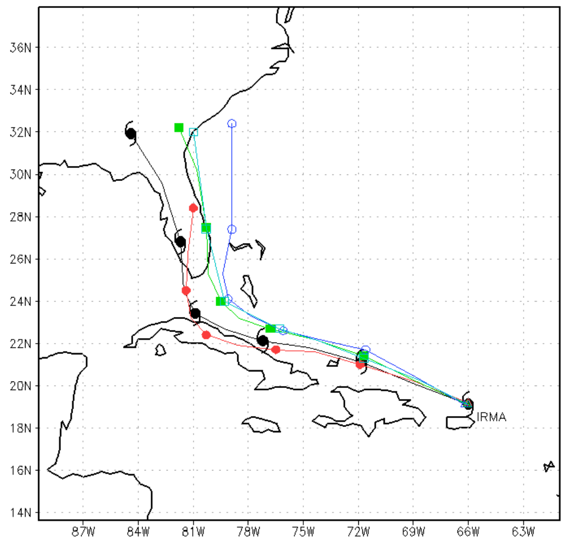

Figure 7.
Forecast tracks of Hurricane Irma from data time 0000 UTC 7 September 2017.
Symbols 24 hours apart. MOGM (red), ECMWF (green), GFS (dark blue), NHC (light blue), observed (black).

Having devastated parts of the eastern Caribbean as a category 5 hurricane, the critical forecasting problem later in the life of Hurricane Irma was the timing of the turn northwards. Initially most model guidance suggested this would happen further east than actually occurred resulting in either a track along the east coast of Florida or staying out to sea. The MOGM was one of the first models to suggest a more westwards track and landfall on the west coast of Florida as shown in the forecast tracks from 0000 UTC 07 September shown in Figure 7. However, it is noticeable that MOGM did have a slow bias, meaning that landfall, although in the correct location, was about 18 hours later than actually occurred. A convection permitting regional ensemble forecast system that was run at the time at the Met Office performed much better for the timing of landfall and is discussed in Paper 5D.3 (Webster *et al*., 2018) at this meeting.

Hurricane Maria was noteworthy for its rapid intensification from a tropical depression to a category 5 hurricane in 60 hours. The MOGM did not predict the rapid intensification well in the lead up to landfall over the eastern Caribbean and Puerto Rico. However, the MOGM tended to over-deepen Maria as measured by central pressure in the period after Puerto Rico landfall as shown in Figure 8. The convection permitting regional ensemble forecast system mentioned above in relation to Hurricane Irma again performed better than the MOGM, this time with respect to capturing the rapid intensification. Paper 5D.3 (Webster *et al*., 2018) contains further details.

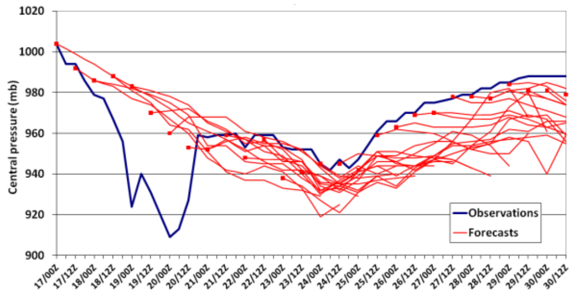

Figure 8.
TC central pressure predictions for Hurricane Maria (September 2017).
MOGM forecasts (red), observations (blue).

3. ATMOSPHERE-OCEAN COUPLED NUMERICAL WEATHER PREDICTION MODEL

The Met Office plans to implement an atmosphere-ocean coupled version of the MOGM in 2020. The main impact on TC prediction is expected to be weaker TCs in cases where a) the TC is slow moving, thus allowing a greater impact from upwelling of cooler waters and b) in the subtropics where the warm mixed layer of the ocean is shallower.

3.1 Near real-time trial performance

Since July 2017 a coupled atmosphere-ocean version of the MOGM has been under trial in near real time. One forecast per day is run by coupling the N1280 MOGM to the NEMO ORCA025 ocean model version GO5 (Megann *et al*., 2014). Apart from coupling to the ocean, the only difference between the Coupled MOGM and Operational (atmosphere only) MOGM is that the Coupled MOGM has 85 vertical levels. The Operational MOGM has 70 levels. The Coupled MOGM is initialised every 24 hours from operational atmosphere (UM) and ocean/sea ice (FOAM) analyses. i.e. no coupled data assimilation.

