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Record-setting performance of the ECMWF IFS in medium-range tropical cyclone track prediction

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Record-setting performance of the ECMWF IFS in medium-range tropical cyclone track prediction

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In November 2007 a number of significant changes in model physics were introduced in Cycle 32r3 (Cy32r3) of the ECMWF Integrated Forecast System (IFS), most notably a reformulation of convective entrainment. The net result was a "beneficial increase in activity" in the tropics (*ECMWF,* 2009) and such parametrization changes are known to have substantial impacts on forecast skill in the convectively-forced components of the tropical circulation and tropical cyclones (TCs) in particular.

The primary forecast aid in operational TC track forecasting is consensus, produced from an ensemble of quasi-independent deterministic model runs. Since Cy32r3, ECMWF's TC track forecasts at the medium-range (72 hours or day 3) have been ~20% *better* than model consensus globally. No individual model has ever consistently out-performed *consensus* by such a large margin. If this skill gain continues, it would mark a major breakthrough in TC track prediction, greater than the 100% improvement in official forecasts from the mid 1990s to 2008 that came from advanced global models.

This article reviews:

- The relationship between model physics, TC analysis and forecasts and the tropical general circulation.
- Dynamical medium-range TC track prediction and the role of multi-model consensus.

Some personal views about the implication of these results for medium-range TC track prediction are given in the conclusion, as the primary objective of the study was to better understand the critical modelling factors.

Tropical large-scale flow, TCs and model changes

Tropical cyclones are not only the greatest high-impact weather event in the tropics, but can be an excellent indicator of general model performance.

For example, one of the more remarkable results from the first ECMWF reanalysis (ERA-15) was the strong dependence of the analysis of TCs on the model, rather than the observations as shown in Figure 1 taken from *Serrano* (1998). The ERA-15 analysis consistently detects about 85% of observed TCs from 1979-1994, but the operational ECMWF model only reaches that detection rate in 1989. The primary difference between the operational and ERA-15 analysis is the model and data assimilation scheme, as the reanalysis used essentially the same observations as in operations. The poor quality of the operational model analysis of TCs was not caused by insufficient observations, but by the modelling.

Next consider changes in the standard ECMWF tropical wind forecast skill score for the period 1980-2008 shown in Figure 2. Comparing this smoothed time series (red line) to TC detection in operations (light blue line in Figure 1), we see a strong correlation between TC detection and the 850 hPa tropical wind forecast score (*ECMWF,* 2008). Similar correlations have been found in the NCEP-NCAR reanalysis and in the second ECMWF reanalysis, ERA-40 (*Uppala et al.,* 2005).

A detailed review of model changes (not given here) suggests that the big jump in tropical forecast skill in 1989 was not due to resolution increases, but more likely from the use of a mass-flux cumulus convection scheme.

Another important feature in Figure 2 is the near 100% improvement in the score from four days in 1995 to seven days in 2005. This improvement can be attributed to the implementation of 3D-Var and 4D-Var in the mid 1990s and general model development, i.e. steady improvements in global numerical weather prediction (NWP). By 2004, the ECMWF deterministic TC track predictions became competitive with the best models of the day, both for global (UK Met Office, NOGAPS and NCEP GFS) and limited-area (GFDL) models, as demonstrated for the Atlantic in Figure 3. Details about these models are given in Table 1.

The strong correlation of the tropical wind score and TC track prediction has also been found with other models and in the reanalyses. This correlation is consistent with our understanding of the dynamics of tropical cyclone motion (*Fiorino & Elsberry,* 1989) and its dependence on the global/large scales of the tropical general circulation. Not only are TCs high-amplitude weather events that challenge a model and push the physics to the limit, but TC track prediction is consistent with other measures of the quality of the large-scale tropical wind field.