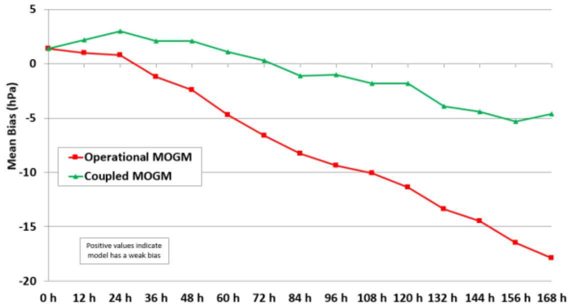

Figure 9.
Central pressure bias for Operational MOGM (red) and Coupled MOGM (green).
July 2017 to March 2018.

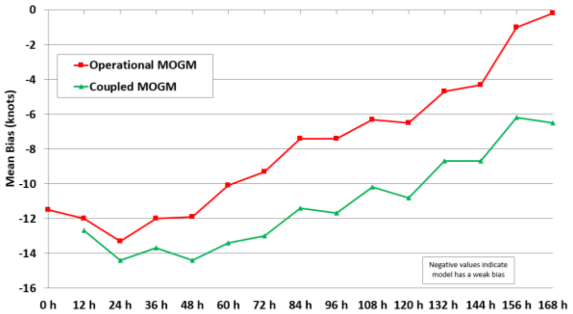

Figure 10.
10m wind bias for Operational MOGM (red) and Coupled MOGM (green).
July 2017 to March 2018.

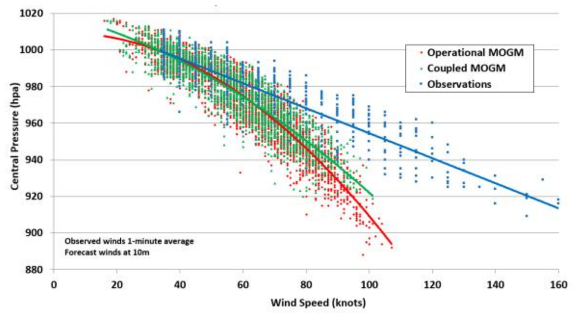

Figure 11.
TC wind-pressure scatter plot.
Operational MOGM (red), Coupled MOGM (green), observations (blue).
July 2017 to March 2018.

For the period July 2017 to March 2018 the Coupled MOGM TC forecast track errors were 2.1% lower than the Operational MOGM. However, as expected, the largest differences were seen in intensity forecasts. Operational MOGM forecasts had a marked tendency to over-deepen TCs (as measured by central pressure) by an increasing amount with increasing lead time. However, this over-deepening bias was much reduced in the Coupled MOGM as shown in Figure 9. The downside of this was that the low bias in TC maximum 10m wind speed was made worse in the Coupled MOGM (Figure 10). The wind-pressure scatter plot (Figure 11) shows that the Coupled

MOGM eradicated the excessively low central pressures seen in the Operational MOGM, whilst there was also a reduction in the highest wind speeds. Overall, the wind-pressure relationship was slightly improved.

3.2 Typhoon Noru

One case that encapsulates the impact of the Coupled MOGM on TC forecasts is Typhoon Noru in the western North Pacific which was active in July/August 2017. Early in its life, Noru moved in an anti-clockwise loop in the latitude band 25-30°N. Intensification was temporarily halted as the TC retraced its previous track, passing over its own wake. It then dipped southwards and rapidly intensified reaching its peak intensity (1-minute average winds 140 knots, central pressure 930 hPa). Noru then turned to the north-west and started slowly weakening as it recurved just south of Japan before accelerating into the mid-latitudes. The observed track and central pressures are shown in Figure 12.

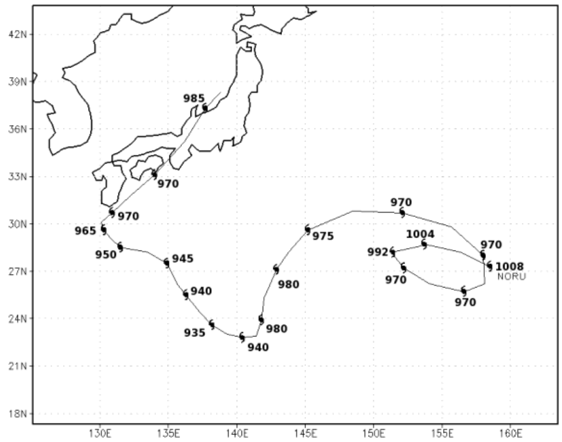

Figure 12.
Observed track and central pressures (hPa) of Typhoon Noru in July 2017.