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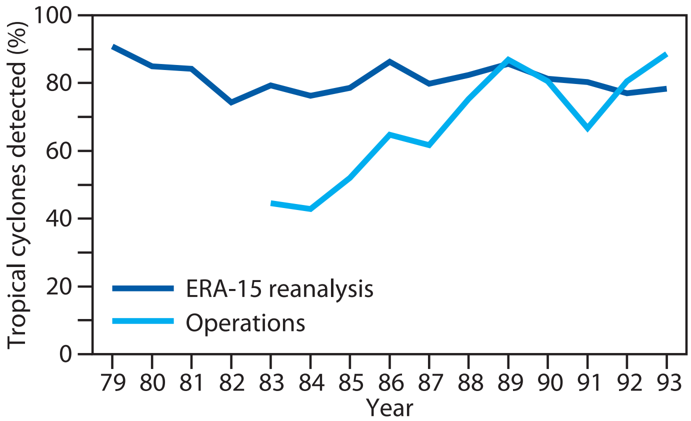

Figure 1 Detection of tropical cyclones (maximum wind > 34 knots) in the northern hemisphere for the ECMWF ERA-15 reanalysis (dark blue line) and operations (light blue line).

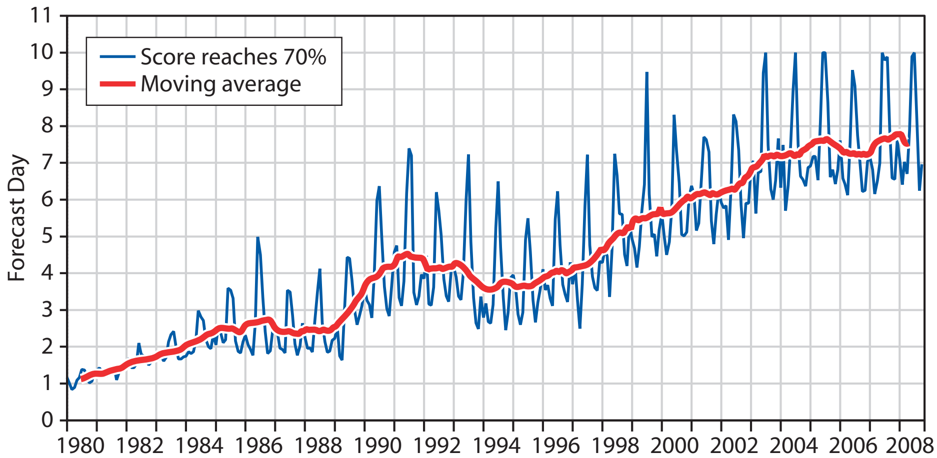

Figure 2 Tropical skill score indicating time in days when the correlation between the analyzed and forecast 850 hPa winds at 12 UTC in the tropics (20°N to 20°S) drops to 70%. Blue line is the monthly score and the red line is the 12-month moving average.

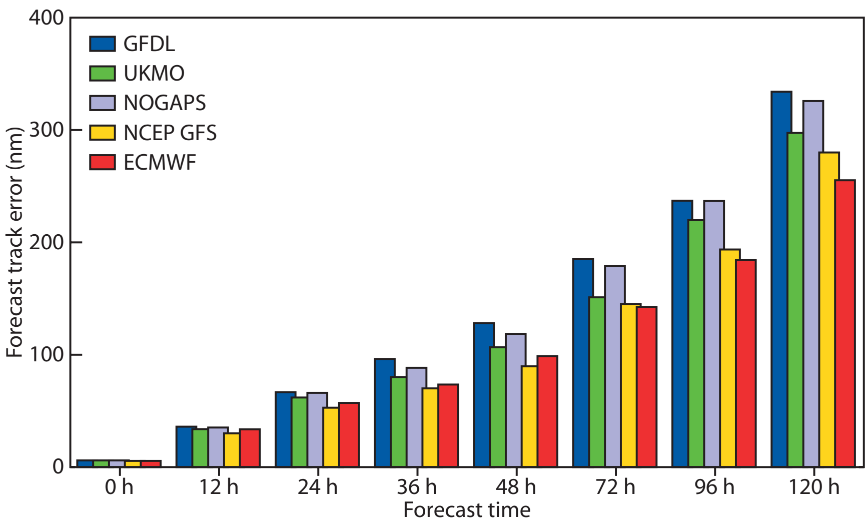

Figure 3 ECMWF track forecast error in the Atlantic basin for 2004, compared to GFDL, UKMO, NOGAPS and NCEP GFS. All raw model output has been post processed in the same way as at the US operational forecast centres. Statistics are homogeneous with ECMWF.