Figure 13 shows the time series of central pressure predictions from the Operational MOGM and Coupled MOGM. During the first phase of Noru's life (21-30 July), the Operational MOGM over-deepened the TC by as much as 57 hPa. Although there was some over-deepening in the Coupled MOGM runs, it was by far less than the Operational MOGM. The rapid intensification phase (30 July – 01 August) was captured better by the Operational MOGM. However, the third stage (02 - 07 August) again saw over-deepening in the Operational MOGM this time by as much as 82 hPa. The Coupled MOGM predicted central pressures much closer to observations and was different to the Operational MOGM by as much as 68 hPa in the 168-hour forecast from data time 0000 UTC 29 July. Figure 14 shows the wake in the sea surface temperature (SST) for this case. The left hand panel shows the difference between the daily mean OSTIA analyses of foundation SST (Donlon *et al*., 2012) from 5 August and 29 July (168 hours apart). The right hand panel shows the difference between the Coupled MOGM 168-hour SST forecast valid on 5 August and the analysed SST on 29 July. The SST cooled by over 4°C in the Coupled MOGM run which would have contributed to the much lower rate of deepening than in the Operational MOGM which would have had a constant SST throughout the forecast. The wake in the Coupled MOGM is stronger than seen in OSTIA, notwithstanding the weak wind bias in the model. While this may point to errors in the model's heat budget of the upper-ocean it is also important to consider error estimates for the OSTIA analyses in the presence of strong cloud cover.

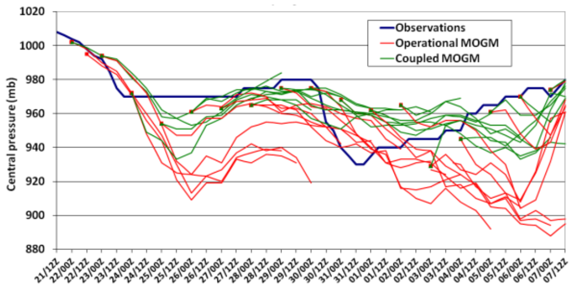

Figure 13.
TC central pressure predictions for Typhoon Noru (July-August 2017).
Operational MOGM (red), Coupled MOGM (green), observations (blue).

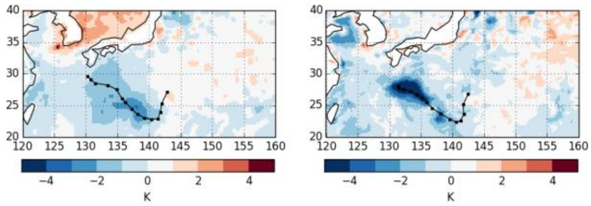

Figure 14.
Observed SST reduction in OSTIA between 29 July and 5 August 2017 (left).
Coupled MOGM forecast SST reduction for the same period (right).

4. ADDRESSING THE WIND-PRESSURE RELATIONSHIP BIAS

Prior to the introduction of GA6 in 2014, TCs were relatively weak in the MOGM with 10m winds rarely exceeding hurricane strength (64 knots) even for the strongest TCs. However, the introduction of the more energetic GA6 model in 2014 and two increases in horizontal resolution in 2014 and 2017 have resulted in much stronger TCs in MOGM predictions. Figure 15 shows the wind-pressure scatter plot for all MOGM forecasts in 2013 and 2017, which illustrates the change in MOGM TC intensity characteristics. Although MOGM forecast central pressures are now often lower than observed (on occasions below 900 hPa), 10m wind speeds still rarely exceed 100 knots, whilst in reality 1-minute average winds sometimes exceed 150 knots. Caution must be exercised comparing 1-minute average winds from TC warning centre advisories with model 10m winds as the latter are instantaneous model values and thus we would not necessarily expect them to exactly correspond to the warning centre values. Notwithstanding this, there is still clearly a weak bias in model maximum 10m winds compared to forecast TC central pressure.