Source	Description
NHC or OFCL	The official track forecast made by the hurricane specialists of the National Hurricane Center (NHC), Miami, Florida, USA.
NOGAPS	US Navy global model; first formal evaluation in 1994 by Joint Typhoon Warning Center (JTWC), Pearl Harbor, Hawaii, USA. From 1992–2001 available twice daily and then four times daily from 2002-2008.
GFDL	Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model run at NCEP. Very few cases in 1992-1993 and run twice daily 1994–1999.
ECMWF	ECMWF global model, deterministic 10-day integration.
UKMO	UK Met Office Unified Model, global operational version. Available 1996-2008 in the Atlantic and 1991-2008 in western North Pacific (WPAC). Model run twice daily at 00 and 12 UTC.
NCEP GFS	US National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model.
CLIPER	CLImatology and PERsistence no-skill statistical model.
BCON	Best/Baseline model CONsensus made at the operational forecast centres.

Table 1 Description of the TC track data from NHC and various models.

Medium-range TC track prediction and multi-model consensus

The large improvement in the ECMWF tropical wind score circa 1990 also marked the beginning of a period of unprecedented gain in dynamical TC forecast skill; that resulted in a near 100% improvement in official TC track predictions from the early 1980s to early 2000s, especially at the 72-hour forecast time or the ‘medium-range’.

There are many reasons to focus on the medium range, both operational and in a modelling sense, but the main reason for concentrating on the 72-hour forecast is because of its value as a model diagnostic. Simply put, the model has to ‘get everything right’ to make a good medium-range track forecast.

By three days into the integration, the model has lost a strong connection with the initial conditions and even a perfect analysis cannot prevent intrinsic model error growth and chaos from causing significant error (~20%) in the solution. Furthermore, TCs are observed to make substantial changes in direction and speed of motion in three days. This change often results from the interaction of the vortex with mid-latitude features such as a break in the subtropical ridge. Thus, model track skill depends on both the forecast of the large-scale ‘steering’ flow and on vortex-large scale interaction that itself depends on changes in the vortex, i.e. the model has to forecast well both vortex and synoptic scales.

For global models, the dynamics of vortex/large-scale flow interaction critical to motion occurs on scales resolved by large-scale models (*Fiorino & Elsberry,* 1989). Thus, high resolution (~10–20 km) is not an *a priori* requirement for skilful medium-range TC track forecasts as indicated by the excellent performance of the global models.

Another milestone in medium-range TC track prediction was when the ECMWF tropical wind score reached seven days in 2003. This milestone coincided with the first operational application of multi-model consensus forecasting in which an ensemble of quasi-independent deterministic model runs are combined to produce a consensus forecast. While a number of schemes for combining the forecasts have been used, a simple average of the tracks has proven as successful as, or better than, more elegant approaches.

The skill of consensus depends on two key factors: (a) the degree of decorrelation of the errors between the individual models and (b) all members must have skill similar to, or close to, the best model (*Goerss,* 2000). The important result from operations is that in the mean, consensus generally has more skill than any of the individual model used in the consensus.

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Trends in the Atlantic basin

The discussion points in the preceding section are illustrated in Figure 4 where we show a time series of the annual-mean 72-hour forecast error (great circle distance between observed 'best track' position and the model forecast) for two representative 'best' models (GFDL and UKMO), CLIPER (the standard no-skill climatology and persistence aid), BCON (best/baseline multi-model consensus aid) and the official National Hurricane Center (NHC) forecast (Table 1 gives details on the models).

In the Atlantic basin, the most consistently skilful model with a long record is the GFDL hurricane model (*Bender et al.,* 2007), but before discussing the models and consensus note the variation in the error of the climatology aid CLIPER. There is a notable downward trend and an oscillation with a roughly 10-year period. A lower CLIPER error implies the hurricanes are behaving in a more climatological manner. However, the CLIPER model was updated in 2000 and the forecast extended from 72 hours to 120 hours, so that part of the change is because of the improved TC databases used in the model development. Nonetheless, there seems to be a downward trend from 2000 to 2007, but a rise in 2008. The significance of the rise is that before 2008, the model and consensus error tended to generally follow CLIPER, but in 2008 model error moved downward despite TC motion being less climatological than in previous years.

From 1992 to 1997 the GFDL model had lower error than the official NHC forecast. However, the number of cases was very small in 1992 and 1993 since the model was still experimental, but by 1995 the model had high availability to the forecasters and was run twice daily. Since 2000, the GFDL model is run at the same frequency as the official forecasts – four times daily. The larger point is not that the GFDL model 'beat' the official human forecasts, but that the model showed skill and that the forecasters were able to successfully use the guidance.

Notice how the models show more year-to-year variability until 2004 when the ECMWF tropical score reached seven days. Skill consistency is perhaps the result of the 'stability' (smaller run-to-run variability) a large observing system gives the global model. This stability is significant for the limited-area GFDL model as the global model (NCEP GFS) provides both initial and lateral boundary conditions that determine the large-scale flow in the outer grid of the GFDL model.

Another feature in Figure 4 is how both the models and the official forecast error slowly vary in a similar manner as CLIPER: rising in the early 2000s and then falling until 2007–2008. The main use of CLIPER is to measure forecast difficulty as high CLIPER errors imply that the TCs did not behave in a climatology manner for that year. If model skill did not follow CLIPER upward in 2008, then the global model analysis may have had even higher quality than in previous years.

The main point is that model and official forecast skill is much greater than CLIPER, with a clear downward trend in the error of both, and that the official forecast is slightly lower than the models. Consequently, from 1992 to 2008 the official forecast error has been cut in more than half from 294 nm (nautical miles) to 127 nm – a greater than 100% improvement. The GFDL model improvement over that time period was not as dramatic, but consensus (BCON) was better than the model and on par with the NHC forecast. Similarly, the track forecasts of the UK Met Office (UKMO) global model show a similar trend.

An alternative view of the error statistics is to calculate a percentage gain or improvement against some baseline as shown in Figure 5. The standard comparison baseline is CLIPER with positive values indicating how much better (lower) the mean forecast error is relative to the baseline (*Franklin,* 2008). The general improvement trend is less pronounced over the 17-year period, but what is more interesting is how the model and consensus are becoming even better vis-à-vis CLIPER from 2006–2008 to over 50%.

To bring the comparison into sharper focus we use the consensus aid BCON as the baseline instead of CLIPER in Figure 6. Clearly the GFDL model is not as skilful as BCON and is ~25% worse. The results from the UK Met Office model are similar to those of the GFDL model, but with much larger year-to-year swings. However, the +16% gain on BCON in 2007 is not significant because of very few cases/storms in the Atlantic for that year. Statistical significance is not addressed here as our purpose is to examine broad trends and relationships (more cases) and not to focus on year-to-year differences.

The degree of degradation varies with the model and year, but what we do not find is a model that is consistently better than consensus at 72 hours. A model can outperform consensus only if it has much lower error than its peers. That is, skill does not come from error compensation, but from better meteorology - good results for physically more-correct reasons.

The main conclusion of this review of medium-range dynamical TC track prediction is that while the models/consensus have steadily improved, no individual model or single deterministic run has ever been more than 10% better than consensus in any one year or any one basin, and on a 5–10 year time scale the individual models are typically 15–20% worse.