This bias in the wind-pressure relationship in the MOGM is similar to that seen in a higher resolution regional configuration of the Met Office Unified Model run over the Philippines region for several years. Short and Petch (2018) found that this bias in the Philippines model was in part due the model's drag coefficient over the ocean increasing with wind speed. Theoretical and experimental studies suggest that at wind speeds above about 65 knots the drag coefficient remains constant or even decreases with wind speed (Donelan *et al*., 2004, Soloviev *et al*., 2014). Given that the MOGM is now able to simulate near surface wind speeds of up to 100 knots, this false assumption in the boundary layer scheme may be contributing to the bias in the wind-pressure relationship shown earlier in Figure 5. As a first attempt at addressing this, a change similar to that tested by Short and Petch (2018) was applied to the MOGM; the drag coefficient was held constant over the ocean for wind speeds above approximately 65 knots.

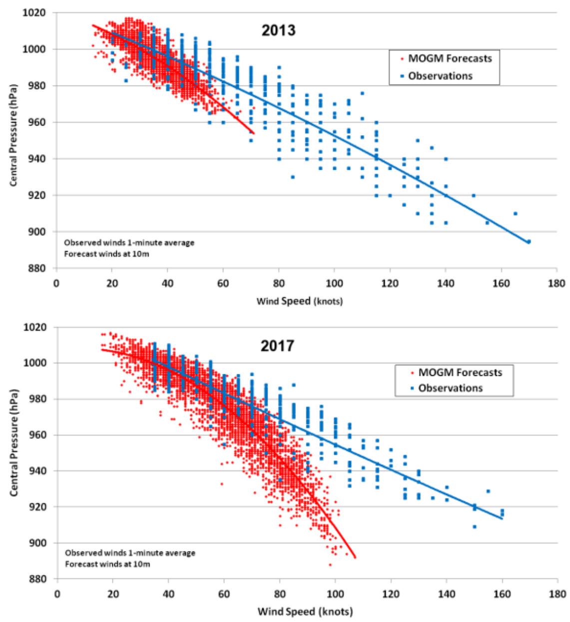

Figure 15.
TC wind-pressure scatter plot. MOGM (red), observations (blue).
2013 (top), 2017 (bottom).

Initial case study trials of capping the drag coefficient for high wind speeds showed promising results with peak wind speeds around TCs and intense mid-latitude depressions increased without change to the central pressure. Thus a longer continuous trial of eight weeks was run covering the period in September 2017 which included several intense TCs which had winds well in excess of 100 knots such as Hurricanes Irma, Jose and Maria and Typhoon Talim. Results contain many cases where TC maximum 10m winds are increased by at least 10 knots and as high as 18 knots with no change in central pressure. For example, Figure 16 shows 96-hour forecasts from data time 0000 UTC 18 September for Hurricane Maria after it had crossed Puerto Rico. The Control forecast (close to current operational configuration) had a central pressure of 951 hPa and a maximum 10m wind of 80 knots. The Trial Model (with capped drag coefficient) had an identical central pressure, but peak wind speeds of 91 knots. The observed intensity at that time was 953 hPa and 110 knots (1-minute average winds).

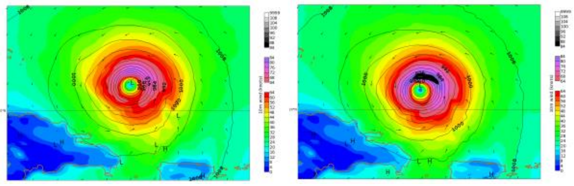

Figure 16.
Hurricane Maria 96-hour forecast from date time 0000 UTC 18 September 2017.
MSLP contours and 10m wind shading. Control (left), Trial with capped drag coefficient (right).

Figure 17 shows the wind-pressure scatter plot for the whole trial period. This indicates a marked shift in the profile in the Trial closer to the observed relationship. Much stronger winds were forecast in the Trial, but with little change in the central pressure. Area based verification metrics indicate there is no detrimental impact to model predictions beyond the immediate vicinity of TCs. Furthermore, a configuration which reduces the drag coefficient at high wind speeds (rather than just capping it) is also being tested. With continued positive results it is likely that one of the revised configurations will be implemented in the MOGM in 2019.