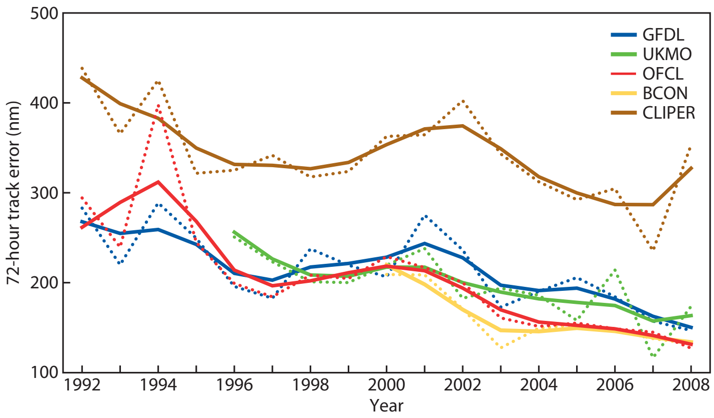

Figure 4 Medium-range (72 hour) mean forecast error in the Atlantic basin for the years 1992–2008 for: a "best" dynamical model (GFDL – blue); the UKMO global Unified Model (UKMO – green), the best/baseline consensus (BCON – yellow), the official NHC forecast (OFCL – red) and the no-skill baseline aid (CLIPER – brown). The solid line is a smoothed version of the dotted time series. The dynamical model track was post-processed to be consistent with operations and the other aids. BCON is only available from 2000 to 2008 and the statistics are homogenous with CLIPER.

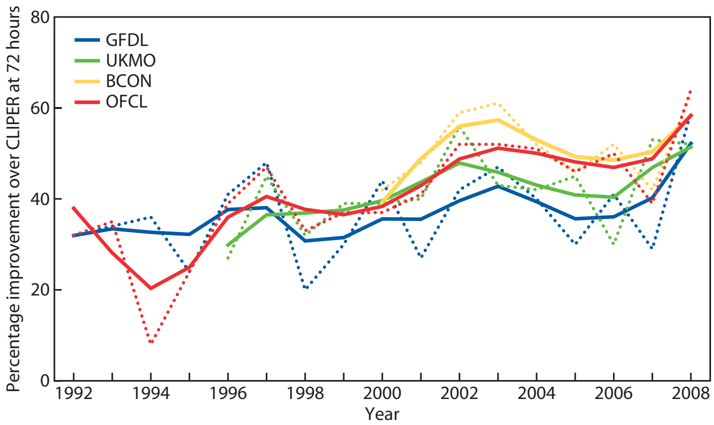

Figure 5 Gain or percentage improvement of forecast error at 72 hours of the GFDL model (blue), UK Met Office model (UKMO – green), concensus forecast (BCON – yellow) and the official NHC forecast (OFCL – red) relative to CLIPER. The solid line is a smoothed version of the dotted time series. Positive values indicate lower forecast error than CLIPER.

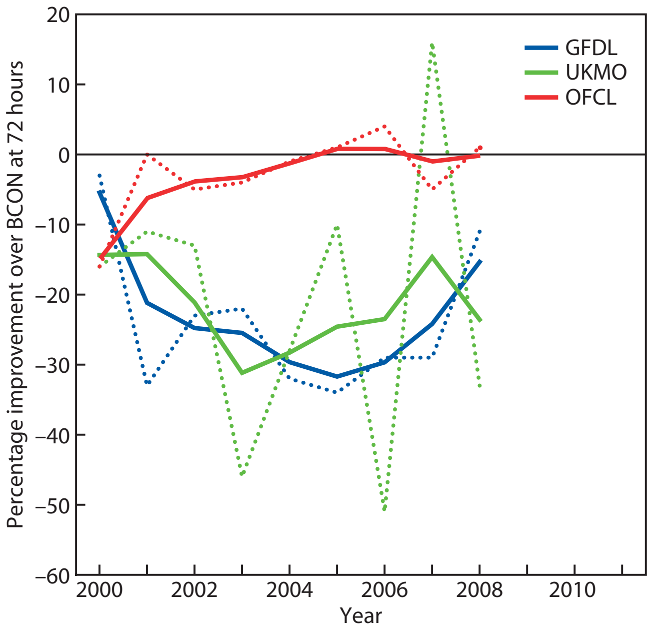

Figure 6 As in Figure 5 but for the percentage improvement of forecast error at 72 hours of the GFDL model (blue), UK Met Office model (UKMO – green) and the official NHC forecast (OFCL – red) relative to consensus (BCON). The solid line is a smoothed version of the dotted time series. Negative values indicate the aid is poorer (higher forecast error) than the baseline.

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Dependence of ECMWF track prediction skill on model changes

We now consider two recent changes to the ECMWF model that would be expected to affect TC track prediction – increased horizontal resolution and improved model physics, especially convection. In February 2006, model resolution increased from T511 to T799 or approximately from 40 km to 25 km. The second change concerns the cumulus parametrization in November 2007.

We collected about one year of TC forecasts before and after each model change to determine if there are detectable impacts on medium-range track prediction. The period between the resolution increase to T799 (February 2006) and the physics change (November 2007) is 21 months and includes two northern hemisphere TC seasons and one for the southern hemisphere. However, the number of northern hemisphere cases in this longer period is not much greater than in the one-year periods because of unusually weak TC activity in 2007. Details of the periods and model changes are given in Table 2, but note that number of verifiable model forecast at 72 hours is similar. Thus, intercomparison between the three periods is not overly biased by differences in number of cases.

The mean forecast error at the standard forecast times for the ECMWF model versus best/baseline consensus, BCON, for all TCs is given in Figure 7. The lower error for the model versus consensus after the physics change is apparent at each forecast time (i.e. compare the difference between the dark and light green bars with that between the dark and light yellow bars). However, showing relative gain makes the difference clearer as seen in Figure 8. The percentage gain/loss of the ECMWF model versus consensus is calculated in the same way as in Figures 5 and 6, but here for three versions of the ECMWF model, again for all TCs globally.

First note how the T511 version of the model was about 20–15% worse (higher mean forecast error) than BCON at all forecast times. This relationship with consensus is typical or slightly better than the best models in the Atlantic (Figure 6) that are 15–25% poorer.

The resolution increase to T799 (yellow versus red bars) shows a distinct improvement in relative skill, particularly at the medium-range, so that by 120 hours the model was on par, or better than consensus. The gains at the longer forecast times likely come from model improvements (e.g. slower error growth).

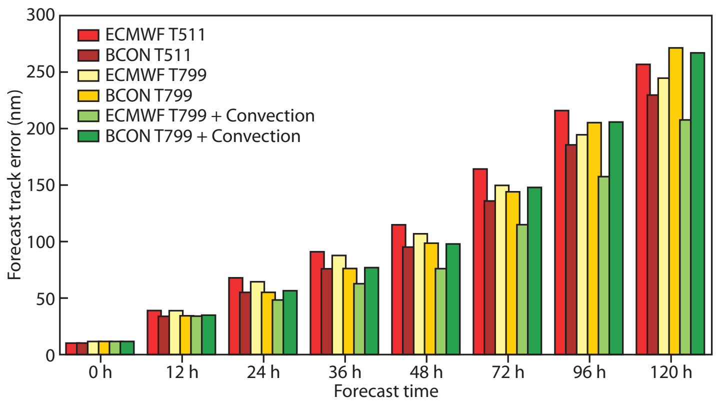

Figure 7 72-hour mean forecast error for all TCs globally for the ECMWF model and BCON for each time period for T511 (red bars), T799 (yellow bars) and T799 plus cumulus convection change (green bars).