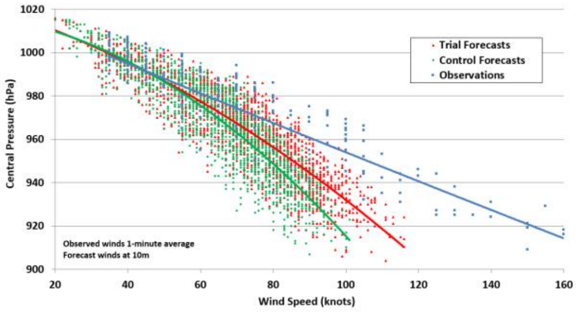

Figure 17.
TC wind-pressure scatter plot.
Control MOGM (red), Trial MOGM with capped drag coefficient (green), observations (blue).
29 August – 23 October 2017.

5. SUMMARY

Following the implementation of the GA6 configuration of the MOGM in 2014, which included changes to the model dynamical core, physics and horizontal resolution and a new form of TC initialisation in 2015, the MOGM performed well in 2016 for TC track predictions and was much better than the previous model configuration for TC intensity predictions. Track forecasts for Hurricane Matthew were particularly good.

In 2017 the MOGM horizontal resolution was increased again. Track forecast errors were reduced in trials and the previous weak bias was considerably reduced. Longer lead time forecasts of TCs from the MOGM are now often too strong (as measured by central pressure). However, 10m winds are still too weak, which is evidence of a bias in the wind-pressure relationship.

Near real-time trials of an atmosphere-ocean coupled version of the MOGM have shown some promising results. Over-deepening which occurs in some cases of slow moving TCs, those which move over their previous track or those in the subtropics is markedly reduced in the coupled MOGM. Operational implementation is planned for 2020.

Recent model changes have revealed a bias in the MOGM's wind-pressure relationship for TCs. Experiments to cap the drag coefficient in the model at higher wind speeds have shown positive results by increasing forecast 10m winds for strong TCs without reducing the central pressure further. If trials results continue to be positive, operational implementation could take place in 2019.

This paper has summarised the impact on TC forecasts of some of the recent changes to the MOGM and provides first results of trials of further model enhancements expected to become operational in the next two years.

6. REFERENCES

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown, and E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophys. Res. Lett*., **31**, L18306. https://doi.org/10.1029/2004GL019460.

Donlon, C.J., M. Martin, J. D. Stark, J. Roberts-Jones, E. Fiedler and W. Wimmer 2012: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA). *Rem. Sens. Env*., **116**, 140-158. https://doi.org/10.1016/j.rse.2010.10.017.

Heming, J.T., 2016: Met Office Unified Model tropical cyclone performance following major changes to the initialization scheme and a model upgrade. *Wea. Forecasting,* **31**, 1433-1449. https://doi.org/10.1175/WAF-D-16-0040.1.

Megann, A., D. Storkey, Y. Aksenov, S. Alderson, D. Calvert, T. Graham, P. Hyder, J. Siddorn and B. Sinha: GO5.0: the joint NERC–Met Office NEMO global ocean model for use in coupled and forced applications. *Geosci. Model Dev*., **7**, 1069–1092. https://doi.org/10.5194/gmd-7-1069-2014.

Short, C.J. and J.Petch, 2018: How well can the Met Office Unified Model forecast tropical cyclones in the Western North Pacific? *Wea. Forecasting*, **33**, 185-201. https://doi.org/10.1175/WAF-D-17-0069.1.

Soloviev, A. V., R. Lukas, M. A. Donelan, B. K. Haus, and I. Ginis, 2014: The air–sea interface and surface stress under tropical cyclones. *Sci. Rep*., **4**, 5306. https://doi.org/10.1038/srep05306.

Stewart, S.R., 2017: National Hurricane Center Report: Hurricane Matthew (AL142016). National Hurricane Center, Miami, USA. https://www.nhc.noaa.gov/data/tcr/AL142016_Matthew.pdf.

Walters, D.N. and Coauthors, 2017: The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. *Geosci. Model Dev*., **10**, 1487-1520. https://doi.org/10.5194/gmd-10-1487-2017.

Webster, S., H.A. Titley and C. Short, 2018: Experimental convection permitting ensemble forecasts for Hurricanes Irma and Maria using the Met Office Unified Model. *American Meteorological Society 33rd Conference on Hurricanes and Tropical Meteorology (Ponte Vedra, USA).* https://ams.confex.com/ams/33HURRICANE/webprogram/Paper340018.html.