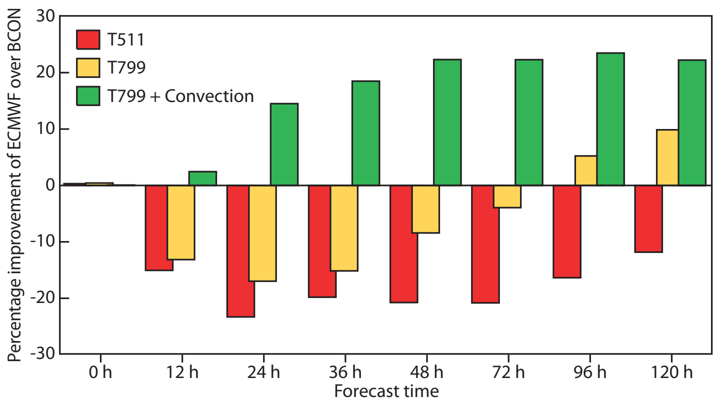

Figure 8 Percentage gain or improvement in 72-hour mean forecast error of ECMWF versus BCON for all TCs globally for T511 (red bars), T799 (yellow bars) and T799 plus cumulus convection change (green bars).

Period	Model changes	Number of cases at 72 hours
February 2005–February 2006	T511 resolution (~ 40 km)	400
February 2006–November 2007	T799 resolution (~ 25 km)	460
November 2007–January 2009	T799 resolution plus modified cumulus convection	432

Table 2 The three time periods considered and main characteristics of the ECMWF model.

The 15–20% *gain* after the physics changes in Cy32r3 (green versus yellow bars) is simply unprecedented and indicates a fundamental advancement in performance for the ECMWF model. The gains at the short-range are particularly impressive and imply an improved analysis as well as a better model.

An important requirement for successful data assimilation is small differences between high-quality observations and the model forecast background (the innovation). A model that makes a short-range forecast (typically six hours) close to these good observations will produce smaller innovations and thereby there is a higher probability the observations will make a positive contribution to the model analysis and forecasts. Simply put, the better the model, the smaller the innovations and the better the analysis/forecast, especially in the short-range (12–36 hours for TCs).

The model changes in November 2007 resulted in a fundamental improvement on scales/meteorology significant to TC track prediction, but the tropical wind score shows only a modest jump in 2007 (Figure 2). While the tropical skill measure does detect fundamental quality, the TC results suggest a more comprehensive metric is needed and that TCs measure another dimension of model skill in the tropics.

The percentage gain was also calculated separately for the Atlantic and western North Pacific (WPAC) basins, though these results are not shown. The pattern of change is similar to the global pattern of improvements at the longer forecast times with increased resolution, and the model better than consensus at all times with the physics change. However, the signal is much stronger in WPAC and even stronger in the southern hemisphere. The 20–30% gain in WPAC with the physics changes is more extreme than found globally and may be partly explained by a stronger influence of convection on the large scales in tropical WPAC.

The more muted response in the Atlantic may be a consequence of approaching an asymptote in skill as the mean 72-hour forecast error for BCON in 2008 was very low at 129 nm with the greatest-ever improvement over CLIPER at 63%. Despite these high levels of skill, the ECMWF model in 2008 achieved an even lower mean forecast error of 116 nm.

To put these statistics in perspective, consider the results from predictability studies, most notably of *Leslie et al.* (1998) where they used nonlinear systems theory and both a barotropic and baroclinic model to estimate 'inherent' predictability limits. At 72 hours all three techniques produced estimates of approximately 120 nm. There was some dependence on basin, but no more than 5%, so that the 120 nm mean forecast error is representative of a lower bound.

Leslie et al. (1998) also compared the estimates to the error of NWP models circa 1995 and found that the models were within 35–40% of the inherent limit. Clearly, this estimate is either too high or the ECMWF model is approaching the 'perfect model' as the model is performing below their limit. The weaker impact in the Atlantic is consistent with approaching a limit.

Summary of the results

We have examined recent trends in dynamical medium-range TC track prediction and the relative role of model resolution versus physics. The medium-range (day 3) was emphasised for two reasons: (a) any TC forecast aid must first make good track predictions before second-order properties such as maximum surface wind speed (intensity) can be considered in the official forecast (i.e. all aspects of the forecast must be physically reasonable and consistent) and (b) by 72 hours into the integration, model errors become dominant (i.e. a good analysis cannot overcome model errors).

The near halving in the mean 72-hour track forecast error for both the models and the official forecasts from ~300 nm in the mid 1990s to ~150 nm in the mid 2000s is a testament to the major advances in global NWP, especially in the modelling of the tropical general circulation.

A consensus, or simple averaging of the track forecasts from multiple, quasi-independent models, was found to have higher skill than any individual model and that the model was typically 20% worse at 72 hours than consensus. However, recent results from the ECMWF global model put this long-standing relationship into question.

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In November 2007 significant changes were made to the ECMWF model physics, including the parametrization of cumulus convection. By comparing TC track forecasts before and after changes in the ECMWF model physics, we found a dramatic improvement in medium-range track skill, especially in the convectively more active, monsoon-trough TC basins of the western North Pacific and the southern hemisphere. The improvement in the Atlantic was less pronounced, possibly due to approaching an asymptote in skill as the model and consensus forecasts in 2008 had the lowest errors in history (*Franklin,* 2008) and were below predictability estimates from the 1990s. We also found that an increase in the ECMWF model resolution in February 2006 had a smaller impact.

Personal views about the implications for medium-range TC track prediction

The implication of these ECMWF model results for the future of TC track prediction and hurricane model forecast improvement are many fold and in my opinion strongly challenge conventional wisdom. The following personal views do not fully follow from the results presented, but represent my interpretation based on over 30 years of experience with TC NWP modelling.

The first notion is that high spatial resolution is a necessary or even a sufficient condition for TC prediction. For TC simulation, the inner core must be resolved, but in regards to motion, dynamical considerations (*Fiorino & Elsberry,* 1989) and the global model results indicate that the resolution of ECMWF model (~ 25 km) is adequate as this model outperformed both the higher-resolution global model (T959L60) of the Japan Meteorological Agency (*JMA,* 2008) and the limited-area models (e.g. GFDL) in 2008.

My second impression is that TC motion becomes a global problem sooner than may have been previously thought. Consequently, by 72 hours small changes in the large-scale, far from the storm, have a significant effect on track, and that global-scale information must be *accurately* communicated into a limited-area model. However, the lateral boundary conditions cannot be mathematically formulated to perform this communication accurately (*Harrison & Elsberry,* 1972). Indeed, even if it were possible, there would be still be a 'physics' barrier because of differences in the parametrizations/physics between the global and limited-area model.

The most accurate approach to high-resolution TC modelling is either a cloud-resolving global model or a two-way interactive nest inside a global model, as opposed to one-way influence of a separate global model on a different limited-area model. The forecast time at which global-scale errors significantly degrade the limited-area model solution could be as early as 48 hours, in which case running such one-way influence models past 48 hours is counter-indicated.

The consensus approach to deterministic forecasting has been very successful over the last nine years and has motivated the application of single- and multi-model ensemble systems to improve consensus by adding solutions with higher skill and greater error decorrelation. However, the ECMWF model was 20% *better* than consensus *globally* in 2008 – a staggering achievement for an NWP model. Hitherto, the models were 20% *worse*. My third suggestion is that the path to better forecasts may not lie in multi-model ensembles, and that we must better understand how the ECMWF model broke through the 1990s predictability limits to find a way forward.

Fourthly, the reasonable assumption that skill, especially for intensity, is critically dependent on the analysis of the TC vortex is debatable. ECMWF is the only operational NWP centre that makes no TC-specific adjustments to the analysis of the TC wind structure. Other modelling systems use either synthetic observations or wholesale vortex replacement. One explanation why the ECMWF 'less-is-more' approach yields better TC track forecasts is that external vortex specification distorts the larger-scale flow around the cyclone and thereby adds error, albeit small, on scales that vortex motion is sensitive. In the current era of a huge observing system and accurate models, small errors do matter, and identifying the critical aspects of the TC vortex analysis problem will be more challenging.

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